Diurnal Cycle of the Asian Summer Monsoon: Air Pump of the Second Kind

GUIXING CHEN

School of Atmospheric Sciences and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China

(Manuscript received 18 March 2019, in final form 6 November 2019)

ABSTRACT

Diurnal variations of rainfall and winds are pronounced over the Asian summer monsoon region, but their activities under different monsoon conditions are not clarified. Here, the diurnal cycle of monsoon flow and its influence are examined using 20-yr satellite rainfall and reanalysis data. A total of 1840 summer days are partitioned into four dynamic groups of strong or weak background flows with large or small diurnal amplitudes of low-level meridional wind. Large-scale southerly wind is found to be strongest after midnight, with a large diurnal amplitude on strong monsoon days over central-north India and southeast China. Such a nocturnal speed-up is closely associated with the Blackadar boundary layer inertial oscillation due to the diurnal heating over low-lying landmass. It acts like a large air pump that injects moisture poleward at night and strengthens monsoonal circulation with anomalous rising motion at the northern rainband of the Asian monsoon. In particular, monsoon southerlies with large nighttime speed-up converge with downslope winds from the Himalayas or northerly anomaly from midlatitudes. Enhanced water vapor convergence facilitates the growth of organized convection, producing substantial rainfall at the Himalayan foothills in predawn hours and at the mei-yu-baiu zone from predawn to noon. When monsoon flow undergoes a small diurnal cycle, rainfall is instead displaced south and mostly recorded in daytime. Both the daily mean and morning peak of rainfall are suppressed on land under weak monsoon southerlies. Moreover, the monsoon diurnal cycle exhibits evident intraseasonal/interannual variations and contributes to rainfall variability. The results highlight that monsoon flow couples with subdaily forcings to strongly regulate the detailed patterns of rainfall and moisture budget over the Asian monsoon regions.

1. Introduction

An abundance of rainfall occurs over Asia during the summer monsoon season, which has a profound influence on a large portion of the global population (Fig. 1). It has long been recognized that monsoon rainfall exhibits large variabilities from hours to interannual time scales (e.g., Li and Yanai 1996; Dai 2001; Goswami and Mohan 2001; Sen Roy and Balling 2007; Ding et al. 2008; Romatschke et al. 2010; Singh and Nakamura 2010; Johnson 2011; Fujinami et al. 2014, 2017). Frequent heavy rainfall takes place under strong monsoon conditions (Ding and Chan 2005; Rajevean et al. 2010; Krishnamurthy and Shukla 2007). In recent years, the

large diurnal variations in winds, convective activities, and rainfall over the Asian monsoon region have drawn remarkable attention (Ohsawa et al. 2001; Hirose and Nakamura 2005; Fujinami et al. 2005; Yu et al. 2007a; Li et al. 2008; Zhou et al. 2008; Chen et al. 2009; Sahany et al. 2010; Xue et al. 2018). Advancing our knowledge of the multiscale variabilities of summer monsoon is important for climate studies, precipitation forecasting, and water resource management (Dai 2006; Basu 2007; Dirmeyer et al. 2012; Yuan et al. 2013a; Li et al. 2018).

The diurnal variation of rainfall becomes pronounced in summer and exhibits evident regional features over Asia. Rainfall usually maximizes in afternoon hours on land over the Indian subcontinent, Indochina Peninsula, and southern China, coinciding with the maximum of surface temperature (Oki and Musiak 1994; Hirose and Nakamura 2005; Yu et al. 2014). The rainfall near dawn instead is more substantial at windward coasts where monsoon flow interacts with local land-sea breeze (Ramage 1952; Johnson 2011; X. Chen et al. 2017; G. Chen et al. 2018). The rainfall

Denotes content that is immediately available upon publication as open access.

Corresponding author: Guixing Chen, chenguixing@mail.sysu.edu.cn

FIG. 1. (a) Topography over Asia and the key regions of this study. (b) JJA mean rainfall in TRMM and 925-hPa winds in JRA-55. (c) JJA rainfall ratio to annual amount and 200-hPa winds averaged over 1998–2017. Short and long barbs denote 2 and 4 m s^{-1} . In (a), the blue rectangles at the Himalayan foothills (26° – 30°N , 75° – 90°E) and central China (28° – 33°N , 110° – 125°E) denote the key areas for estimating rainfall, while the red rectangles to the south at central-north India and southeast China are for estimating monsoon southerlies. The bold dashes in (b) denote the tropical and northern rainfall zones, and the thin dashes denote the elevations at an interval of 1000 m.

is also observed after midnight at low-lying areas such as the Himalayan foothills, Sichuan basin, and East China plain (Sahany et al. 2010; Bao et al. 2011; Yuan et al. 2012). A distinct peak of rainfall near sunrise is seen in the East Asian summer rainband particularly during the mei-yu/

baiu period (Geng and Yamada 2007; Yamada et al. 2007; Chen et al. 2013). The seasonality and regionality in rainfall diurnal cycle suggest that a variety of atmospheric processes may respond to the differential diabatic heating over inhomogeneous surfaces over Asia.

Along with the seasonal change of monsoon flow, the low-level winds also undergo remarkable diurnal variation during summer. The southerly winds over Bangladesh and southern China become the strongest from midnight to predawn (Terao et al. 2006; G. Chen et al. 2009; H. Chen et al. 2010; Fujinami et al. 2017). Daily wind anomalies (mostly as ageostrophic wind) rotate clockwise from easterly in the afternoon to southerly wind at midnight. Such an inertial oscillation reflects a response to the diurnally varying frictional effect of ABL mixing and the Coriolis effect (Blackadar 1957). Meanwhile, the differential heating at coasts, plateaus, or sloped terrains can induce a diurnal change in pressure gradient, resulting in land–sea breeze (LSB) or mountain–plains solenoid (MPS) circulations (Holton 1967). Regional pressure gradients may be coupled with global pressure tide to produce a planetary-scale LSB between the Asian continent and western North Pacific (Huang et al. 2010). The Blackadar and Holton theories are often combined to explain the wind diurnal variations, although the former may have a larger contribution (Du and Rotunno 2014; Shapiro et al. 2016). Diurnal variation of low-level winds also exhibits a strong dependence on background flows. Chen et al. (2009, 2013) noted that a large diurnal amplitude tends to occur on strong monsoon days at southeast China, which is referred to as the diurnal monsoon variability (DMV). Xue et al. (2018) analyzed the strong monsoon periods and found that “the commonly recognized diurnal monsoon variability can be explained by the Blackadar inertial oscillation theory” (p. 5090). Recent studies also show diurnal variations of southerly monsoon flow and rainfall under different synoptic-scale conditions relating to the intra-seasonal oscillations (ISOs) over Bangladesh and southern China (Fujinami et al. 2017; X. Chen et al. 2019). As the DMV occurs in a broad geographical area, it may relate to both large-scale monsoon circulations and regional forcings. So far, a climatology of the DMV with different intensities of background monsoon flow and diurnal amplitude remains to be clarified.

It has been well recognized that the diurnal variation of low-level winds, particularly nocturnal low-level jets (LLJs), can strongly regulate rainfall (e.g., Tuttle and Davis 2006; Monaghan et al. 2010; Trier et al. 2014; Du and Chen 2019). The enhanced low-level winds after midnight also produce nocturnal rainfall over many areas of the Asian summer monsoon (Terao et al. 2006; G. Chen et al. 2009, 2013; H. Chen et al. 2010; Kanada et al. 2014; Fujinami et al. 2017; Shin et al. 2019). For

instance, the nocturnal LLJ in southwesterly monsoon flow can transport abundant moisture, strengthen low-level ascent, and generate convective instability by the convergence at the mei-yu-baiu front, triggering heavy rains in predawn hours (G. Chen et al. 2017; Xue et al. 2018; Zeng et al. 2019). Moist monsoon flow may also couple with local-scale MPS/LSB to produce nocturnal rainfall at plains or windward coasts (Johnson 2011; Romatschke and Houze 2011; Sun and Zhang 2012; X. Chen et al. 2017; G. Chen et al. 2018; Fu et al. 2018; Zhang et al. 2018; Pan and Chen 2019). These previous studies, while mostly focusing on a summer mean or specific periods, indicate that the DMV can likely be effective in generating nocturnal rainfall, and thus it may play an important role in the warm-season climate over Asia.

In summer, the sensible heat-driven surface circulation converges toward the Tibetan Plateau with upper divergence, which acts like a seasonal large-scale air pump and contributes to the formation of the Asian summer monsoon (e.g., Yeh et al. 1957; Yanai et al. 1992; Wu et al. 1997, 2015). At shorter time scales, the continental-scale upper divergent circulation over Asia undergoes a pronounced diurnal pulsation and exhibits a close association with afternoon deep convection over the Indian subcontinent (Krishnamurti and Kishtawal 2000). Large diurnal changes in convective activity coupled with the convergent/divergent circulations are also observed over the Tibetan Plateau (Ye and Wu 1998; Chow and Chan 2009). The Tibetan high and tropical easterly jet at its southern flanks are intensified (suppressed) in early evening (morning), which appears to be an integral part of the monsoon system. Such a diurnal mode of monsoon with afternoon-peak rainfall seems to express an adjustment of atmospheric circulation to the daytime solar heating on land. However, because the low-level winds are suppressed in daytime but strengthened at night, we may expect another diurnal mode of the monsoon flow with a delayed phase that instead regulates the nocturnal rainfall (Chen et al. 2009, 2013; Fujinami et al. 2017; Xue et al. 2018). It is currently unclear how this diurnal mode with enhanced large-scale monsoon flow at night affects the climate over Asia. Moreover, the Asian summer monsoon has two major subsystems: the Indian and East Asian summer monsoon (ISM and EASM). The ISM and EASM regions differ somewhat in background winds, synoptic-scale disturbances, and terrains (Fig. 1; Tao and Chen 1987; Goswami et al. 2003; Ding and Chan 2005). A comparison of them may help us a better understanding of the monsoon variabilities over Asia.

In this study, the role of DMV in the Asian summer climate is examined using 20 years of satellite rainfall and atmospheric reanalysis data. The DMV will be partitioned into four dynamic quadrants based on the

daily mean and diurnal amplitude of monsoon flow, so that the multiscale features can be clarified. Specific focus is placed on the DMV's characteristics and influence on precipitation over the ISM and EASM regions. The rest of the article is organized as follows. Section 2 introduces the data and methods used in this study. Section 3 shows the summer-mean diurnal cycles of rainfall and winds. In section 4, the statistics of four DMV groups and associated atmospheric circulations are illustrated. The detailed influence of the DMV on precipitation activity and moisture budget as well as their intraseasonal/interannual variations are examined in section 5. Finally, conclusions and a discussion are given in section 6.

2. Dataset used in this study

In this study, the analysis utilizes the Japanese 55-Year Reanalysis (JRA-55) to depict atmospheric conditions. JRA-55 is a recent global reanalysis with improved model processes and data assimilation scheme (Kobayashi et al. 2015). It provides 6-hourly assimilated atmospheric data at a spatial resolution of 1.25° longitude/latitude. The performance of JRA-55 and other three reanalysis datasets for representing the diurnal cycles has been extensively evaluated (Chen et al. 2014). JRA-55 is shown to faithfully capture the diurnal variations of winds, temperature, and humidity as well as their regionality and seasonality over East Asia. It also captures well the spatial patterns, seasonal change, and long-term variations of rainfall diurnal cycle, indicating an excellent representation of moist processes at a wide range of time scales.

