Modulation of the diurnal cycle of tropical deep convective clouds by the MJO

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[1] The infrared cloud amount with cloud tops above 180 hPa from the International Satellite Cloud Climatology Project D1 cloud product and the Tropical Rainfall Measurement Mission 3B42 precipitation product are employed to study the impact of the Madden-Julian Oscillation (MJO) on the diurnal cycle of tropical deep convective cloud amount (DCC). Our analysis demonstrates that the diurnal cycle of tropical DCC is enhanced over both land and water during the convectively active phase of the MJO, while it is reduced during the convectively suppressed phase of the MJO. However, the diurnal phase of DCC is not significantly affected by the MJO. The analysis also indicates that the MJO modulation of the diurnal amplitude is much larger over the eastern Indian Ocean (around 50% of the mean diurnal amplitude) than over the western Pacific and the Maritime Continents (around 20% of the mean diurnal amplitude).

1. Introduction

[2] The diurnal (24 hour) cycle and the Madden-Julian Oscillation (MJO) are two fundamental modes of variability of the tropical deep convection. Both have been extensively studied for several decades [e.g., Wallace, 1975; Yang and Slingo, 2001; Tian et al., 2004; Madden and Julian, 1972; Lau and Waliser, 2005]. Previous studies have suggested an interesting scale interaction between the diurnal cycle and the MJO. Many studies have indicated that the diurnal cycles of tropical sea surface temperature (SST) and deep convection are strongly modulated by the MJO [e.g., Sui and Lau, 1992; Weller and Anderson, 1996; Chen and Houze, 1997; Sui et al., 1997a, 1997b; Johnson et al., 1999]. For example, Weller and Anderson [1996] and Johnson et al. [1999] documented that the diurnal cycle of SST at the equatorial west Pacific during the Tropical Ocean Global Atmosphere-Coupled Ocean-Atmosphere Experiment (COARE) is much larger during the periods of low wind than during the westerly wind phase of the MJO. Chen and Houze [1997] showed that the diurnal cycle of tropical deep convective cloud systems is much larger with an early morning maximum during the convectively active phase of the MJO, while it is much smaller with a peak in the afternoon during the convectively suppressed phase of the MJO. Similarly, Sui et al. [1997a, 1997b] found significant differences in diurnal variation of surface rain rate between the convectively active and suppressed phases of the MJO but no difference in the diurnal phase between these two MJO phases.

[3] Other studies have shown that the diurnal cycle can influence the MJO. For example, Johnson et al. [1999] and Slingo et al. [2003] indicated that the diurnal cycle of SST during the suppressed phase of the MJO may lead to a triggering of cumulus congestus clouds, which serve to moisten the free troposphere and hence precondition the atmosphere for the next active phase of the MJO. They also suggested that the strong diurnal cycle over the Maritime Continent (MC) may be responsible for the weakening of the MJO over this region. Woolnough et al. [2006] demonstrated that the diurnal cycle of SST can modulate the intraseasonal SST variation and in turn the MJO using a one-dimensional ocean mixed layer model.

[4] The studies of Sui and Lau [1992], Weller and Anderson [1996], Chen and Houze [1997], Sui et al. [1997a, 1997b], and Johnson et al. [1999] have significantly advanced our understanding of the impact of the MJO on the diurnal cycle of tropical deep convection; however, they are still limited in a number of ways. These studies are mainly based on a few MJO events with quite different characteristics during the COARE from November 1992 to February 1993 [Weller and Anderson, 1996; Chen and Houze, 1997; Sui et al., 1997a, 1997b; Johnson et al., 1999] or the First GARP Global Experiment in the winter of 1979 [Sui and Lau, 1992]. MJO events differ significantly from event to event in the strength, propagation speed, and spatial variability—particularly longitudinally. Thus, generalizing the conclusions of the above studies should be done cautiously. Also, these studies are limited to the western Pacific (WP) and/or the MC thus do not include the Indian Ocean (IO), where most MJO events initiate and intensify. In this study, we will use the International Satellite Cloud Climatology Project (ISCCP) D1 cloud product and the Tropical Rainfall Measurement Mission (TRMM) precipitation product to provide a more comprehensive study of the modulation of the diurnal cycle of tropical deep convection by the MJO.

