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Diurnal-scale signatures of monsoon rainfall over the Indian region from TRMM satellite observations

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[1] One of the most important modes of summer season precipitation variability over the Indian region, the diurnal cycle, is studied using the Tropical Rainfall Measuring Mission 3-hourly, 0.25° × 0.25° 3B42 rainfall product for nine years (1999–2007). Most previous studies have provided an analysis of a single year or a few years of satellite- or station-based rainfall data. Our study aims to systematically analyze the statistical characteristics of the diurnal-scale signature of rainfall over the Indian and surrounding regions. Using harmonic analysis, we extract the signal corresponding to diurnal and subdiurnal variability. Subsequently, the 3-hourly time period or the octet of rainfall peak for this filtered signal, referred to as the "peak octet," is estimated, with care taken to eliminate spurious peaks arising out of Gibbs oscillations. Our analysis suggests that over the Bay of Bengal, there are three distinct modes of the peak octet of diurnal rainfall corresponding to 1130, 1430, and 1730 Indian standard time (IST), from the north central to south bay. This finding could be seen to be consistent with southward propagation of the diurnal rainfall pattern reported by earlier studies. Over the Arabian Sea, there is a spatially coherent pattern in the mode of the peak octet (1430 IST), in a region where it rains for more than 30% of the time. In the equatorial Indian Ocean, while most of the western part shows a late night/early morning peak, the eastern part does not show a spatially coherent pattern in the mode of the peak octet owing to the occurrence of a dual maxima (early morning and early/late afternoon). The Himalayan foothills were found to have a mode of peak octet corresponding to 0230 IST, whereas over the Burmese mountains and the Western Ghats (west coast of India) the rainfall peaks during late afternoon/early evening (1430–1730 IST). This implies that the phase of the diurnal cycle over inland orography (e.g., Himalayas) is significantly different from coastal orography (e.g., Western Ghats). We also find that over the Gangetic plains, the peak octet is around 1430 IST, a few hours earlier compared to the typical early evening maxima over land.

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1. Introduction

[2] The diurnal and seasonal cycles form the most fundamental forced modes of variability of the global climate as they closely follow the motion of Earth and the associated solar forcing. The diurnal cycle has been a subject of research for several decades, but the scarcity of observational data sets with high temporal and spatial resolution has led to conclusions which may not be generalized to a reasonable extent. Many studies have provided an analysis of a single year or few years of satellite- or station-based rainfall data [e.g., *Imaoka and Spencer*, 2000; *Sorooshian et al.*, 2002; *Nesbitt and Zipser*, 2003; *Yang and Smith*, 2006; *Basu*, 2007] and hence, the robustness of the results needs to be validated against a long enough data set, such that the sample time series chosen for analysis represents the population to a fair degree. Studies based on surface observations [e.g., *Gray and Jacobson*, 1977; *Dai*, 2001] as well as those based on satellite- or radar-derived cloudiness and precipitation [e.g., *Hendon and Woodberry*, 1993; *Janowiak et al.*, 1994; *Chen and Houze*, 1997] show that the convective maximum preferentially occurred during late afternoon/early evening over land and in the early morning over the open oceans. However, some studies [e.g., *McGarry and Reed*, 1978; *Shin et al.*, 1990] showed an afternoon maximum in precipitation over the oceans. *Ohsawa et al.* [2001] analyzed station and remotely sensed observations of rainfall in tropical Asia and found that the maximum convective activity occurs during the early evening over land and late night/early morning over coastal regions and windward sides of mountains. *Mapes et al.* [2003a] studied the diurnal cycle of rainfall in northwestern South America and found an afternoon maximum rainfall over most of the land region

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and a strong night/morning maximum over the ocean. *Yang and Smith* [2006] used Tropical Rainfall Measuring Mission (TRMM) observations for 1998 to provide a detailed description of the possible mechanisms that govern the diurnal cycle of tropical rainfall.

[3] *Dai* [2001] provided the first comprehensive global study of the diurnal cycle of precipitation, using 3-hourly in situ weather reports from 1975 to 1997. More recently, *Dai et al.* [2007] analyzed four different rainfall products (in situ and remotely sensed) and evaluated their ability to resolve diurnal-scale signatures of rainfall. *Liu and Zipser* [2008] used 9 years of TRMM Precipitation Radar (PR), Visible and Infrared Scanner (VIRS), and Lightning Imaging Sensor measurements and found that the diurnal cycles over land show a late afternoon maximum of precipitation systems, whereas over the oceans, the diurnal cycle is interpreted as having contributions from nocturnal precipitation systems as well as from early afternoon showers.