The precipitation analysis uses the rainfall estimate of Tropical Rainfall Measuring Mission (TRMM 3B42 v7), which has been calibrated by rain gauge monthly records (Huffman et al. 2007). TRMM provides 3-hourly rain rate at a spatial resolution of 0.25° longitude/latitude. It has been shown to represent well the spatial pattern of rainfall diurnal cycle, which resembles rain gauge observations (e.g., Zhou et al. 2008; Chen et al. 2018). To relieve a possible effect of the systematic bias in diurnal cycle, we pay attention on the difference of satellite rainfall among four DMV conditions. The analysis covers a 20-yr-long period from 1998 to 2017, with emphasis on summer (JJA), having a total of 1840 days. The diurnal deviations of any variables at the specific synoptic hours (e.g., 0600, 1200, 1800, and 0000 UTC) are obtained by subtracting the daily mean. Given local standard time (LST = UTC + 6–8 h) over Asia, the four synoptic hours denote near noon, late afternoon (or sunset), near midnight, and predawn (or sunrise), respectively.

3. Diurnal cycles of summer rainfall and winds over Asia

a. Spatial patterns of the diurnal variations in summer rainfall

Figure 1b shows that the Asian monsoon has southern and northern rainbands (e.g., Wu et al. 2015). The southern one features high rainfall amount along the tropical coasts at 10° – 23° N with onshore monsoon southwesterlies (Xie et al. 2006). The northern rainband appears at the zone of 26° – 35° N extending from the Himalayan foothills to East Asia. It is related to the southerly monsoon flow from lower latitudes of $\sim 25^{\circ}$ N. The northern rainband is thus a key part of monsoon meridional circulation with low-level southerly wind and upper-level return flow (Figs. 1b,c), which is the focus of this study (Fig. 1a).

Figure 2 shows the JJA-mean diurnal cycles of rainfall derived from satellite observation. From noon to early afternoon, rainfall mainly appears on coastal land (Fig. 2a). At late afternoon or sunset, rainfall is dominant over heated landmasses such as the Indochina Peninsula, Indian subcontinent, and Tibetan Plateau (Fig. 2b). In contrast, rainfall is suppressed over oceans and low-lying areas surrounding the Tibetan Plateau. The terrain-dependent features reveal a strong influence of thermal contrast by daytime heating (Krishnamurti and Kishtawal 2000; Chow and Chan 2009; Yuan et al. 2012).

Figure 2c shows that, from midnight to predawn, rainfall becomes evident at the Himalayan foothills, Sichuan basin, North China plain, and the seas around the Korean peninsula and Japan. In the morning after sunrise, rainfall is still obvious at the Himalayan foothills and Sichuan basin (Fig. 2d). Rainfall instead intensifies at central China and the East China Sea ($\sim 30^{\circ}$ N), displaced south compared to that in previous hours (cf. Figs. 2d,c). The spatial patterns resemble well the highest daily-mean rainfall at tropical oceans and the northern rainband (Fig. 1b), suggesting that the morning rain systems contribute greatly to the total rainfall amount (Johnson 2011). These areas with prevalent morning rainfall also experience frequent extreme rainfall events (Hamada et al. 2014). Thus, the diurnally varying processes and atmospheric conditions associated with the nocturnal rainfall should be regarded as a key component of the Asian monsoon system.

b. Spatial patterns of the diurnal variations in horizontal winds and convergence

Figure 3 shows the diurnal cycles of horizontal winds and divergence. At 0600 UTC, the northerly anomaly appears over East Asia, while the easterly/northeasterly anomaly is seen over South Asia (Fig. 3a). Strong convergence occurs at coasts/islands due to local sea breeze,

FIG. 2. (a)–(d) Normalized diurnal cycle of summer rainfall derived from TRMM in 1998–2017. The longitudinal variation in local standard time is marked along the x coordinate. Note that, as satellite products overestimate afternoon–evening rainfall but underestimate predawn–morning rainfall, a correction of -0.15 is added to (a),(b) and of $+0.15$ is added to (c),(d) following Chen et al. (2018).

FIG. 3. Diurnal variations of the horizontal winds (short and long bars denoting 0.5 and 1 m s^{-1}) and divergence (shading) at (a)–(d) 925 and (e)–(h) 200 hPa. The variables are anomalies from daily mean. The longitudinal variation in local standard time is marked along the x coordinate.

while moderate convergence is seen over oceans due to continent-scale “land–sea” breeze (Huang et al. 2010). A southerly anomaly is seen at upper levels with divergence over oceans (Fig. 3e). At 1200 UTC (near sunset), a low-level easterly anomaly prevails over the western Pacific, East Asia, and the Indian subcontinent (Fig. 3b). Low-level winds are convergent at the east of Tibetan and Deccan Plateaus where deep convection develops with an upper divergent circulation (Figs. 3b,f). It acts like an air pump over terrains driven by daytime heat at diurnal time scale (Krishnamurti and Kishtawal 2000; Chow and Chan 2009). However, low-level northerly/easterly anomalies are nearly opposite to the background flow over India and East Asia (cf. Figs. 3a,b and 1b). This suggests a suppressed phase of monsoon southwesterlies on land in the afternoon hours.

Figure 3c shows that, at 1800 UTC, a low-level southerly anomaly is seen over East Asia and India. It enhances background flow and leads to a nocturnal acceleration of monsoon flow (Chen et al. 2009; Fujinami et al. 2017; Xue et al. 2018). The induced low-level convergence is evident at the Himalayan foothills and the low-lying areas of East Asia where nocturnal rainfall develops (Figs. 3c and 2c). The nocturnal southerly wind seems to regulate the northern rainband of Asian monsoon, which inspires in-depth analyses in sections 4 and 5. The low-level southerly (Fig. 3c) and upper-level northerly anomalies (Fig. 3g) suggest an enhanced monsoonal circulation at night. At 0000 UTC near sunrise, a low-level westerly anomaly prevails over East Asia and India (Fig. 3d). Local convergence still appears at the Himalayan foothills with downslope winds. Over East Asia, strong convergence is displaced south to the latitudes of $\sim 30^\circ\text{N}$, where the southwesterly winds from southern China converge with the northerly anomaly from northern China, the Korean peninsula, and Japan. Low-level convergence and upper divergence are also observed over oceans (Figs. 3d,h). The patterns are collocated with the morning rainfall at the offshore areas, Himalayan foothills, and mei-yu-baiu zone (Fig. 2d).

Figure 4 further shows the diurnal cycles of local meridional circulation over ISM and EASM regions. At 0600 UTC, the upward branch of the circulation appears at low latitudes (Figs. 4a,e). Rising motion develops at the Himalayan slope and manifests the growing MPS. At 1200 UTC, rising motion dominates over central-north India ($\sim 24^\circ\text{N}$) and the Himalayas ($30^\circ\text{--}31^\circ\text{N}$) (Fig. 4b). It extends to the upper troposphere due to afternoon deep convection. The warm moist air is elevated at central-north India and the Himalayan slope as shown by the bulging of equivalent potential temperature (θ_e). The northerly wind forms at the upper troposphere as a part of the diurnal divergent circulation (Krishnamurti

and Kishtawal 2000). The downward branch is mainly located over oceans to the south of 20°N . The sinking motion is also extensive over East Asia due to a subsidence from the Tibetan Plateau (Fig. 4f).

Figures 4c and 4g show that at 1800 UTC the upward branch is established at the Himalayan foothills, the Indo-Gangetic plain ($\sim 26^\circ\text{N}$), and eastern China ($\sim 35^\circ\text{N}$). It is closely related to the enhanced southerly wind, with a maximum of $\sim 1\text{ m s}^{-1}$ at $\sim 925\text{ hPa}$ and an elevated high θ_e . Monsoonal circulation is thus intensified after midnight even though the continent is cooled. At 0000 UTC, the upward branch develops at southern coasts with an increasing morning rainfall (Figs. 4d,h). Rising motion remains at central China ($\sim 29^\circ\text{N}$), but it decays at the Himalayan foothills and the Indo-Gangetic plain. The difference is likely due to the meridional winds that are still convergent after sunrise over East Asia (Fig. 3d).

4. Diurnal monsoon variability and associated atmospheric circulations

a. Definitions of the southerly monsoon flow and its diurnal cycle

During the boreal summer, strong low-level westerly/southwesterly flow dominates the Asian tropical areas (Fig. 1b; Li and Yanai 1996). The prevailing winds tend to turn northward at the latitudes near 25°N and affect the northern rainband. Figures 5a and 5b show the patterns of rainfall and low-level winds regressed onto the standardized daily rainfall at the northern rainband of ISM and EASM, as in Fujinami et al. (2017). Positive rainfall anomalies ($\geq 8\text{ mm day}^{-1}$) are observed at the Himalayan foothills and central China. Accordingly, a southwesterly wind anomaly at 925 hPa appears at central-north India and southeast China. Over there, the meridional wind component has a maximum positive correlation with the rainfall of northern rainband. The correlation coefficient is marginally larger than that between the zonal wind component and rainfall, implying that the fluctuations in southerlies are more tied to the rainfall. Likewise, the regression patterns of rainfall diurnal difference and wind diurnal deviation suggest that the nocturnal rainfall is also tied to the southerly wind anomaly at night (Figs. 5c,d). Thus, the low-level meridional wind, which is evident in two rectangular regions ($20^\circ\text{--}25^\circ\text{N}$, $75^\circ\text{--}90^\circ\text{E}$ and $22.5^\circ\text{--}27.5^\circ\text{N}$, $110^\circ\text{--}125^\circ\text{E}$) at both daily and diurnal time scales, can measure the monsoon southerlies of the ISM and EASM (Fig. 1a). Such a definition using monsoon southerlies is also applied in other studies focusing on the northern rainband of the Asian monsoon (Wang and Fan 1999; Ding and Chan 2005). In this study, the daily mean and the diurnal deviation at 1800 UTC of the 925-hPa

FIG. 4. Diurnal variations of the monsoon meridional circulation over the (a)–(d) ISM and (e)–(h) EASM regions. Diurnal deviations of vertical motion (shading) and meridional wind (streamline color) are derived by subtracting the daily mean. The contours denote the equivalent potential temperature (θ_e) above 342 K (338 K) with an interval of 2 K in the left (right) panel.

Regression to the northern rainband

FIG. 5. Regression patterns of rainfall (shading) and horizontal wind (vectors) at 925 hPa based on the normalized daily rainfall time series at the northern rainband of the (a) ISM and (b) EASM. (c), (d) As in (a), (b), but in a diurnal perspective, that is, the regression of the rainfall difference (AM hours minus PM hours) and the diurnal deviation of winds at 1800 UTC based on the normalized time series of rainfall diurnal difference. Only areas of rainfall that are statistically significant at the 99% level are shaded. Blue solid lines show the correlation coefficient between the rainfall series and the meridional wind component at 925 hPa. The correlation coefficient above 0.1 (at the 99% confidence level) is plotted. The thin dashes denote the elevation at an interval of 1000 m.

southerly wind are used to represent the intensities of the background monsoon and its diurnal amplitude, respectively.

We further examine the seasonal change of two indices to clarify the representation of monsoon activities. Figure 6a shows that the daily-mean low-level southerly wind increases markedly at June and stays strong at July–August over both the ISM and EASM regions, corresponding to the establishment of the summer monsoon. Figure 6b shows that the diurnal amplitude of low-level winds increases rapidly in May and becomes largest in JJA, suggesting an intensified diurnal cycle in the warm season. The diurnal amplitude of southerly wind reaches $\sim 0.9 \text{ m s}^{-1}$ in JJA in the ISM region, which is slightly stronger than that in the EASM region. Thus, low-level southerly winds at both daily and diurnal time scales undergo a pronounced seasonal change, in close association with the summer monsoon over Asia. The

daily mean and diurnal cycle of upper-level northerly winds also become most evident in JJA, as a returning flow of monsoonal circulation.