2. Data and Methodology

[5] The infrared (11 μm) cloud amount with cloud tops above 180 hPa (colder than 215 K), referred to as deep convective cloud amount (DCC) [e.g., Fu et al., 1990], from the ISCCP D1 cloud product [Rossow and Schiffer, 1999] was used in this study to characterize the diurnal cycle of tropical deep convection. The data are on a global 280-km equal-area grid with 2.5° latitude by 2.5° longitude resolution at the equator and cover from 1 July 1998 to 30 June 2005.
2005 at a temporal resolution of 3 hours. During this period, METEOSAT-5 was operating and covering the IO between 35°E and 100°E while GMS covered the MC and the WP from 100°E to 180°. As a result, the selected ISCCP data are ideal for studying the influence of the MJO on the diurnal cycle of tropical deep convection. In this study, we will focus mainly on the Indo-Pacific warm pool and the boreal winter (November – April) since the MJO convective activity is most active in this region during this season [Wang and Rui, 1990]. A similar study but for the boreal summer (May – October) will be reported separately.

To identify MJO events, the TRMM 3B42 precipitation data from 1 January 1998 to 31 March 2006 and the methodology of Tian et al. [2006] were used. The rainfall was first binned into 5-day average (i.e. pentad) values on 1.0° by 1.0° grids from the original 3-hour and 0.25° by 0.25° resolution. Intraseasonal anomalies were obtained by removing the annual cycle and then band-pass filtering (30–90 days) the data. To isolate the dominant structure of the MJO, an extended empirical orthogonal function (EEOF) was applied using time lags of ±5 pentads on boreal winter data for the region 30°S–30°N and 30°E–150°W. Next, MJO events were chosen based on the amplitude pentad time series of the first EEOF mode [see Tian et al., 2006, Figure 2]. The peak amplitude dates of the selected 18 MJO events are 18 Jan. 1999, 22 Feb. 1999, 24 Nov. 1999, 17 Feb. 2000, 14 Nov. 2000, 19 Dec. 2000, 28 Jan. 2001, 27 Feb. 2001, 18 Jan. 2002, 9 Nov. 2002, 19 Dec. 2002, 28 Jan. 2003, 19 Mar. 2003, 4 Dec. 2003, 18 Jan. 2004, 27 Feb. 2004, 23 Apr. 2004, and 24 Mar. 2005.

The above analysis was performed at each grid point in the area of our study. Over most regions in the Indo-Pacific warm pool, the first diurnal harmonic explains over 90% of the total variance of the diurnal cycle except for a few regions, where the semi-diurnal cycle is strong. Thus, the first diurnal harmonic is a reliable representative of the diurnal cycle in this region. In subsection 3.3, the area-mean “MJO diurnal cycle” for selected regions will be plotted and compared to the diurnal amplitudes and phases of the first diurnal harmonic to further check its reliability in representing the diurnal cycle.

3. Results
3.1. Diurnal Amplitudes and Phases of the “Mean Diurnal Cycle”

Figure 1a shows the daily mean DCC based on the “mean diurnal cycle”. The distribution of the mean DCC is consistent with the well-known locations of boreal winter tropical deep convection, with local maxima over the equatorial Africa, the Indo-Pacific warm pool, as well as the inter-tropical convergence zone and southern Pacific convergence zone (SPCZ). The whole-area maxima (~6%) are located over the large islands of the MC, such as Sumatra, Borneo, and New Guinea, as well as the SPCZ. The diurnal amplitude and phase of the “mean diurnal cycle” of DCC are presented in Figures 1b and 1c, respectively. Large diurnal variations in DCC (around 2–4%) are observed over the deep convective regions, such as the equatorial Africa, the Indo-Pacific warm pool, and the SPCZ. Figures 1b and 1c also demonstrate a clear land-sea contrast in the diurnal amplitudes and phases. Over land, the diurnal amplitude of DCC is much larger (around 3.5%, about 60% of the mean), and the diurnal phase of DCC is the late afternoon and early evening (1700–2200 LST). Over the ocean, the diurnal amplitude of DCC is smaller (around 1%, only about 20% of the mean). The diurnal phase of oceanic DCC is around the morning (0300–1000 LST). The present results agree with the general characteristics of diurnal cycle of tropical
3.2. Diurnal Amplitudes and Phases of the “MJO Diurnal Cycle”: MJO Modulation