[4] *Hirose and Nakamura* [2005] and *Hirose et al.* [2008] analyzed the spatial and diurnal variation of precipitation systems over the Asian region using data from TRMM PR. They found that large convective systems (>10,000 km^2) develop mostly in the evening, following the time of maximum occurrence of smaller systems (100 km^2), over nearly flat landmasses, like inland India. They reported widespread systems developing over the foothills of the Himalayas in the late night/early morning period. They also found early afternoon (1400—1600 LT) rainfall over most of the Tibetan Plateau. Maximum rainfall in the southern part of the Bay of Bengal (BOB) and the nearby coast was reported to occur during early afternoon and morning, respectively.

[5] The most comprehensive study of the diurnal cycle over the tropics was done by *Kikuchi and Wang* [2008]. Using two TRMM products, namely, 3B42 (discussed in section 2) and 3G68 (consisting of rainfall estimates from TRMM Microwave Imager (TMI), PR, and the TMI-PR combined algorithm gridded at 0.5° × 0.5°) for the period 1998–2006, they made an attempt to provide a unified view of the diurnal variation of the global tropical precipitation. On the basis of the amplitude, peak time, and phase propagation characteristics of the diurnal precipitation they divided the tropical diurnal cycle into three regimes: oceanic (0600–0900 LST), continental (1500–1800 LST), and coastal (2100–1200 LST for seaside and 1200–2100 LST for landside). Another study that focuses on comparing the estimates of the peak hour of rainfall from different rainfall data products is that of *Yamamoto et al.* [2008]. They found that, in general, the estimates of the peak hour from three sources, namely, PR, TMI, and VIRS, have systematic differences over a few regions such as western North America, the Tibetan Plateau, and the Gulf of Mexico. *Johnson* [2008] presented a review of the diurnal cycle of convection, with an emphasis on the Asian monsoon. The study reported that the dominant pattern of diurnal variability is a maximum in rainfall over land during the afternoon/evening and a morning maximum over the oceans. However, there are regions with notable exceptions to the typical diurnal pattern of rainfall over both land (e.g., late night/early morning maxima over areas surrounding the Tibetan Plateau) and ocean (e.g., daytime maxima over the BOB).

[6] Over the Indian land region, *Pathan* [1994] analyzed hourly rainfall data of 33 rain gauge stations for the period 1959–1968 and found a midnight to late morning maxima over coastal and island stations, whereas an afternoon/evening maxima was observed over the inland stations. *Krishnamurti and Kishtawal* [2000] studied the diurnal mode of the Asian summer monsoon using satellite data from Meteosat-5 (infrared cloud images and cloud motion winds) and TRMM (TMI-based rainfall). They concluded that during the afternoon hours the diurnal divergent circulation has an ascending lobe over north central India, whereas the descending lobe reaches out radially toward central and southern parts of China, the equatorial Indian Ocean, and the western Arabian Sea. *Gambheer and Bhat* [2001] analyzed INSAT-1B pixel data and reported that over the central BOB precipitation is preferred during morning to noon hours, while 2200–0400 LST appears to be the least favored period. *Barros et al.* [2004] used a combination of in situ and remotely sensed precipitation measurements to investigate the diurnal cycle of convective activity and the associated orographic controls over the Himalayas and northern India.

[7] *Basu* [2007] used hourly precipitation data from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN) over India and neighboring regions for a single year (2004) to analyze the diurnal variations of rainfall during the summer monsoon season. The study found that the rainfall maxima occurred between 0300 and 0600 LT along the Himalayan foothills, whereas over most of the oceanic regions around India, the peak was between 0300 and 0900 UTC. In addition, it was found that the time of maxima in rainfall over land varied from 1500–1800 LT in the east to 1800–2100 LT in the west. *Sen Roy and Balling* [2007] analyzed hourly precipitation data from 78 stations spread across the Indian subcontinent for the period 1980–2000. They showed that the maximum precipitation along the west coast is during predawn hours. *Sen Roy* [2008] studied the spatial variations in the diurnal patterns of winter precipitation over the Indian land, using hourly precipitation data over stations spread across the subcontinent for the months of January and February from 1980 to 2002. The author reported that the weakest diurnal patterns were observed over central India (CI) during the winter season, with the time of maximum rainfall between midnight and predawn hours.