We further estimate the daily mean and diurnal amplitude of low-level southerly winds for all 1840 summer days in 1998–2017. To facilitate the analysis, anomalies of the two indices are estimated by subtracting their summer mean. The summer days can be categorized into four dynamic quadrants of monsoon southerlies, as shown in Figs. 7a and 7c. The quadrants to the right (Q1/Q4) denote strong monsoon conditions with stronger-than-normal daily southerly wind, while those to the left (Q2/Q3) denote weak monsoons. The daily southerly wind over the ISM (EASM) region has a mean of 3.00 m s^{-1} (4.97 m s^{-1}) in Q1/Q4 and 0.63 m s^{-1} (0.08 m s^{-1}) in Q2/Q3, with a standard deviation of 1.47 m s^{-1} (3.03 m s^{-1}). The upper quadrants (Q1/Q2) have a large diurnal variation with an above-normal amplitude of nocturnal southerly wind,

FIG. 6. Monthly variations of the meridional wind at 925 (red) and 200 hPa (blue) over central-north India (open circles) and southeast China (closed circles). The areas for average are shown in Fig. 1a.

while the bottom quadrants (Q3/Q4) have a relatively small diurnal variation. The diurnal amplitude over ISM (EASM) has a mean of 1.21 m s^{-1} (1.18 m s^{-1}) in Q1/Q2 and 0.60 m s^{-1} (0.43 m s^{-1}) in Q3/Q4, with a standard deviation of 0.38 m s^{-1} (0.48 m s^{-1}). Therefore, the four dynamic groups are distinguishable from each other.

Figures 7a and 7c show that the intensity of diurnal amplitude is correlated with that of daily mean, with a correlation coefficient of $+0.24$ ($+0.34$) over the ISM (EASM) above the 99.9% confidence level. About 60% of summer days are characterized by the strong monsoons coupling with a large diurnal cycle (Q1) or the weak monsoons with a small diurnal cycle (Q3), while the other 40% are categorized as Q2/Q4. The large (small) wind diurnal variation thus tends to occur in the strong (weak) monsoon condition. The statistics also agree with previous studies in that the wind diurnal amplitude is roughly proportional to background wind speed (Chen et al. 2013; Shapiro et al. 2016; Xue et al. 2018). Figures 7b and 7d further show that the southerly wind anomaly at 1800 UTC is well correlated with the easterly wind anomaly at 1200 UTC, with a correlation efficient of -0.40 (-0.53) over the ISM (EASM),

implying a clockwise rotation of deviation wind vectors. The diurnal variability thus exhibits as an important property of summer monsoon.

We also see that the strong monsoon southerlies (Q1/Q4) tend to occur successively in several days or even weeks, in a possible relation to the ISOs. Spectrum analysis shows that the daily southerlies exhibit large variance in the periods of 30–60 days and 8–20 days (figure not shown). In particular, the spectral density of the quasi-biweekly oscillation (QBWO) exceeds the 95% confidence level in most years. The features are consistent with many previous studies in that the QBWO is one dominant ISO mode in subtropical Asia (Goswami and Mohan 2001; Kikuchi and Wang 2009; Fujinami et al. 2014). The activities of DMV during the active/break phases of ISOs are discussed in section 5c. Through comparing four DMV groups, we further clarify the characteristics and influence of diurnal variability under different monsoon conditions.

b. Asian monsoon system under four dynamic quadrants

Figure 8 shows that the spatial patterns of low-level winds and daily rainfall. Under strong monsoons over ISM (Q1/Q4), southwesterly winds dominate central-north India (Figs. 8a,d). Abundant rainfall occurs on land to the north of 22°N , with two maxima at central-north India and the Himalayan foothills. The enhanced northern rainband with strong southwesterlies at central-north India and Bangladesh is analogous to that during the active phase of the ISOs (Fujinami et al. 2017). Rainfall is more evident at the Himalayan foothills in Q1 (Fig. 8a), but it is stronger at central-north India in Q4 (Fig. 8d), showing an impact of different nocturnal southerlies. In Q2/Q3, monsoon flow exhibits as a weak westerly wind and produces rainfall over southeast India (east of 80°E around 20°N) (Figs. 8b,c). Rainfall at the Himalayan foothills weakens with the suppressed southerlies at central-north India. These differences in winds and rainfall under strong/weak monsoon conditions are similar to those in the different phases of QBWO (e.g., Fujinami et al. 2014, 2017).

Figures 8e–h show that abundant rainfall also occurs over subtropical East Asia under strong monsoons (Q1/Q4), while it appears in the tropical areas under weak monsoons (Q2/Q3). In Q1, rainfall is pronounced at the mei-yu-baiu zone ($30^\circ\text{--}35^\circ\text{N}$) where both daily and diurnal components of southerly winds are convergent (Fig. 8e). Rainfall is displaced to southeast China ($21^\circ\text{--}30^\circ\text{N}$) with a small wind diurnal cycle in Q4 (Fig. 8h). Rainfall also increases slightly over North China at $\sim 35^\circ\text{N}$ in Q2 compared to Q3 (Figs. 8f,g). These

FIG. 7. Scatterplots of the diurnal deviation of southerly wind at 1800 UTC with (a),(c) daily-mean southerly wind and (b),(d) diurnal deviation of zonal wind at 1200 UTC. The anomalies are estimated by subtracting the climate-mean amplitude. The blue contours denote the distribution density of the dots. The occurrence days of four DMV quadrants are marked in (a),(c). The correlation coefficient of two variables is shown at the right bottom of each figure.

differences among four groups suggest that daily monsoon flow determines the large-scale pattern of rainfall, while its diurnal cycle greatly modulates the regional feature, highlighting the importance of DMV in regional climate. The detailed impacts of the DMV on precipitation systems and moisture budget will be clarified in section 5.

We further examine the atmospheric conditions of four DMV groups, with emphasis on those after daytime heating but prior to the nocturnal southerly acceleration. Figure 9 shows the anomalies of temperature, geopotential height, and zonal wind near sunset. In Q1, a positive temperature anomaly of up to 1.5 K occurs in the ABL (Figs. 9a,e) as a result of daytime heating and vertical turbulent mixing. An easterly wind anomaly more than 1 m s^{-1} dominates the ABL. In contrast, the ABL temperature deviation becomes small in Q4 (Figs. 9d,h), and the weak

daytime heating is likely due to the cloudiness of active moist convection (Figs. 8d,h). The 925-hPa easterly wind anomaly in Q4 (-0.6 m s^{-1}) is weaker than that in Q1 (-1.0 m s^{-1}), with a difference comparable to one standard deviation of Q1/Q4 ($\sim 0.4 \text{ m s}^{-1}$). It leads to the large difference of southerly anomaly at midnight between Q1 and Q4 (Fig. 7). Under weak monsoons, a large wind anomaly is also related to a relatively warm ABL in Q2 (Figs. 9b,f), compared to that in Q3 (Figs. 9c,g). Overall, the ABL temperature deviation at 1200 UTC is closely tied to the easterly wind anomaly, with a correlation efficient of -0.40 (-0.37) over India (East Asia) above a confidence level of 99.9%. The more active vertical mixing within the mixed layer seems to act as a stronger frictional force in monsoon flow. The induced easterly wind anomaly then veers to a southerly wind at night (Figs. 7b,d). The ABL thermal condition is thus a key factor affecting the

FIG. 8. Spatial patterns of daily-mean rainfall and 925-hPa winds as well as the diurnal amplitude of southerly wind (blue contours for above 1 m s^{-1}) under four DMV conditions. Regional centers at the northern rainband (marked by “R”) are the focus of this study, while central-north India and southeast China are denoted by “CNI” and “SEC,” respectively. The dashed lines denote the elevation at an interval of 1000 m.

FIG. 9. Longitude–vertical sections of the diurnal anomalies of zonal wind (shading), temperature (red contour), and geopotential height at 1200 UTC (black contour) deviated from daily mean under four DMV conditions over the ISM (22.5°–25°N) and EASM region (25°–27.5°N).

amplitude of DMV over both the ISM and EASM regions, which is also seen in the Bangladesh area (Fujinami et al. 2017). Geopotential deviation instead exhibits little difference among the four groups (Fig. 9), implying that it plays a secondary role. The ABL temperature deviation is relatively large over India, while the west–east pressure gradient is more evident over East Asia with a relatively low pressure over western terrain. The difference seems to explain the wind deviations that are mostly confined in ABL

over the ISM region but are extended up to 500 hPa over the EASM region.

Figure 9 also shows that the wind diurnal variations at 80°–90°E and 110°–125°E are more pronounced in Q1 than in Q2, due to the presence of southwesterly monsoon flow. Wind diurnal amplitude is roughly proportional to background wind speed (Figs. 7a,c). The daytime heating in the prevailing southwesterly monsoon flow is thus crucial for driving wind diurnal variations. These statistics match the prediction of the

Blackadar theory of boundary layer inertial oscillation (Chen et al. 2009, 2013; Du and Rotunno 2014; Shapiro et al. 2016; Fujinami et al. 2017; Xue et al. 2018). As the southwesterly monsoon usually features warm conditions and obvious ambient winds, it is thus conducive to a high occurrence of large diurnal cycle (Q1). On the days when monsoon flow is accompanied by active rainfall on land at $\sim 25^\circ\text{N}$ (Figs. 8d,h) and relatively cool ABL (Figs. 9d,h), it instead leads to a small diurnal cycle of low-level winds (Q4).

c. Monsoonal (anti-Hadley) circulation at diurnal time scale

Section 3b shows that the diurnal cycle of winds regulate horizontal convergence and meridional circulation in summer. Here, the detailed influence of the four DMV groups is examined. Figure 10a shows that, in Q1, low-level southerly wind at central-north India ($22^\circ\text{--}25^\circ\text{N}$) increases from $\sim 2\text{ m s}^{-1}$ at 0600/1200 UTC to 4 m s^{-1} at 1800 UTC. The induced midlevel rising motion increases from -0.02 to -0.16 Pa s^{-1} at the Himalayan foothills (south of 27°N). In Q4, southerly wind instead remains above 2.5 m s^{-1} and undergoes a small diurnal cycle, resulting in a moderate rising motion from -0.04 to -0.12 Pa s^{-1} at the foothills (Fig. 10d). The difference of diurnal anomalies at 1800 UTC between Q1 and Q4 is as large as one standard deviation ($\sim 0.04\text{ Pa s}^{-1}$). In Q2/Q3, both southerly wind and rising motion to the south of 27°N weaken (Figs. 10b,c). It is concluded that the large-scale southerly monsoon flow and its nocturnal speed-up over central-north India are important to drive the rising motion at the Himalayan foothills. In contrast, rising motion over the Himalayas (north of 27°N) is strongest in daytime, relating to thermally driven MPS, and exhibits less difference among the four DMV groups (Figs. 10a–d).