Diagrams similar to Figure 1 but based on the “MJO diurnal cycle” (not shown) indicate a clear MJO impact on the diurnal cycle. To highlight the role of the MJO in the diurnal cycle, MJO anomalies of daily means, diurnal amplitudes and phases at each lag (i.e. ±5 pentads) were computed from the difference between the “MJO diurnal cycle” and the “mean diurnal cycle”. Figure 2 shows the MJO anomalies of diurnal amplitudes of DCC (relative to the mean in Figure 1b). For simplicity, only lags -3 to +3 pentads of the MJO cycle are shown. The black contour lines overlaid on the color shading are the corresponding TRMM rainfall MJO anomalies. Over the Indo-Pacific warm pool, where MJO convection is active, the modulation of the diurnal amplitude by the MJO is evident. For example, the positive (negative) MJO anomalies of diurnal amplitude and their eastward propagation are coincident with the positive (negative) rainfall MJO anomalies and their eastward propagation. This implies that the diurnal cycle of DCC is enhanced during the convectively active phase of the MJO (with activity measured by the TRMM rainfall anomaly), while it is reduced during the convectively suppressed phase of the MJO. The MJO anomalies of diurnal amplitude vary up to ±0.5%. This represents about 15–60% of the mean diurnal amplitude in Figure 1b (see detailed discussions in subsection 3.3).

To help understand the influence of the MJO on the diurnal amplitude, Figure 3 displays MJO anomalies of the
Area-weighted mean diurnal anomalies of DCC relative to its daily mean for each MJO lag based on the “MJO diurnal cycle” for four selected regions (see boxes in Figure 1a and text): (a) EIO, (b) WP, (c) MC land region, and (d) MC oceanic region. The color red denotes positive diurnal anomalies, while the color blue indicates negative diurnal anomalies. Note that the diurnal anomalies over water (Figures 4a, 4b, and 4d) were amplified by a factor of 4 so the same color scale can be used over both land and water. The superimposed solid black line denotes the TRMM rainfall MJO anomaly (mm day⁻¹, scale given on top of Figure 4a), while the dashed black line indicates the daily mean DCC (% scale given on top of Figure 4b). The analogous figure to Figure 2 but for diurnal anomalies of DCC is presented in Figure 4. Variations in the x-direction illustrate the changes in the diurnal cycle, while the variations in the y-direction indicate the impact of the MJO. The four selected regions (see boxes in Figure 1a) are: (a) Eastern IO (EIO) (10°S–5°N, 75°E–95°E), where most MJO events intensify; (b) WP (10°S–10°N, 150°E–180°), corresponding to the COARE large-scale array; (c) MC (15°S–10°N, 100°E–150°E) land region (land fraction > 65%; based on ISCCP land-sea mask), where most MJO events typically undergo weakening; and d) MC oceanic region (land fraction < 35%). Note that the diurnal anomalies over water (Figures 4a, 4b, and 4d) are amplified by a factor of 4 so the same color scale can be used over both land and water. Consistent with diurnal amplitude and phase maps in Figures 1b and 1c, there exists a distinct land-sea contrast in the diurnal anomalies of DCC in Figure 4. Over the islands of the MC (Figure 4c), the diurnal anomalies of DCC are much larger (around ±3.5%, about 60% of the mean), and maximum DCC occurs in the late afternoon and early evening (1700–2200 LST). On the other hand, the diurnal anomalies of DCC are relatively smaller (around ±1%) over water (the EIO, the WP, and the MC oceanic region, Figures 4a, 4b, and 4d), only about 20% of the mean. The oceanic DCC tends to peak in the early morning (~0300–0400 LST) in the EIO and the WP and late morning (0600–0900 LST) in the MC oceanic region. Figure 4 indicates that the diurnal anomalies of DCC over both land and water are larger during the convectively active phase of the MJO and smaller during the convectively suppressed phase of the MJO. For example, over the islands of the MC, the diurnal anomalies of DCC range from around −4% to +4% during the convectively active phase of the MJO, while they vary from around −3% to +3% during the convectively suppressed phase. Thus, the diurnal anomalies over the islands of the MC are weakened about 25% during the convectively suppressed phase of the MJO compared to the convectively active phase. Over the EIO, the WP, and the MC oceanic region, the diurnal anomalies of DCC vary from around −1% to +1% during the convectively active phase of the MJO, while they vary from around −0.5% to +0.5% during the convectively suppressed phase. Therefore, over water the diurnal anomalies are reduced about 50% during the convectively suppressed phase of the MJO compared to the convectively active phase, with the most significant oceanic MJO modulation occurring over the EIO and weakest MJO modification over the WP. The MJO modulation of the diurnal
anomalies for the four regions agrees with the MJO anomalies of the diurnal amplitude in Figure 2. Also evident from these diagrams and consistent with the discussions above, the MJO appears to have no impact at all on the diurnal phase of DCC over land or water. The overall agreement between the diurnal anomalies in Figure 4 and the diurnal amplitudes and phases in Figures 1, 2, and 3 also demonstrates the representativeness of the first diurnal harmonic in describing the diurnal cycle as mentioned in section 2.