[8] Although there have been a number of studies on the diurnal cycle, the diurnal-scale variability of summer monsoon (June through September (JJAS)) rainfall at finer spatial scales over the Indian and surrounding regions is yet to be comprehensively documented. Since the region of interest (Indian land and its neighboring oceans) consists of sharp geographical features such as coastlines and narrow mountains, it is essential to use a data set that provides high spatial and temporal resolution. Of late, high temporal and spatial resolution global data sets of rainfall have been available from satellites, and this provides an ideal opportunity to study the diurnal cycle of rainfall over this region. Thus, the main aim of this study is to explore and document the finer spatial structure of the diurnal cycle of Indian

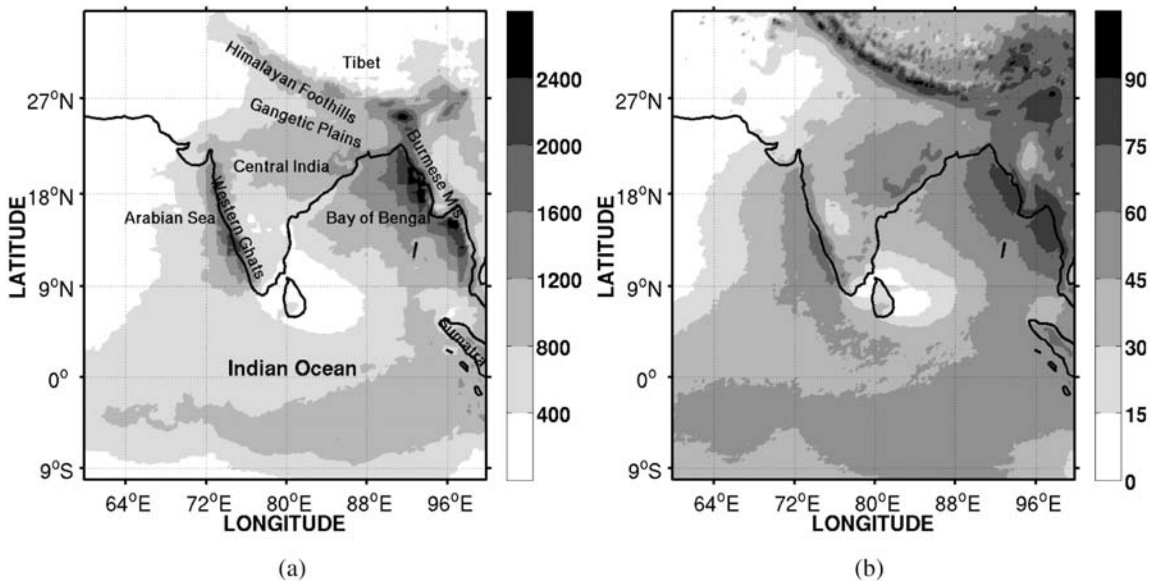


Figure 1. (a) Climatology of JJAS seasonal accumulation (mm) for the region 60°–100°E, 10°S–35°N. (b) Climatology of the percentage of rainy days for the same region during JJAS. The climatology is calculated on the basis of 3-hourly, 0.25° rainfall observations from 1999 to 2007.

monsoon rainfall and also to compare and contrast our findings with previous studies.