Figures 10e and 10h show that, over East Asia, the southerly monsoon flow from the tropics can induce rising motion at the subtropics ($27^\circ\text{--}35^\circ\text{N}$), but their diurnal variations differ markedly between Q1 and Q4. In Q1, southerly wind over southeast China (south of 27°N) is suppressed in daytime (Fig. 10e). Rising motion weakens at 1200 UTC and corresponds to a relatively fine weather at low latitudes. At 1800 UTC, southerly wind increases to $\sim 6\text{ m s}^{-1}$ at $\sim 27^\circ\text{N}$ and strengthens rising motion at the mei-yu-baiu zone adjacent to the north. At 0000 UTC of next day, the southerly wind still prevails at low latitudes, but it decreases to a minimum at midlatitudes. Rising motion is thus sustained by the midlatitude northerly anomaly and extended slightly southward (Fig. 10e), in contrast to a decline of rising motion at the Himalayan foothills (Fig. 10a). Figure 10h shows that, in Q4, the southerly wind is strong

throughout the day at low latitudes and induces convergence at $27^\circ\text{--}32^\circ\text{N}$. This feature corresponds to the active moist convection and cool ABL over southeast China (Figs. 8h and 9h). Unlike Q1, rising motion remains weak at 1800 UTC in Q4 because of a small southerly speed-up. In Q2/Q3, vertical motion weakens at the subtropics and undergoes a small diurnal cycle under suppressed monsoons (Figs. 10e,f). A difference between Q1/Q4 and Q2/Q3 thus suggests that the southerly monsoon flow acts to drive strong rising motion at the mei-yu-baiu zone. The difference between Q1 and Q4 further highlights that the nocturnal speed-up of monsoon flow can greatly regulate the diurnal phase of rising motion.

Figure 11 shows the vertical structures of regional meridional circulation at 1800 UTC under four DMV conditions. Over the ISM region, the nocturnal southerly speed-up in Q1 is evident below 700 hPa, with a maximum of 1.2 m s^{-1} at 925 hPa at $\sim 24^\circ\text{N}$ and an elevated high θ_e (Fig. 11a). It strengthens rising motion by a diurnal amplitude of -0.06 Pa s^{-1} at the Himalayan foothills, which is comparable to the daily mean. A returning flow of -0.6 m s^{-1} appears at the upper troposphere. The large diurnal cycle of monsoon flow thus leads to the enhanced meridional circulation at night (Figs. 11a and 4d). In Q2, nocturnal southerly wind also induces an anomalous rising motion at the Himalayan foothills (Fig. 11b). However, this effect is not collocated with the daily-mean rising motion that is displaced to the south of 22°N (not shown). In Q3/Q4, the weak nocturnal southerly wind results in a small amplitude of rising motion, thereby contributing little to the meridional circulation (Figs. 11c,d). Over East Asia, the nocturnal southerly wind also regulates the upward branch of monsoon circulation (Figs. 11e–h). The warm moist flow especially in Q1 acts to intensify rising motion at $27^\circ\text{--}35^\circ\text{N}$, where it is superimposed on the daily one enhancing the meridional circulation. The upward branch is a relatively wide at the mei-yu-baiu zone, compared to that at the Himalayan foothills.

It has been well recognized that the sensible heating over huge terrains such as the Tibetan Plateau can induce low-level convergence and rising motion during the warm season (e.g., Yeh et al. 1957; Yanai et al. 1992; Li and Yanai 1996; Wu et al. 1997, 2012). The intense sensible heating in daytime also drives the diurnal pulsation of convergent/divergent circulation and afternoon deep convection over terrains, as shown in Figs. 3c,g and 4c (Krishnamurti and Kishtawal 2000; Chow and Chan 2009). Such a sensible heat-driven air pump contributes to drive monsoon circulation at both seasonal and diurnal time scales. Here, this study

FIG. 10. Latitude–time variations of southerly wind at 925 hPa (contour) and midlevel vertical motion (shading) under four DMV conditions. The vertical motion is derived at 600 hPa at most latitudes and at 400 hPa over the Tibetan Plateau (north of 27°N in the left column). The average is made on the longitudes of 75°–90°E (ISM) and 110°–125°E (EASM) as shown in Fig. 1a. The variables over the ISM region have been shifted so that the elevation just to the north of 27°N is higher than 1000 m, dividing the Himalayan slopes and foothills. Local standard time is marked along the x coordinate at the bottom.

reveals a new process governing the monsoon circulation, in which the nocturnal acceleration of southerly monsoon flow plays a key role. Although wind diurnal variations are essentially initiated by the

heating over landmass in daytime, they are strongly regulated by the inertial oscillation at night. Deviating winds at low latitudes rotate to strengthen monsoon southerlies after midnight and strengthen low-level

FIG. 11. As in Fig. 4, but for the monsoon meridional circulation at 1800 UTC under four DMV conditions.

convergence at their northern terminus. Rising motion is thus displaced to the adjacent north of heated lands, and the rainfall peak is delayed to predawn or morning, which is distinct from the known air pump with an

afternoon peak of rainfall. Therefore, the DMV can be regarded as an air pump of the second kind, which may explain the prevalent morning rainfall at the northern rainband of the Asian monsoon.

5. Impacts of DMV on the diurnal cycles of rainfall and moisture budget

a. Diurnal cycles of precipitation systems under four DMV conditions

In this section, the influence of DMV on summer rainfall and the moisture budget are further examined. Figures 12a–d show that, over the ISM region, rainfall usually maximizes at late afternoon over central-north India and the Tibetan Plateau, while its peak occurs at predawn at the Himalayan foothills with an elevation below 1000 m. In Q1, the rain rate at the foothills is weak ($\sim 5 \text{ mm day}^{-1}$) in the afternoon and becomes most intense ($25\text{--}30 \text{ mm day}^{-1}$) at predawn (Fig. 12a). The dominant predawn rainfall coincides with the nocturnal speed-up of monsoon flow and enhanced convergence (Fig. 10a). In Q4, the rain rate at the foothills features an afternoon minimum of $\sim 7 \text{ mm day}^{-1}$ and a predawn peak of $20\text{--}25 \text{ mm day}^{-1}$ (Fig. 12d). The diurnal range of rainfall in Q4 is thus smaller than that in Q1, as a result of weak DMV (Fig. 10d). The afternoon rainfall at central-north India becomes strong and comparable to the nocturnal rainfall at the foothills. Under weak monsoons (Q2/Q3), rainfall weakens at both the Himalayan foothills and central-north India, while it increases over ocean south of 20°N (Figs. 12b,c). The rain rate at the foothills is $\sim 3 \text{ mm day}^{-1}$ ($\sim 4 \text{ mm day}^{-1}$) in the afternoon and $\sim 20 \text{ mm day}^{-1}$ ($\sim 15 \text{ mm day}^{-1}$) at predawn in Q2 (Q3). Both the daily mean and diurnal range of rainfall in Q2 (Q3) are smaller than at in Q1 (Q4). The diurnal range thus seems to increase with mean daily rainfall under strong monsoons, with enhanced rainfall at predawn given a large wind diurnal amplitude.

Over East Asia, rainfall is also abundant in the mei-yu-baiu zone ($27^\circ\text{--}35^\circ\text{N}$) under strong monsoons (Figs. 12e,h), while it is suppressed and features an afternoon peak under weak monsoons (Figs. 12f,g). In Q1, rainfall at $23^\circ\text{--}27^\circ\text{N}$ occurs at afternoon and decays in evening, implying short-lived convection (Fig. 12e). The rainfall at $30^\circ\text{--}35^\circ\text{N}$ grows at night and maximizes at predawn, and it shifts south to $\sim 30^\circ\text{N}$ in the morning after sunrise. Such long-duration rain systems explain the morning peak of rainfall over eastern China (e.g., Yu et al. 2007b). The rainfall pattern matches the rising motion enhanced by large-scale nocturnal southerly wind (Fig. 10e), highlighting the importance of wind diurnal cycle in the East Asian rainband (Chen et al. 2013; Yang and Li 2018). In contrast, in Q4, rainfall is confined at $27^\circ\text{--}32^\circ\text{N}$ in daytime (Fig. 12h), likely due to organized convection propagating from the lee of the Tibetan Plateau to southeast China (e.g., Wang et al. 2004). The associated cloudiness is thought to induce a relatively cold ABL and thereby a small diurnal cycle of

winds (Figs. 8h and 9h). The weak nocturnal convergence corresponds to a weak morning rainfall in Q4 (Figs. 10h and 12h). The difference of rainfall diurnal cycle over East Asia is thus surprisingly large between Q1 and Q4 because of the DMV, although the difference at given hour is smaller than one standard deviation because rainfall intensity can vary highly from day to day. Overall, the rainfall at the Himalayan foothills and mei-yu-baiu zone becomes most intense at predawn/morning when strong monsoon is coupled with a large diurnal cycle (Q1).

To further clarify the response of precipitation systems to DMV, a huge population of rain events are categorized basing on their size of contiguous rainy area with a rain rate above 1 mm h^{-1} in satellite estimate. In this respect, mesoscale organized (isolated) precipitation systems can be marked as large (small) events, and their rainfall volume agrees well with ground observations (Ebert and McBride 2000; Demaria et al. 2011). Figures 13a–d show the diurnal cycle of the rainfall budget over the ISM region. A major part of the rainfall amount ($\sim 75\%$) can be attributed to the meso- α -scale rain events with an area size larger than $2 \times 10^4 \text{ km}^2$, whereas less rainfall comes from small to medium events. The largest amount is due to the rain events with an area size of $\sim 10^5 \text{ km}^2$, suggesting an importance of moist organized convection. Meso- α -scale events produce a primary peak of rainfall at predawn and a secondary peak at afternoon under a large southerly acceleration in Q1/Q2 (Figs. 13a,b). The accumulated rainfall is particularly large in Q1, with 62% from late night to morning and 38% from afternoon to evening. In contrast, the predawn and afternoon peaks of rainfall are comparable with each other given a small southerly speed-up in Q3/Q4 (Figs. 13c,d). Therefore, the meso- α -scale rain events in response to DMV contribute greatly to the morning rainfall during the monsoon season.

Figures 13e–h show that, over East Asia, there is an evident rainfall amount under strong monsoon southerlies (Q1/Q4) and less rainfall under weak southerlies (Q2/Q3). The monsoon rainfall is mainly attributable to the activity of meso- α -scale events (Figs. 13e,h), consistent with the findings of previous study (Chen et al. 2013). It is interesting to see that the rainfall by meso- α -scale events is dominant during the afternoon (~ 1700 LST) in Q4, whereas it is more extensive during 0500–1100 LST in Q1. Long-duration rain events have been noted to explain the morning peak of rainfall over central China (Yu et al. 2007b; Chen et al. 2010). The growth of organized convection is closely associated with the nocturnal maxima of low-level southwesterly winds over southern China (G. Chen et al. 2017; Xue et al. 2018). The wide convective cores with a nocturnal peak also occur at the Himalayan foothills where the

FIG. 12. Latitude–time variations of rainfall (shading) under four DMV conditions. The average is made on the longitudes of 75° – 90° E (ISM) and 110° – 125° E (EASM) as shown in Fig. 1a. The variables over the ISM region have been shifted so that the elevation (dashed line) just to the north of 27° N is higher than 1000 m, dividing the Himalayan slopes and foothills. Local standard time is marked along the x coordinate at the bottom.