[16] To quantify the relative importance of the MJO and diurnal cycle in the mean DCC and the impact of MJO on the diurnal amplitude, the mean DCC, MJO anomalies, diurnal amplitudes, and MJO modulation of the diurnal amplitude of DCC for these four regions are summarized in Table 1. Here, the MJO anomaly is defined as half the maximum-minimum difference of the mean DCC within a MJO cycle. Similarly, the MJO modulation of the diurnal amplitude is defined as half the maximum-minimum difference of diurnal amplitude within a MJO cycle. Table 1 indicates that the mean DCC ranges from 2.9% (EIO) to 4.4% (WP) over ocean and is largest (6%) over the islands of the MC. The diurnal amplitudes vary from 0.6% over the EIO to 3.5% over the islands of the MC, revealing the clear land-sea contrast with a large diurnal variation (about 60% of the mean) over the islands of the MC and a small diurnal variation (about 20% of the mean) over the ocean. The MJO anomalies change from 0.9% over the WP to 1.0% over the EIO indicating a considerable regional difference. The influence of the MJO on the mean DCC is weakest over the WP and the MC land region (around 20% of the mean) and largest over the EIO (around 60% of the mean). Accordingly, the regional variations of the MJO modulation of the diurnal amplitude seem to follow those of the MJO anomalies. It is also weakest over the WP and the MC land region (around 20% of the mean diurnal amplitude) and largest over the EIO (around 50% of the mean diurnal amplitude). The MJO modulation of the diurnal amplitude ranges from 0.3% over the EIO to 0.5% over the islands of the MC.

4. Discussion and Conclusions

[17] Our results have a number of notable similarities and contradictions to those from previous studies. Based on the two MJO events over the tropical western Pacific during the 1979 boreal winter, Sui and Lau [1992] found that periods of active MJO are characterized by diminished diurnal cycle and vice versa. Their findings are opposite, in this regard, to our results. Chen and Houze [1997] examined the impact of the two MJO events during the COARE on the diurnal variation of tropical deep convection over the western Pacific warm pool using GMS data. They indicated that the diurnal cycle of deep convective cloud systems is amplified and has an early morning maximum during the convectively active phase of the MJO as a result of spatially large and long-lived cloud systems, while it is suppressed and with an afternoon peak during the convectively suppressed phase of the MJO due to spatially small and short-lived cloud systems. Their conclusions agree with ours regarding the diurnal amplitude but contradict ours regarding the diurnal phase. Similarly, Sui et al. [1997a, 1997b] showed that diurnal variations of surface rain rate from radar reflectivity are much larger (0.29–0.48 mm hour$^{-1}$) during the convectively active phase of the MJO and much smaller (0–0.15 mm hour$^{-1}$) during the convectively suppressed phase of the MJO [Sui et al., 1997b, Figures 4 and 12]. However, they did not find any difference in the diurnal phase between these two MJO phases. Their results are consistent with ours regarding the impact of the MJO on both the diurnal amplitude and phase. The above studies of Sui and Lau [1992], Chen and Houze [1997], and Sui et al. [1997a, 1997b] are mainly based on a couple of MJO events from one winter season. In contrast, the results presented here are based on the composite of 18 MJO events from seven winter seasons, and thus are expected more robust. In addition, the regions of the above studies were limited to the WP and the MC, while our analysis includes the broader area of the Indo-Pacific warm pool including the IO, and thus is expected to more completely cover the regional variations. Please note that the diurnal cycles of the tropical clouds depends on the cloud type and height [Tian et al., 2004] and thus it is expected that the impact of the MJO on the diurnal cycle might be different for different cloud types [Johnson et al., 1999; Slingo et al., 2003]. We will address this issue in more detail in a separate paper.

[18] To summarize, we have found that the diurnal cycle of tropical DCC over both land and water is enhanced during the convectively active phase of the MJO, while it is reduced during the convectively suppressed phase of the MJO. However, the MJO appears to have no impact at all on the diurnal phase of DCC over land or water. In particular, we have found that the MJO modulation of the diurnal amplitude is much larger over the EIO (around 50% of the mean diurnal amplitude) than that over the WP and the MC (around 20% of the mean diurnal amplitude).

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