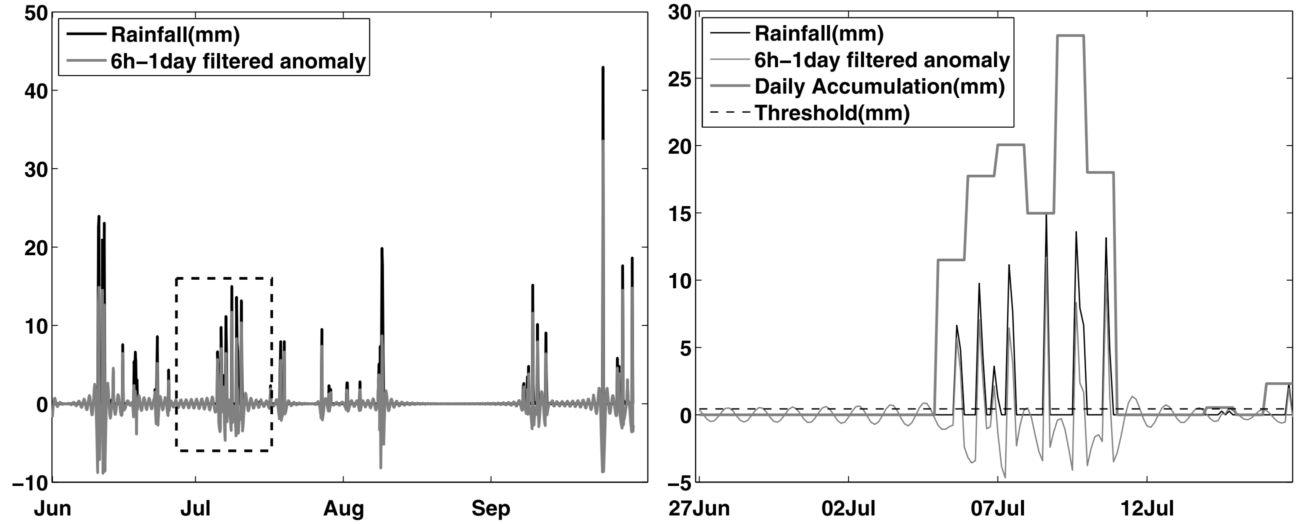
2. Data Description and Methodology

[9] The 3-hourly TRMM product 3B42 data [e.g., see *Kummerow et al.*, 1998; *Adler et al.*, 2000; *Huffman et al.*, 2007] for the period 1999–2007 are used for our analysis (1998 has not been considered for the analysis owing to a large number of missing points over the region of interest). The 3-hourly averaged values are centered at the middle of each 3 h period; for instance, the rain rate corresponding to 0000 UTC represents the average value between 2230 and 0130 UTC. The spatial resolution of this data set is 0.25° × 0.25°, and the domain covered is 50°S–50°N, 0°–360°E. This product is an optimal combination of various high-quality microwave estimates to adjust infrared estimates from high-frequency geostationary observations (see http://trmm.gsfc.nasa.gov/3b42.html). The data set thus manages to avoid the risk of aliasing longer time scale variability onto the diurnal cycle and hence provides an opportunity to study the diurnal-scale variability of rainfall. In addition to 3B42, there are several other TRMM products like 3G68 which are suitable for the study of the diurnal cycle of rainfall. However, the primary advantage of the former product is its greater spatial coverage at any given point in time. Also, since rainfall retrieval using passive microwave sensors could introduce phase and amplitude errors, we have validated our results from TRMM observations against previous studies over land and with analysis of in situ observations over the Bay of Bengal.

[10] The region of our study is limited to 10°S–35°N, 60°E–100°E, encompassing India, Burma, Sumatra, the Bay of Bengal, the Arabian Sea, and the equatorial Indian Ocean. The Indian summer monsoon season, namely, JJAS, has been chosen for our analysis. Figures 1a and 1b show the nine year climatology of the seasonal (JJAS) rainfall accumulation and the seasonal percentage of rainy days, respectively, for this region. The low-rain regions (raining less than 30% of the time) over India and the Arabian Sea are clearly seen and so are the heavy rainfall regions of the Burmese mountains, northeast India, and the Western Ghats (west coast of India). It is interesting to note that while the foothills of the Himalayas have a higher percentage of rainy days (75%–90%) than the Western Ghats (60% –75%), the total accumulation is significantly larger over the Western Ghats.

[11] In order to study the diurnal-scale characteristics of rainfall, we first compute the Fourier transform of the JJAS 3-hourly rainfall at each grid point for every year. (The number of samples per grid point per year is 122 × 8 = 976.) Since our interest is to estimate the octet of day when the peak rainfall occurs, it is appropriate to retain the subdiurnal characteristics. Therefore, a time series of rainfall anomalies is constructed by removing the seasonal 3-hourly mean as well as all time scales greater than 1 day. In other words, our reconstructed time series consists of rainfall anomalies (about the seasonal 3-hourly mean) at all time scales between 6 h (Nyquist period) and 1 day. It is important to note that estimating the time of maximum rainfall every day could be influenced by larger time scales, and hence the proposed filtering is important for isolating the diurnal-scale characteristics. (On a related note, we demonstrate in section 3 that looking only at the climatology of the 3 h rainfall will not always lead to an accurate assessment of the diurnal-scale signature.)