FIG. 13. Rainfall amount accumulated from the rain events with respect to area sizes under four DMV conditions. The statistics are made for the northern rainband of the (left) ISM and (right) EASM. The total amount of each group is marked at the top left corner, with a sum of four groups denoting the seasonal rainfall. The triangle marks a size threshold of $2 \times 10^4 \text{ km}^2$ for meso- α -scale rain events. Local standard time is marked along the y coordinate to the right.

moist monsoon flows converge with the downslope winds from the Himalayas (Romatschke et al. 2010; Romatschke and Houze 2011). This study further reveals their particularly active occurrence under strong monsoon southwesterlies when coupling with a large diurnal cycle (Q1). It highlights a strong connection of the Asian monsoon flow and moist convection at both seasonal and diurnal time scales.

b. Modulation of regional moisture budget by DMV

Figures 14a–d show the daily mean and nocturnal deviation of moisture fluxes over the ISM region. The daily-mean pattern (streamline) exhibits as a cyclonic circulation like monsoonal low, with a southerly flow over Bangladesh and an easterly flow along the Himalayas. The center of cyclonic circulation is established at northwestern India in Q1/Q4 (Figs. 14a,d), whereas it is located at northeastern India and Bangladesh in Q2/Q3 (Figs. 14b,c). It is related to the different locations of monsoon lows/depressions that are strongly controlled by ISOs (Sikka 1977; Goswami et al. 2003; Krishnamurthy and Ajayamohan 2010; Hunt et al. 2016; Fujinami et al. 2017; Hatsuzuka and Fujinami 2017). Central-north India is dominated by the southwesterly flux converging to the Himalayan foothills with enhanced precipitable water in Q1/Q4, whereas it is affected by the northerly flux diverging at the foothills but converging to eastern India in Q2/Q3.

Figure 14a shows a pronounced northward flux of water vapor (vectors) by the nocturnal speed-up of monsoon flow in Q1. The diurnal amplitude reaches $\sim 40 \text{ kg (m s}^{-1})^{-1}$ and is comparable to the daily mean over most of the central-north India, implying an evident transient transport by the DMV. Deviation flux overlies the background flux to strengthen the poleward transport of moisture at night. It also converges to the Himalayan foothills and the Indo-Gangetic plain, in terms of both intensity and direction. Figure 14b shows that the deviation southerly flux in Q2 has a smaller magnitude than that in Q1 because of the decayed humidity. It is collocated with the daily southeasterly flux at the foothills, but it is opposite to the daily northerly flux over northern India. Given the small diurnal cycle in Q3/Q4, the deviation flux at night is much small and exhibits a westerly component particularly in Q3 (Figs. 14c,d). It seems to offset the daily easterly flux at the Himalayan foothills, suggesting a weak influence of wind diurnal variations over there.

Figures 15a–d show the 6-hourly variations of precipitable water, vertically integrated moisture flux and convergence, and rainfall averaged over northern ISM region. In Q1, precipitable water has a high daily value and reaches its peak at night (Fig. 15a). Northward moisture flux associated with monsoon southerlies strengthens considerably

from 1200 to 1800 UTC, resulting in a remarkable increase of flux convergence from -6 to $-14 \times 10^{-5} \text{ kg s}^{-1}$. Accordingly, rainfall increases rapidly and reaches a peak of $\sim 14 \text{ mm day}^{-1}$ at 21 UTC, which is much higher than the afternoon peak of $\sim 9 \text{ mm day}^{-1}$. Moisture flux and convergence decay in the following morning with a subsequent decline of rainfall. In Q4, precipitable water also has a high daily value but it decreases slightly at night (Fig. 15d). Moisture flux and convergence in Q4 have a daily mean comparable to that in Q1, but their nocturnal increase is less evident. The rainfall amount at 0900 UTC seems comparable to that at 2100 UTC. In Q2, all four terms undergo diurnal variations with phases similar to those in Q1, but their daily values and nocturnal peaks are much smaller (Fig. 15b). The regulation of wind diurnal variations on moisture budget thus seems to decay under weak monsoon southerlies. The nocturnal peaks of moisture flux/convergence and rainfall become the smallest in Q3 (Fig. 15c).

Over East Asia, the daily moisture flux is large in Q1/Q4 (Figs. 14e,h), whereas it is relatively small in Q2/Q3 (Figs. 14f,g). The differences are caused by the change of atmospheric circulation relating to the western Pacific subtropical high (e.g., Ding and Chan 2005). Strong southerly flux in Q1/Q4 originates at low latitudes and turns to become southwesterly flux at subtropical areas where it brings in a large amount of precipitable water. In Q1 (Fig. 14e), it undergoes a large nocturnal speed-up with the maximum amplitude of $50\text{--}70 \text{ kg (m s}^{-1})^{-1}$ over East China plain and East China Sea where nocturnal LLJs prefer to occur (Du et al. 2015; Shin et al. 2019). This diurnal component is superimposed over the daily-mean monsoon southerlies, strengthening the poleward flux by $\sim 25\%$ at night. The DMV thus acts to inject more energy into the East Asian rainband at night through transporting the warm moist air that is built up at low latitudes in the preceding daytime. The nocturnal speed-up of moisture flux over southeast China is smaller in Q4 (Fig. 14h). Nocturnal southerly fluxes also differ between Q2 and Q3, but both of them are superimposed over the weak background flow (Figs. 14f,g).

Figures 15e–h show the moisture budget averaged over central China. Moisture flux in Q1 increases markedly at 1800 UTC and results in a maximum convergence at 0000 UTC (Fig. 15e), which is several hours lag compared to that over the ISM region. It coincides with a relatively high precipitable water and rainfall that last for the morning hours. In Q4, all four variables have a daily mean as high as in Q1, but they have a much smaller increase at 1800 or 0000 UTC (Fig. 15h). Moisture flux and convergence undergo a relatively large increase at night in Q2 compared to Q3, although their daily means are small

FIG. 14. Six-hourly variations of precipitable water (shading), daily-mean water vapor fluxes (streamline with color for magnitude), and diurnal deviation of water vapor fluxes at 1800 UTC (vectors). In the left panels, "C" denotes the center of cyclonic circulation of daily fluxes.

FIG. 15. Diurnal variations of precipitable water (PW), column-integrated northward moisture flux (qv) at the southern boundary, moisture flux convergence [$-\text{DIV}(qv)$], and precipitation (P) over the (top) ISM and (bottom) EASM regions. The statistics are made for an average at the northern rainband (i.e., the blue rectangles in Fig. 1a). Local standard time is marked along the x coordinate at the bottom. All variables are also given at a unit of mm or mm day^{-1} along the y coordinate to the right.

under weak monsoons. Nevertheless, the large net moisture flux at night in Q1/Q2 acts to produce an evident morning rainfall, while the small one in Q3/Q4 corresponds to the suppressed morning rainfall and dominant afternoon rainfall.

Previous studies have shown that the enhanced southerly winds at night play a role in regulating moisture budget over East Asia (Chen et al. 2013). In particular, diurnal variation of ageostrophic winds is crucial for the net moisture flux at the mei-yu-baiu front (Xue et al. 2018). Net moisture flux by southerly low-level jets due to boundary layer inertial oscillation can contribute the most to the formation of nocturnal precipitation even at basins or foothills, while the shallow nighttime downslope flows contribute less (Zhang et al. 2019). Yang and Li (2018) analyzed the moisture-related rainfall budget over central-east China and also revealed that the rainfall diurnal cycle is dominated by water vapor convergence. The statistics of this study further highlight that the water vapor convergence is strongly regulated by the DMV at large scale, with a diurnal range comparable to daily mean. As the strong monsoon flow is usually coupled with a large diurnal cycle, it thus becomes most efficient at night in regulating the regional moisture budget over the Asian monsoon regions.

c. Intraseasonal and interannual variations of rainfall associated with the DMV

It is recognized that ISOs are one of the dominant modes of precipitation and wind fields over the Asian monsoon region (e.g., Goswami and Mohan 2001; Annamalai and Slingo 2001). This section briefly examines how much rainfall intraseasonal variability can be attributed to the DMV, with emphasis on the predominant QBWO as noted in section 4a. The active/break phases of ISOs are defined when the 8–20-day filtered rainfall series at the northern rainband exceeds ± 0.5 standard deviation. Figures 16a and 16b show that the occurrences of strong monsoon days (Q1/Q4) are pronounced (suppressed) during the active (break) phase of the ISOs over the ISM region. The strong monsoons account for a major portion of high rainfall amount during the active phase (Fig. 16a), as also shown in previous studies (Shrestha et al. 2012; Fujinami et al. 2014, 2017). It is worth noting that the dominant Q1 occurrence produces the largest fraction of rainfall especially in the morning hours. In contrast, the Q1/Q4 occurrences produce much weak rainfall during the break phase of the ISOs (Fig. 16b). Similar differences among the four DMV conditions are also seen in the 30–60-day ISOs (figures not shown) or the ISOs over the EASM region (Figs. 16c,d). The results suggest that the diurnal cycle of southerly monsoon flow is closely

related to the intraseasonal variations of rainfall in the northern rainband of the Asian monsoon.

The monsoon system also exhibits large interannual variability and affects the regional and/or global climate (e.g., Ding and Chan 2005). It is unclear whether the DMV varies with years and influences the long-term variations of summer rainfall. Figures 17a and 17e show that the diurnal amplitude of 925-hPa meridional wind undergoes an evident interannual variation over both the ISM and EASM regions. It is highly correlated with the interannual variation of daily monsoon southerlies, implying that a large diurnal cycle tends to occur in strong monsoon years. The DMV interannual variation can be well represented by the number of Q1 days that varies over 20 years. The interannual variation is relatively large over the ISM region, with the number of Q1 days ranging from 12 to 43 (Fig. 17a). It oscillates at a period of 4–5 years, with peaks at 1998, 2003, 2007, 2010, and 2016, coinciding with the decaying phases of El Niño events. The DMV fluctuates at a shorter period of 2–3 years over the EASM region (Fig. 17e), similar to the tropospheric quasi-biennial oscillation (Lau and Sheu 1988; Huang et al. 2006). An interesting linkage of DMV to the tropical ocean–atmosphere system deserves further analysis, although it is beyond the scope of this paper. Nevertheless, such a tight relationship among monsoon indices based on daily/diurnal components indicates that large-scale circulations may modulate subdaily regional forcings to regulate the weather and climate over Asia.

Over the ISM region, the DMV exhibits pronounced interannual variations (Fig. 17a). The Q1 days ($\sim 29\%$ of summer days) can account for a major portion of the interannual variance ($\sim 54\%$) of the poleward moisture transport to the northern ISM region (Fig. 17b). The correlation coefficient of the moisture flux by Q1 with the summer mean is as high as $+0.86$. The Q4 contributes the second largest part of interannual variance of moisture transport ($\sim 28\%$), while Q2 and Q3 explain much less. Accordingly, the DMV contributes greatly to the interannual variations of moisture convergence and rainfall at the Himalayan foothills, with a large fraction from midnight to morning (Figs. 17c,d). The strong (weak) DMV years are usually characterized by above-normal (below-normal) summer rainfall. The correlation coefficient between the rainfall by strong monsoons (Q1/Q4) and total rainfall amount is up to $+0.60$ (Fig. 17d). Moreover, the percentage of morning rainfall in summer is positively correlated with the occurrence of Q1 days ($+0.34$) rather than Q4 days (-0.33). Such a strong contribution of DMV to the interannual variations of moisture flux and rainfall is also seen over East Asia (Figs. 17e–h). The features

FIG. 16. Rainfall amount attributed to four DMV quadrants during the (a) active and (b) break phases of the 8–20-day ISOs at the northern rainband of ISM region. The thin bars denote the climate-mean rainfall by four DMV quadrants. The closed circles denote the occurrence percentage of four DMV days, while the open circles denote the summer mean. (c),(d) As in (a) and (b), but for the EASM region.

agree with previous studies in that the long-term variations of summer monsoon play a role in modulating the rainfall diurnal cycle (Sen Roy and Balling 2007; Yuan et al. 2013b; Chen et al. 2014). Here, it is highlighted that strong monsoon southerlies with a large diurnal cycle play a leading role in regulating the interannual variations of the northern rainband.

6. Summary and discussion

The local/subregional effects of diurnally varying low-level winds over India and China have received attention. This paper places the effects into a broad geographical

context covering the Asian monsoon circulation. We propose to decompose the diurnal variability into strong or weak background flows with large or small diurnal amplitude ranges. We compare the four DMV groups to clarify their related atmospheric conditions, rainfall systems, and moisture budget, as well as their similarities and differences over the ISM and EASM regions. We further examine how the DMV changes on longer time scales (e.g., intraseasonal and interannual). It is concluded that the DMV plays an important role in the Asian monsoon climate. The findings are summarized below.

- 1) The daily mean and diurnal amplitude of 925-hPa southerly wind increase evidently in summer over

FIG. 17. Interannual variations of (a),(e) monsoon indices of daily southerlies V and diurnal amplitude V^* as well as Q1 days, (b),(f) northward moisture flux at the southern boundary, (c),(g) moisture flux convergence, and (d),(h) JJA rainfall amount over the (left) ISM and (right) EASM regions. The statistics are made for an average at the northern rainband (i.e., the blue rectangles in Fig. 1a). In (a),(e), the line in black (blue) denotes the daily mean (diurnal amplitude) of southerly wind, and the line in red denotes the occurrence days of Q1. In (b)–(d) and (f)–(h), the lines in black denote the sum of four DMV quadrants; the lines in red denote the values from Q1 days, with the dark blue indicating the fraction from midnight to morning.

central-north India and southeast China, and they represent the monsoon intensities at the northern sector of the Asian monsoon. A majority of summer days are identified as the strong (weak) monsoon with a large (small) diurnal cycle. The diurnal amplitude range is correlated with the strength of background flow and diurnal heating in the ABL, which matches that predicted by the Blackadar inertial oscillation theory. Wind diurnal amplitude is particularly large in the days when the prevailing monsoon southerlies undergo a strong daytime heating, resulting in the wind speed maximum after midnight. The enhanced monsoon southerlies then

converge with the downslope winds from the Himalayas at midnight/predawn or the northerly anomaly from East Asian midlatitudes at predawn/morning. They contribute greatly to the meridional circulation with anomalous rising motion at the Himalayan foothills or the mei-yu-baiu zone, favoring the growth of moist organized convection from midnight to morning. Such a speed-up of large-scale monsoon southerlies at night can be regarded as an air pump of the second kind, which is distinct from the thermally driven air pump coupled with afternoon convection over the terrains of central-north India and the Tibetan Plateau.

- 2) Strong southerly monsoon flow brings in abundant rainfall at subtropical areas, and its diurnal cycle is found to further regulate regional rainfall features. The monsoon southerlies with a large diurnal cycle can produce the most intense rainfall. The rain rate reaches its peak at predawn at the Himalayan foothills, while it is sustained from predawn to noon at the mei-yu-baiu zone. In contrast, the monsoon southerlies with a small diurnal cycle tend to produce more afternoon rainfall, which is displaced south to central-north India and southeast China. The DMV thus explains a surprisingly large difference in the patterns of regional rainfall under strong monsoons especially over East Asia. Under weak monsoons, both the daily mean and diurnal range of rainfall at northern rainband weaken. The rainfall differences are attributed to the meso- α -scale rain events by moist organized convection that tend to produce the morning (afternoon) peak of rainfall, as a response to a large (small) diurnal cycle of monsoon southerlies.
- 3) The nocturnal speed-up of monsoon flow can induce an evident northward transport of water vapor over the ISM and EASM regions. The diurnal amplitude of water vapor flux can be comparable to the daily mean over central-north India or up to $\sim 25\%$ over East Asia. The enhanced flux after midnight can intensify moisture convergence at a magnitude comparable to that by daily monsoon southerlies. The enhanced monsoon flow thus acts like the large-scale conveyor of moisture to the subtropical areas at night. The subdaily regulation of rainfall/moisture budget weakens under a small wind diurnal cycle or weak monsoons. Meanwhile, the DMV intensity varies largely from year to year over both India and East Asia, in association with the interannual variation of monsoon intensity. The occurrence of strong monsoon southerlies with a large diurnal cycle contributes a particularly large portion of the interannual variances of net moisture flux and rainfall. Strong (weak) monsoons are also related to the active (break) phase of ISOs. It indicates that large-scale atmospheric circulations and subdaily forcings jointly regulate the regional climate over the Asian monsoon regions.

A conceptual model of the diurnal cycle of Asian summer monsoon is proposed as Fig. 18. In afternoon, the Indian subcontinent and terrains are heated (Fig. 18a). The pumping effect of thermal heating results in convergent airflow toward the Tibetan Plateau or large mountain ranges (Krishnamurti and Kishtawal 2000; Chow and Chan 2009). The thermal instability and

orographic lifting induce local deep convection over terrains with upper-level divergence. However, large-scale monsoon flow slows down in daytime due to the frictional drag of ABL turbulent mixing over the continent. After sunset, the boundary layer wind anomaly decouples the cooled surface and rotates clockwise to intensify monsoon southerlies from midnight to predawn as a result of inertial oscillation (Fig. 18b). The enhanced monsoon southerlies converge with down-slope winds from the terrain and strengthen updrafts at the foothills and plain. The supergeostrophic monsoon flow also acts as a moisture conveyor and contributes greatly to the net moisture flux at night. The dynamic lifting and moist condition facilitate the growth of organized convection at the Himalayan foothills and the Indo-Gangetic plain. These processes work similarly over East Asia, except that the boundary lifting occurs at the mei-yu-baiu front (Figs. 18c,d). The rainfall tends to persist from predawn to next noon due to a sustained convergence of the southwesterlies from southeast China with the northerly anomaly from the midlatitudes. The summer monsoon diurnal cycle thus seems to express the second kind of atmospheric response to the thermal forcing on land. Its effect, like a large-scale air pump at night, plays a crucial role in producing the prevalent morning rainfall at the northern branch of the Asian monsoon. We may see that the huge terrain serves as a seasonal heat source driving the monsoon system (e.g., Yeh et al. 1957; Yanai et al. 1992; Wu et al. 2015, 2016), and the thermally forced daytime convection and nighttime monsoon southerlies further regulate the monsoon system at a shorter diurnal time scale.

Further studies are needed to address the following aspects. First, comparing the two kinds of diurnally varying air pump would quantify their relative importance in the monsoon climate (Krishnamurti and Kishtawal 2000; Chen et al. 2013). Issues to be solved include their influence on the diurnal variations of moist energy, water budget, rainfall systems, and extreme weather, as well as their similarities and/or differences in the ISM and EASM regions. A key issue may be the interaction of DMV with local MPS/LSB circulations and meso- and synoptic-scale weather systems to regulate the rainfall maxima near mountainous terrain, plains, and coasts (Hunt et al. 2016; Rao et al. 2016; X. Chen et al. 2017; G. Chen et al. 2018; Zhang et al. 2019; Pan and Chen 2019; Du and Chen 2019). An objective classification of synoptic-scale disturbances along with DMV may aid to clarify multiscale interactions in monsoon regions (Sikka 1977; Goswami et al. 2003; Fujinami et al. 2017). Another issue is the modulation of ISOs, which leads to the differences of rainfall diurnal cycle during the active and break monsoon spells (Singh and Nakamura 2010;

FIG. 18. Schematics of the Asian monsoon circulation after diurnal heating. (a) Air pump directly driven by the daytime thermal contrast over terrains over the ISM region. (b) Air pump of the second kind associated with the speed-up of southerly monsoon flow at night. (c),(d) As in (a),(b), but for the EASM region. Arrows in red (green) denote the positive (negative) phase of the circulation.

Deshpande and Goswami 2014; Fujinami et al. 2017; Anandh et al. 2018; Chen et al. 2019).

Second, the physical processes involved in the response of the DMV to large-scale conditions deserve further analyses (Xue et al. 2018; Shin et al. 2019; Zeng et al. 2019). As indicated, monsoon flow passing the land-mass with strong (weak) daytime heating tends to undergo a large (small) diurnal cycle. The dynamics of wind diurnal variations should be clarified considering the cloudiness, radiative forcings, surface contrast, and boundary layer processes under various background conditions. Long-term change of the DMV and rainfall diurnal cycle would provide a new view of how regional forcings couple with external forcings to regulate the monsoon climate (Yuan et al. 2013a; Chen et al. 2014; Huang and Chen 2015). The feedback of diurnally

varying processes to large-scale circulation will also be an interesting subject (Yanai et al. 1992; Willetts et al. 2017). The latent heating by convection on land may deepen monsoon trough and increase the moisture transport to the continent, implying an upscale effect of the moist convection. These key issues will be explored in ongoing works.

Acknowledgments. The author is grateful to three anonymous reviewers and Editor Dr. Hisashi Nakamura for the helpful comments. He also thanks GSFC/TSDIS of NASA for providing TRMM data and JMA for providing JRA-55 data. This study is supported by the National Key Research and Development Program of China (Grant 2016YFA0600704) and the National Natural Science Foundation of China (Grant 41575068).