[12] Figure 2a shows the rainfall time series (thin black line) at a particular grid point (75°E, 20°N) for the year 1999. Also shown in Figure 2a is the filtered and reconstructed time series (thin gray line), sampled every 3 h, corresponding to the 6 h to 1 day time scale. Following the reconstruction, for each day (eight samples), the octet of



(a) (b)

Figure 2. (a) Three-hourly rainfall time series (solid black line) at (75°E, 20°N) in 1999. The solid gray line represents the 6 h to 1 day rainfall anomaly; that is, all scales larger than 1 day have been filtered out after traditional Fourier decomposition of the 3-hourly rainfall. (b) The portion marked by the rectangle (27 June to16 July) in Figure 2a is zoomed to illustrate spurious Gibbs oscillations which are a by-product of the inability of Fourier decomposition to approximate strong isolated spikes (intermittency). In order to account for these spurious oscillations, we set a threshold equal to 10% of the seasonal daily mean at the corresponding grid point and year. If the daily accumulation (thick gray line) is less than the threshold (black dashed line), then that day is not considered in the filtered anomalies (thin gray line) for the purpose of estimating the peak octet statistics. In this illustrative example, the seasonal daily mean at (75°E, 20°N) for 1999 is ~4.4 mm/d, and the threshold is 0.44 mm/d, and thus, the days that are considered for estimating the peak octet are 6–11 July.

day when the maximum rainfall (in the filtered time series) occurs is estimated, and this is called the "peak octet." Given that the sampling rate is 3-hourly, our estimate of the peak octet would be the 3 h interval represented by one of [0230, 0530, 0830, 1130, 1430, 1730, 2030, 2330 Indian standard time (IST)]. Before we estimate the peak octet, we perform a simple thresholding to account for any spurious Gibbs oscillations. These oscillations are a by-product of the inability of Fourier transform to represent highly intermittent signals such as rainfall. To illustrate this potential pitfall, a part of Figure 2a (marked by the dashed rectangle) is magnified and shown in Figure 2b. It is evident from Figure 2b that if one were to estimate the peak octet each day from the diurnal rainfall anomalies, one would include all the local maxima of the spurious oscillations around any strong spike in the original rainfall time series owing to the Gibbs phenomena. For instance, in Figure 2b, one would have included the local maxima from 27 June to 4 July, when in fact there was no rainfall during those days.

[13] In order to avoid these spurious oscillations (and the related local maxima), we use the following criterion for each grid point: If on a particular day, the total rainfall (i.e., daily accumulation) is less than a threshold, that day in the filtered time series is not included for the estimation of peak octet. In our analysis presented here, the threshold used is 10% of the seasonal daily mean (which is a function of year and grid point). For instance, at (75°E, 20°N) the daily accumulation is shown as a thick gray line, and the threshold value (≈0.5 mm/d) is shown as a constant black dashed line in Figure 2b. Thus, those days when the black dashed line is above the thick gray line, the peak octet is not estimated. Referring back to the case of 27 June through 4 July, with this thresholding approach, one can easily see that the spurious Gibbs oscillations are eliminated. We also used a higher threshold (to the extent that the sample size does not reduce considerably) and found that there are no significant differences in our estimates of the peak octet.

3. Results and Discussion

[14] Before we estimate the peak octet statistics, as a first step in our analysis, we looked at the climatology (1999–2007) of JJAS composites of the 3-hourly rainfall rates (Figure 3). The general observation from the rainfall climatology is that the strongest diurnal variability is seen over the topographically rich regions (i.e., the Himalayan foothills, western Sumatra, and the Burmese mountains), CI and the BOB. Specifically, (1) over CI, rainfall appears to start around 1430 IST and peak at 1730 IST (Figures 3d and 3e); (2) the Burmese mountains also receive most of the rainfall around 1430–1730 IST (Figures 3d and 3e); (3) over the Himalayan foothills, the maximum amplitude of rainfall is seen during late night/early morning (i.e., 0230–0530 IST, Figures 3a and 3h); (4) BOB receives most of its rainfall during the period 0530–1430 IST (Figures 3a–3d); (5) the Sumatra region receives a burst of heavy rain during a very short time span, around 1730 IST (Figures 3e and 3f); and, finally, (6) the Western Ghats do not show significant