REFERENCES

- Anandh, P. C., N. K. Vissa, and C. Broderick, 2018: Role of MJO in modulating rainfall characteristics observed over India in all seasons utilizing TRMM. *Int. J. Climatol.*, **38**, 2352–2373, <https://doi.org/10.1002/joc.5339>.
- Annamalai, H., and J. M. Slingo, 2001: Active/break cycles: Diagnosis of the intraseasonal variability of the Asian summer monsoon. *Climate Dyn.*, **18**, 85–102, <https://doi.org/10.1007/s003820100161>.
- Bao, X., F. Zhang, and J. Su, 2011: Diurnal variations of warm-season precipitation east of the Tibetan Plateau over China. *Mon. Wea. Rev.*, **139**, 2790–2810, <https://doi.org/10.1175/MWR-D-11-00006.1>.
- Basu, B. K., 2007: Diurnal variation in precipitation over India during the summer monsoon season: Observed and model predicted. *Mon. Wea. Rev.*, **135**, 2155–2167, <https://doi.org/10.1175/MWR3355.1>.
- Blackadar, A. K., 1957: Boundary-layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **38**, 283–290, <https://doi.org/10.1175/1520-0477-38.5.283>.
- Chen, G., W. Sha, and T. Iwasaki, 2009: Diurnal variation of precipitation over southeastern China: 2. Impact of the diurnal monsoon variability. *J. Geophys. Res.*, **114**, D21105, <https://doi.org/10.1029/2009JD012181>.
- , —, M. Sawada, and T. Iwasaki, 2013: Influence of summer monsoon diurnal cycle on moisture transport and precipitation over eastern China. *J. Geophys. Res. Atmos.*, **118**, 3163–3177, <https://doi.org/10.1002/jgrd.50337>.
- , T. Iwasaki, H. Qin, and W. Sha, 2014: Evaluation of the warm-season diurnal variability over East Asia in recent reanalyses JRA-55, ERA-Interim, NCEP CFSR, and NASA MERRA. *J. Climate*, **27**, 5517–5537, <https://doi.org/10.1175/JCLI-D-14-00005.1>.
- , —, —, and Z. Wen, 2017: Diurnal cycle of a heavy rainfall corridor over East Asia. *Mon. Wea. Rev.*, **145**, 3365–3389, <https://doi.org/10.1175/MWR-D-16-0423.1>.
- , R. Lan, W. Zeng, H. Pan, and W. Li, 2018: Diurnal variations of rainfall in surface and satellite observations at the monsoon coast (South China). *J. Climate*, **31**, 1703–1724, <https://doi.org/10.1175/JCLI-D-17-0373.1>.
- Chen, H., R. Yu, J. Li, W. Yuan, and T. Zhou, 2010: Why nocturnal long-duration rainfall presents an eastward-delayed diurnal phase of rainfall down the Yangtze River valley. *J. Climate*, **23**, 905–917, <https://doi.org/10.1175/2009JCLI3187.1>.
- Chen, X., F. Zhang, and K. Zhao, 2017: Influence of monsoonal wind speed and moisture content on intensity and diurnal variations of the mei-yu season coastal rainfall over South China. *J. Atmos. Sci.*, **74**, 2835–2856, <https://doi.org/10.1175/JAS-D-17-0081.1>.
- , —, and J. H. Ruppert, 2019: Modulations of the diurnal cycle of coastal rainfall over South China caused by the boreal summer intraseasonal oscillation. *J. Climate*, **32**, 2089–2108, <https://doi.org/10.1175/JCLI-D-18-0786.1>.
- Chow, K. C., and J. C. Chan, 2009: Diurnal variations of circulation and precipitation in the vicinity of the Tibetan Plateau in early summer. *Climate Dyn.*, **32**, 55–73, <https://doi.org/10.1007/s00382-008-0374-x>.
- Dai, A., 2001: Global precipitation and thunderstorm frequencies. Part II: Diurnal variations. *J. Climate*, **14**, 1112–1128, [https://doi.org/10.1175/1520-0442\(2001\)014<1112:GPATFP>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<1112:GPATFP>2.0.CO;2).
- , 2006: Precipitation characteristics in eighteen coupled climate models. *J. Climate*, **19**, 4605–4630, <https://doi.org/10.1175/JCLI3884.1>.
- Demaria, E. M. C., D. A. Rodriguez, E. E. Ebert, P. Salio, F. Su, and J. B. Valdes, 2011: Evaluation of mesoscale convective systems in South America using multiple satellite products and an object-based approach. *J. Geophys. Res.*, **116**, D08103, <https://doi.org/10.1029/2010JD015157>.
- Deshpande, N. R., and B. N. Goswami, 2014: Modulation of the diurnal cycle of rainfall over India by intraseasonal variations of Indian summer monsoon. *Int. J. Climatol.*, **34**, 793–807, <https://doi.org/10.1002/joc.3719>.
- Ding, Y., and J. C. Chan, 2005: The East Asian summer monsoon: An overview. *Meteor. Atmos. Phys.*, **89**, 117–142, <https://doi.org/10.1007/s00703-005-0125-z>.
- , Z. Wang, and Y. Sun, 2008: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *Int. J. Climatol.*, **28**, 1139–1161, <https://doi.org/10.1002/joc.1615>.
- Dirmeyer, P. A., and coauthors, 2012: Simulating the diurnal cycle of rainfall in global climate models: Resolution versus parameterization. *Climate Dyn.*, **39**, 399–418, <https://doi.org/10.1007/s00382-011-1127-9>.
- Du, Y., and R. Rotunno, 2014: A simple analytical model of the nocturnal low-level jet over the Great Plains of the United States. *J. Atmos. Sci.*, **71**, 3674–3683, <https://doi.org/10.1175/JAS-D-14-0060.1>.
- , and G. Chen, 2019: Heavy rainfall associated with double low-level jets over southern China. Part II: Convection initiation. *Mon. Wea. Rev.*, **147**, 543–565, <https://doi.org/10.1175/MWR-D-18-0102.1>.
- , Y.-L. Chen, and Q. Zhang, 2015: Numerical simulations of the boundary layer jet off the southeastern coast of China. *Mon. Wea. Rev.*, **143**, 1212–1231, <https://doi.org/10.1175/MWR-D-14-00348.1>.
- Ebert, E. E., and J. L. McBride, 2000: Verification of precipitation in weather systems: Determination of systematic errors. *J. Hydrol.*, **239**, 179–202, [https://doi.org/10.1016/S0022-1694\(00\)00343-7](https://doi.org/10.1016/S0022-1694(00)00343-7).
- Fu, Y., and Coauthors, 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. *Climate Dyn.*, **51**, 1971–1989, <https://doi.org/10.1007/s00382-017-3992-3>.
- Fujinami, H., S. Nomura, and T. Yasunari, 2005: Characteristics of diurnal variations in convection and precipitation over the southern Tibetan Plateau during summer. *SOLA*, **1**, 49–52, <https://doi.org/10.2151/sola.2005-014>.
- , T. Yasunari, and A. Morimoto, 2014: Dynamics of distinct intraseasonal oscillation in summer monsoon rainfall over the Meghalaya-Bangladesh-western Myanmar region: Covariability between the tropics and mid-latitudes. *Climate Dyn.*, **43**, 2147–2166, <https://doi.org/10.1007/s00382-013-2040-1>.
- , T. Sato, H. Kanamori, and F. Murata, 2017: Contrasting features of monsoon precipitation around the Meghalaya Plateau under westerly and easterly regimes. *J. Geophys. Res.*, **122**, 9591–9610, <https://doi.org/10.1002/2016JD026116>.
- Geng, B., and H. Yamada, 2007: Diurnal variations of the Meiyu/Baiu rain belt. *SOLA*, **3**, 61–64, <https://doi.org/10.2151/sola.2007-016>.
- Goswami, B. N., and R. S. A. Mohan, 2001: Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *J. Hydrometeorol.*, **14**, 1180–1198, [https://doi.org/10.1175/1520-0442\(2001\)014<1180:ioaivo>2.0.co;2](https://doi.org/10.1175/1520-0442(2001)014<1180:ioaivo>2.0.co;2).
- , R. S. Ajayamohan, P. K. Xavier, and D. Sengupta, 2003: Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophys. Res. Lett.*, **30**, 1431, <https://doi.org/10.1029/2002GL016734>.
- Hamada, A., T. Murayama, and Y. N. Takayabu, 2014: Regional characteristics of extreme rainfall extracted from TRMM PR

- measurements. *J. Climate*, **27**, 8151–8169, <https://doi.org/10.1175/JCLI-D-14-00107.1>.
- Hatsuzuka, D., and H. Fujinami, 2017: Effects of the South Asian monsoon intraseasonal modes on genesis of low pressure systems over Bangladesh. *J. Climate*, **30**, 2481–2499, <https://doi.org/10.1175/JCLI-D-16-0360.1>.
- Hirose, M., and K. Nakamura, 2005: Spatial and diurnal variation of precipitation systems over Asia observed by the TRMM Precipitation Radar. *J. Geophys. Res.*, **110**, D05106, <https://doi.org/10.1029/2004JD004815>.
- Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19**, 199–205, <https://doi.org/10.3402/tellusa.v19i2.9766>.
- Huang, R., J. Chen, G. Huang, and Q. Zhang, 2006: The quasi-biennial oscillation of summer monsoon rainfall in China and its cause (in Chinese). *Chin. J. Atmos. Sci.*, **30**, 545–560.
- Huang, W., and K. C. Chen, 2015: Trends in pre-summer frontal and diurnal rainfall activities during 1982–2012 over Taiwan and Southeast China: Characteristics and possible causes. *Int. J. Climatol.*, **35**, 2608–2619, <https://doi.org/10.1002/joc.4159>.
- , J. Chan, and S. Wang, 2010: A planetary-scale land-sea breeze circulation in East Asia and the western North Pacific. *Quart. J. Roy. Meteor. Soc.*, **136**, 1543–1553, <https://doi.org/10.1002/qj.663>.
- Huffman, G. J., and Coauthors, 2007: The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol.*, **8**, 38–55, <https://doi.org/10.1175/JHM560.1>.
- Hunt, K. M., A. G. Turner, and D. E. Parker, 2016: The spatio-temporal structure of precipitation in Indian monsoon depressions. *Quart. J. Roy. Meteor. Soc.*, **142**, 3195–3210, <https://doi.org/10.1002/qj.2901>.
- Johnson, R. H., 2011: Diurnal cycle of monsoon convection. *The Global Monsoon System: Research and Forecast*, C.-P. Chang et al., Eds., World Scientific, 257–276, https://doi.org/10.1142/9789814343411_0015.
- Kanada, S., H. Tsuguti, T. Kato, and F. Fujibe, 2014: Diurnal variation of precipitation around western Japan during the warm season. *SOLA*, **10**, 72–77, <https://doi.org/10.2151/sola.2014-015>.
- Kikuchi, K., and B. Wang, 2009: Global perspective of the quasi-biweekly oscillation. *J. Climate*, **22**, 1340–1359, <https://doi.org/10.1175/2008JCLI2368.1>.
- Kobayashi, S., and Coauthors, 2015: The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*, **93**, 5–48, <https://doi.org/10.2151/jmsj.2015-001>.
- Krishnamurthy, V., and J. Shukla, 2007: Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall. *J. Climate*, **20**, 3–20, <https://doi.org/10.1175/JCLI3981.1>.
- , and R. S. Ajayamohan, 2010: Composite structure of monsoon low pressure systems and its relation to Indian rainfall. *J. Climate*, **23**, 4285–4305, <https://doi.org/10.1175/2010JCLI2953.1>.
- Krishnamurti, T. N., and C. M. Kishtawal, 2000: A pronounced continental-scale diurnal mode of the Asian summer monsoon. *Mon. Wea. Rev.*, **128**, 462–473, [https://doi.org/10.1175/1520-0493\(2000\)128<0462:APCSDM>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0462:APCSDM>2.0.CO;2).
- Lau, K.-M., and P. J. Sheu, 1988: Annual cycle, quasi-biennial oscillation, and southern oscillation in global precipitation. *J. Geophys. Res.*, **93**, 10 975–10 988, <https://doi.org/10.1029/JD093iD09p10975>.
- Li, C., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land–sea thermal contrast. *J. Climate*, **9**, 358–375, [https://doi.org/10.1175/1520-0442\(1996\)009<0358:TOAIVO>2.0.CO;2](https://doi.org/10.1175/1520-0442(1996)009<0358:TOAIVO>2.0.CO;2).
- Li, J., R. Yu, and T. Zhou, 2008: Seasonal variation of the diurnal cycle of rainfall in southern contiguous China. *J. Climate*, **21**, 6036–6043, <https://doi.org/10.1175/2008JCLI2188.1>.
- Li, P., K. Furtado, T. Zhou, H. Chen, J. Li, Z. Guo, and C. Xiao, 2018: The diurnal cycle of East Asian summer monsoon precipitation simulated by the Met Office Unified Model at convection-permitting scales. *Climate Dyn.*, <https://doi.org/10.1007/s00382-018-4368-z>.
- Monaghan, A. J., D. L. Rife, J. O. Pinto, C. A. Davis, and J. R. Hannan, 2010: Global precipitation extremes associated with diurnally varying low-level jets. *J. Climate*, **23**, 5065–5084, <https://doi.org/10.1175/2010JCLI3515.1>.
- Ohsawa, T., H. Ueda, T. Hayashi, A. Watanabe, and J. Matsumoto, 2001: Diurnal variations of convective activity and rainfall in tropical Asia. *J. Meteor. Soc. Japan*, **79**, 333–352, <https://doi.org/10.2151/jmsj.79.333>.
- Oki, T., and K. Musiake, 1994: Seasonal change of the diurnal cycle of precipitation over Japan and Malaysia. *J. Appl. Meteor.*, **33**, 1445–1463, [https://doi.org/10.1175/1520-0450\(1994\)033<1445:SCOTDC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1994)033<1445:SCOTDC>2.0.CO;2).
- Pan, H., and G. Chen, 2019: Diurnal variations of precipitation over North China regulated by mountain-plains solenoid and boundary-layer inertial oscillation. *Adv. Atmos. Sci.*, **36**, 863–884, <https://doi.org/10.1007/s00376-019-8238-3>.
- Rajeevan, M., S. Gadgil, and J. Bhate, 2010: Active and break spells of the Indian summer monsoon. *J. Earth Syst. Sci.*, **119**, 229–247, <https://doi.org/10.1007/s12040-010-0019-4>.
- Ramage, C. S., 1952: Diurnal variation of summer rainfall over east China, Korea and Japan. *J. Meteor.*, **9**, 83–86, [https://doi.org/10.1175/1520-0469\(1952\)009<0083:DVOSRO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1952)009<0083:DVOSRO>2.0.CO;2).
- Rao, T. N., K. Saikranthi, B. Radhakrishna, and S. V. Bhaskara Rao, 2016: Differences in the climatological characteristics of precipitation between active and break spells of the Indian summer monsoon. *J. Climate*, **29**, 7797–7814, <https://doi.org/10.1175/JCLI-D-16-0028.1>.
- Romatschke, U., and R. A. Houze, 2011: Characteristics of precipitating convective systems in the South Asian monsoon. *J. Hydrometeorol.*, **12**, 3–26, <https://doi.org/10.1175/2010JHM1289.1>.
- , S. Medina, and R. A. Houze, 2010: Regional, seasonal, and diurnal variations of extreme convection in the South Asian region. *J. Climate*, **23**, 419–439, <https://doi.org/10.1175/2009JCLI3140.1>.
- Sahany, S., V. Venugopal, and R. S. Nanjundiah, 2010: Diurnal-scale signatures of monsoon rainfall over the Indian region from TRMM satellite observations. *J. Geophys. Res.*, **115**, D02103, <https://doi.org/10.1029/2009JD012644>.
- Sen Roy, S., and R. C. Balling, 2007: Diurnal variations in summer season precipitation in India. *Int. J. Climatol.*, **27**, 969–976, <https://doi.org/10.1002/joc.1458>.
- Shapiro, A., E. Fedorovich, and S. Rahimi, 2016: A unified theory for the Great Plains nocturnal low-level jet. *J. Atmos. Sci.*, **73**, 3037–3057, <https://doi.org/10.1175/JAS-D-15-0307.1>.
- Shin, U., T.-Y. Lee, and S.-H. Park, 2019: Environment and processes for heavy rainfall in the early morning over the Korean peninsula during episodes of cloud clusters associated with mesoscale troughs. *J. Meteor. Soc. Japan*, **97**, 633–655, <https://doi.org/10.2151/jmsj.2019-036>.
- Shrestha, D., P. Singh, and K. Nakamura, 2012: Spatiotemporal variation of rainfall over the central Himalayan region revealed by TRMM Precipitation Radar. *J. Geophys. Res.*, **117**, D22106, <https://doi.org/10.1029/2012JD018140>.
- Sikka, D. R., 1977: Some aspects of the life history, structure and movement of monsoon depressions. *Pure Appl. Geophys.*, **115**, 1501–1529, <https://doi.org/10.1007/BF00874421>.