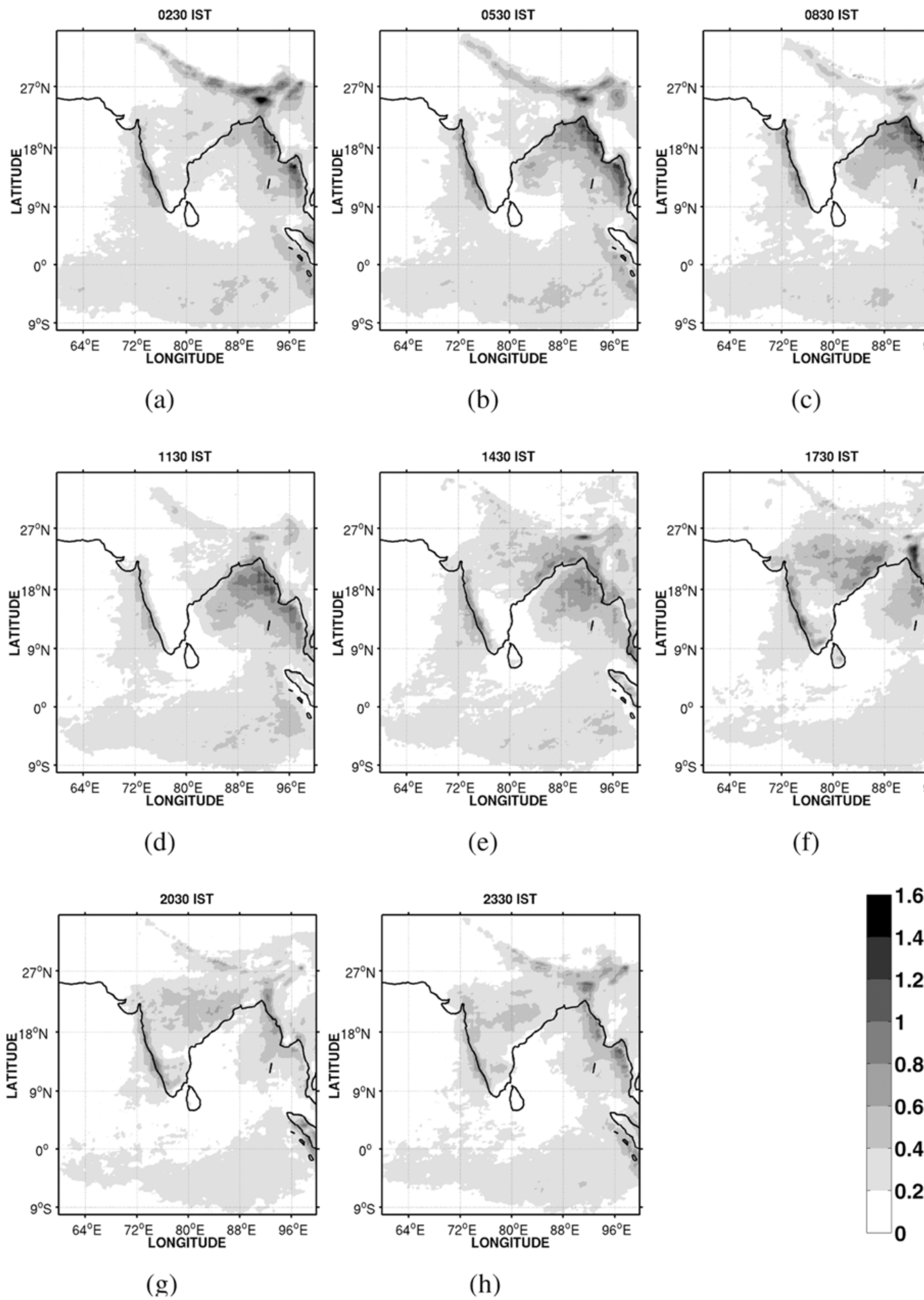


Figure 3. (a–h) The climatology (1999–2007) of rainfall for JJAS corresponding to the eight octets, 0230 IST through 2330 IST, at 3-hourly intervals. The gray scale represents rainfall intensity in mm/h.

rainfall variability during the course of the day, suggesting that perhaps there is no strong diurnal cycle in this region.

[15] These observations suggest that the land region in the tropics tends to receive its highest rainfall (on a diurnal scale) during the afternoon to late evening hours. This aspect has been reported by several previous studies using single-year or station data [e.g., *Krishnamurti and Kishtawal*, 2000; *Pathan*, 1994; *Yang and Smith*, 2006; *Dai et al.*, 2007; *Basu*, 2007; *Liu and Zipser*, 2008]. In order to study the diurnal cycle in greater detail, we follow the procedure outlined in section 2, namely, analyzing the filtered (reconstructed) rainfall time series corresponding to the time scales of 6 h to 1 day.

3.1. Spatial Distribution of Daily Rainfall Anomalies

[16] The filtered rainfall (or rainfall anomalies) time series is constructed for each grid point and each year. A 3-hourly climatology of these rainfall anomalies is then estimated for each grid point on the basis of 122 days (JJAS) and 9 years of data, and its spatial distribution is shown in Figure 4. A strong anomaly (positive or negative) suggests the presence of a prominent diurnal cycle. A strong positive anomaly over a grid point at any given octet would have a corresponding strong negative anomaly at some other octet. The following observations can be made from Figure 4.