- Singh, P., and K. Nakamura, 2010: Diurnal variation in summer monsoon precipitation during active and break periods over central India and southern Himalayan foothills. *J. Geophys. Res.*, **115**, D12122, <https://doi.org/10.1029/2009JD012794>.
- Sun, J., and F. Zhang, 2012: Impacts of mountain-plains solenoid on diurnal variations of rainfalls along the mei-yu front over the East China plains. *Mon. Wea. Rev.*, **140**, 379–397, <https://doi.org/10.1175/MWR-D-11-00041.1>.
- Tao, S., and L. Chen, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.
- Terao, T., M. N. Islam, T. Hayashi, and T. Oka, 2006: Nocturnal jet and its effects on early morning rainfall peak over northeastern Bangladesh during the summer monsoon season. *Geophys. Res. Lett.*, **33**, L18806, <https://doi.org/10.1029/2006GL026156>.
- Trier, S. B., C. A. Davis, and R. E. Carbone, 2014: Mechanisms governing the persistence and diurnal cycle of a heavy rainfall corridor. *J. Atmos. Sci.*, **71**, 4102–4126, <https://doi.org/10.1175/JAS-D-14-0134.1>.
- Tuttle, J. D., and C. A. Davis, 2006: Corridors of warm season precipitation in the central United States. *Mon. Wea. Rev.*, **134**, 2297–2317, <https://doi.org/10.1175/MWR3188.1>.
- Wang, B., and Z. Fan, 1999: Choice of South Asian summer monsoon indices. *Bull. Amer. Meteor. Soc.*, **80**, 629–638, [https://doi.org/10.1175/1520-0477\(1999\)080<0629:COSASM>2.0.CO;2](https://doi.org/10.1175/1520-0477(1999)080<0629:COSASM>2.0.CO;2).
- Wang, C. C., G. T. J. Chen, and R. E. Carbone, 2004: A climatology of warm-season cloud patterns over East Asia based on GMS infrared brightness temperature observations. *Mon. Wea. Rev.*, **132**, 1606–1629, [https://doi.org/10.1175/1520-0493\(2004\)132<1606:ACOWCP>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1606:ACOWCP>2.0.CO;2).
- Willett, P. D., J. H. Marsham, C. E. Birch, D. J. Parker, S. Webster, and J. Petch, 2017: Moist convection and its upscale effects in simulations of the Indian monsoon with explicit and parameterized convection. *Quart. J. Roy. Meteor. Soc.*, **143**, 1073–1085, <https://doi.org/10.1002/qj.2991>.
- Wu, G., W. Li, H. Guo, H. Liu, J. Xue, and Z. Wang, 1997: Sensible heat driven air-pump over the Tibetan Plateau and its impacts on the Asian summer monsoon. *Collections in the Memory of Zhao Jiuzhang*, D. Ye, Ed., Chinese Science Press, 116–126.
- , Y. Liu, B. He, Q. Bao, A. Duan, and F. Jin, 2012: Thermal controls on the Asian summer monsoon. *Sci. Rep.*, **2**, 404, <https://doi.org/10.1038/srep00404>.
- , and Coauthors, 2015: Tibetan Plateau climate dynamics: Recent research progress and outlook. *Natl. Sci. Rev.*, **2**, 100–116, <https://doi.org/10.1093/nsr/nwu045>.
- , H. Zhuo, Z. Wang, and Y. Liu, 2016: Two types of summertime heating over the Asian large-scale orography and excitation of potential-vorticity forcing. I. Over Tibetan Plateau. *Sci. China Earth Sci.*, **59**, 1996–2008, <https://doi.org/10.1007/s11430-016-5328-2>.
- Xie, S.-P., H. Xu, N. H. Saji, Y. Wang, and W. T. Liu, 2006: Role of narrow mountains in large-scale organization of Asian monsoon convection. *J. Climate*, **19**, 3420–3429, <https://doi.org/10.1175/JCLI3777.1>.
- Xue, M., X. Luo, K. Zhu, Z. Sun, and J. Fei, 2018: The controlling role of boundary layer inertial oscillations in mei-yu frontal precipitation and its diurnal cycles over China. *J. Geophys. Res. Atmos.*, **123**, 5090–5115, <https://doi.org/10.1029/2018JD028368>.
- Yamada, H., B. Geng, H. Uyeda, and K. Tsuboki, 2007: Thermodynamic impact of the heated landmass on the nocturnal evolution of a cloud cluster over a Mei-yu-Baiu front. *J. Meteor. Soc. Japan*, **85**, 663–685, <https://doi.org/10.2151/jmsj.85.663>.
- Yanai, M., C. Li, and Z. Song, 1992: Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *J. Meteor. Soc. Japan*, **70**, 319–351, https://doi.org/10.2151/jmsj1965.70.1b_319.
- Yang, X., and X. Li, 2018: Budget analyses of precipitation and energetics associated with torrential rainfall events over Zhejiang, Fujian and Jiangxi. *SOLA*, **14**, 185–191, <https://doi.org/10.2151/sola.2018-033>.
- Ye, D., and G. Wu, 1998: The role of the heat source of the Tibetan Plateau in the general circulation. *Meteor. Atmos. Phys.*, **67**, 181–198, <https://doi.org/10.1007/BF01277509>.
- Yeh, T. C., S. W. Lo, and P. C. Chu, 1957: On the heat balance and circulation structure in troposphere over Tibetan Plateau (in Chinese). *Acta Meteor. Sin.*, **28**, 108–121.
- Yu, R., T. Zhou, A. Xiong, Y. Zhu, and J. Li, 2007a: Diurnal variations of summer precipitation over contiguous China. *Geophys. Res. Lett.*, **34**, L01704, <https://doi.org/10.1029/2006GL028129>.
- , Y. Xu, T. Zhou, and J. Li, 2007b: Relation between rainfall duration and diurnal variation in the warm season precipitation over central eastern China. *Geophys. Res. Lett.*, **34**, L13703, <https://doi.org/10.1029/2007GL030315>.
- , J. Li, H. Chen, and W. Yuan, 2014: Progress in studies of the precipitation diurnal variation over contiguous China. *J. Meteor. Res.*, **28**, 877–902, <https://doi.org/10.1007/s13351-014-3272-7>.
- Yuan, W., R. Yu, M. Zhang, W. Lin, H. Chen, and J. Li, 2012: Regimes of diurnal variation of summer rainfall over subtropical East Asia. *J. Climate*, **25**, 3307–3320, <https://doi.org/10.1175/JCLI-D-11-00288.1>.
- , —, —, —, J. Li, and Y. Fu, 2013a: Diurnal cycle of summer precipitation over subtropical East Asia in CAM5. *J. Climate*, **26**, 3159–3172, <https://doi.org/10.1175/JCLI-D-12-00119.1>.
- , —, and J. Li, 2013b: Changes in the diurnal cycles of precipitation over eastern China in the past 40 years. *Adv. Atmos. Sci.*, **30**, 461–467, <https://doi.org/10.1007/s00376-012-2092-x>.
- Zeng, W., G. Chen, Y. Du, and Z. Wen, 2019: Diurnal variations of low-level winds and rainfall response to large-scale circulations during a heavy rainfall event. *Mon. Wea. Rev.*, **147**, 3981–4004, <https://doi.org/10.1175/MWR-D-19-0131.1>.
- Zhang, Y., F. Zhang, C. Davis, and J. Sun, 2018: Diurnal evolution and structure of long-lived mesoscale convective vortices along the mei-yu front over the East China Plains. *J. Atmos. Sci.*, **75**, 1005–1025, <https://doi.org/10.1175/JAS-D-17-0197.1>.
- , M. Xue, K. Zhu, and B. Zhou, 2019: What is the main cause of diurnal variation and nocturnal peak of summer precipitation in Sichuan Basin, China? The key role of boundary layer low-level jet inertial oscillations. *J. Geophys. Res.*, **124**, 2643–2664, <https://doi.org/10.1029/2018JD029834>.
- Zhou, T., R. Yu, H. Chen, A. Dai, and Y. Pan, 2008: Summer precipitation frequency, intensity, and diurnal cycle over China: A comparison of satellite data with rain gauge observations. *J. Climate*, **21**, 3997–4010, <https://doi.org/10.1175/2008JCLI2028.1>.