[17] 1. Over central India, positive anomalies start appearing around 1430 IST and peak at 1730 IST, followed by a gradual decay, with most of the region showing negative anomalies by 0230 IST, the next day (Figures 4d, 4e, and 4h).

[18] 2. BOB shows an interesting structure in the rainfall anomalies from the head bay southward. The head bay shows a positive anomaly from 0530 to 0830 IST, whereas the central bay shows a negative anomaly during the same period (Figures 4a and 4b). By 1130 IST, the positive anomaly can be seen appearing in the central bay (for instance, note the zero crossing of the sign of anomalies over the central bay from 0530 to 1130 IST), with a reduction in the amplitude of positive anomaly over the head bay (Figure 4c). The positive anomalies appear farther southward, and the head bay shows negative anomalies by 1430–1730 IST (Figures 4d and 4e), with the central and south bay showing positive anomalies during the same period.

[19] 3. Another interesting aspect to be noted is the contrast in the behavior of the diurnal-scale signature over central India and the northern half of the Bay of Bengal (NBOB). When NBOB has strong negative anomalies (no/low rainfall), central India appears to have strong positive anomalies (high rainfall) (Figures 4d and 4e) and vice versa. This suggests that convergence over one region (say, CI) is perhaps accompanied by a subsidence over the other region (NBOB). *Krishnamurti and Kishtawal* [2000] reported a similar behavior in their study using wind observations and concluded that, during the afternoon hours, the diurnal circulation has an ascending lobe over north central India and a descending lobe over the surrounding regions.

[20] 4. The Himalayan foothills show a large positive anomaly at around 0230 IST, which rapidly decays and becomes negative by 1130 IST (Figures 4a, 4c, and 4h).

[21] 5. Over the Burmese mountains (along the eastern part of the Bay of Bengal), there is a large positive anomaly, corresponding to the peak octet of the diurnal cycle, at around 1430–1730 IST (Figures 4d and 4e).

[22] 6. Over the Western Ghats, a small positive anomaly is noticed in the octet corresponding to 1430 IST, which peaks at 1730 IST. During the rest of the day, the anomalies are predominantly negative. It is important to note that from the 3 h rainfall climatology (Figure 3), there was no strong signature of diurnal rain; however, upon appropriate filtering, a strong diurnal-scale signature becomes clearly evident.

[23] 7. The Sumatra region shows a very strong diurnal cycle: a "burst" of high positive anomaly over a 3 h interval around 1730 IST (Figure 4e) and negative anomalies during the rest of the day.

[24] Having given a qualitative picture of the spatial distribution of the climatological diurnal-scale variability of rainfall, we combine these findings into a concise, quantitative picture using a simple measure, namely, the mode of the peak octet. Specifically, for each grid point, every year (during JJAS), we estimate the peak octet each day (i.e., local maxima per eight samples) after accounting for spurious Gibbs oscillations by applying a threshold of 10% of the seasonal daily mean on the daily accumulation (as described in section 2).

3.2. Interannual Variability of Diurnal Cycle

[25] Figure 5a shows the spatial distribution of the mode of the peak octet for 1999. (The number of samples, per grid point per year that are used in calculating the mode would be approximately of the order of the number of rainy days. For instance, in those regions where it is raining $\approx$80% of the time (e.g., see Himalayan foothills in Figure 1b), the number of samples per year per grid point would be $122 \times 0.8 \approx 100$.) The most prominent diurnal signatures are over central India (1730 IST), the Burmese mountains (1430 and 1730 IST), the Himalayan foothills (0230 and 0530 IST), and Sumatra (1730 IST).

[26] One could further quantify the peak octet by zooming into smaller regions and studying the frequency distribution of the peak octet. Figures 5b and 5c show the frequency distributions for all 9 years (1999–2007) for the Bay of Bengal (dashed rectangle in Figure 5a) and central India (solid rectangle in Figure 5a), respectively. There are two important observations: (1) central India has a relatively well defined mode in the distribution of peak octets (Figure 5c), suggesting that there is a predominant time of the day when maximum rainfall occurs; however, the frequency distribution of the peak octets over the Bay of Bengal (Figure 5b) suggests the presence of multiple modes (also evident in Figure 5a, as one moves from the north central to the south bay); and (2) the behavior during above/near normal (within +1 standard deviation of the long-term mean) monsoon years (e.g., 1999 and 2003) and below normal (within or less than -1 standard deviation of the long-term mean) monsoon years (e.g., 2002 and 2004) is not significantly different. This suggests that there is no significant interannual variability associated with the diurnal cycle of rainfall. *Sen Roy and Balling* [2007], using station data, also reported a similar robustness of the diurnal cycle (over the Indian land) against interannual variations, in the form of El Niño–Southern Oscillation and La Niña years.

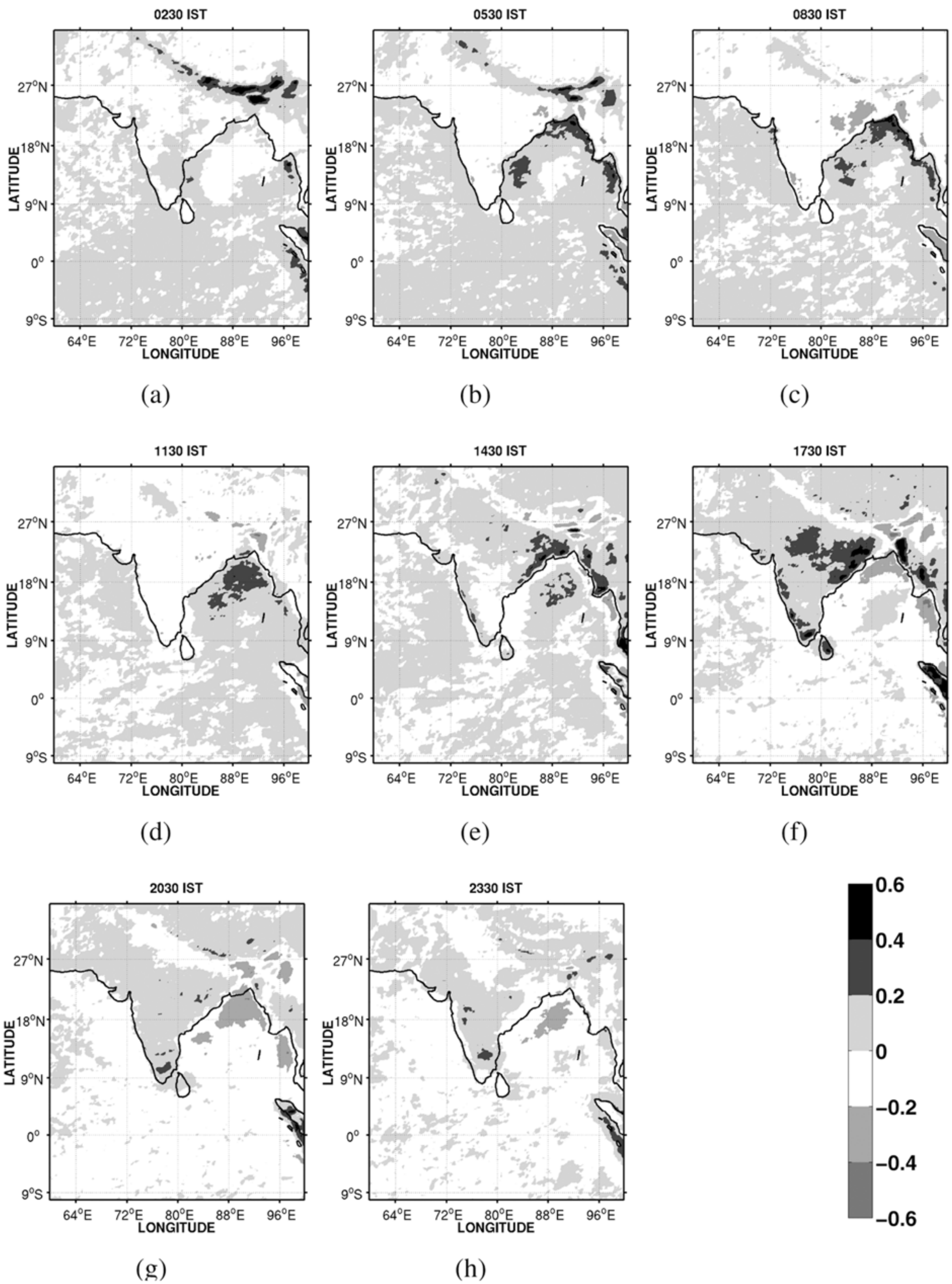


Figure 4. Same as Figure 3 but for filtered rainfall anomalies. The filtered anomalies contain time scales between 6 h and 1 day. See the text for more details. The gray scale represents rainfall anomaly amplitude in mm/h.

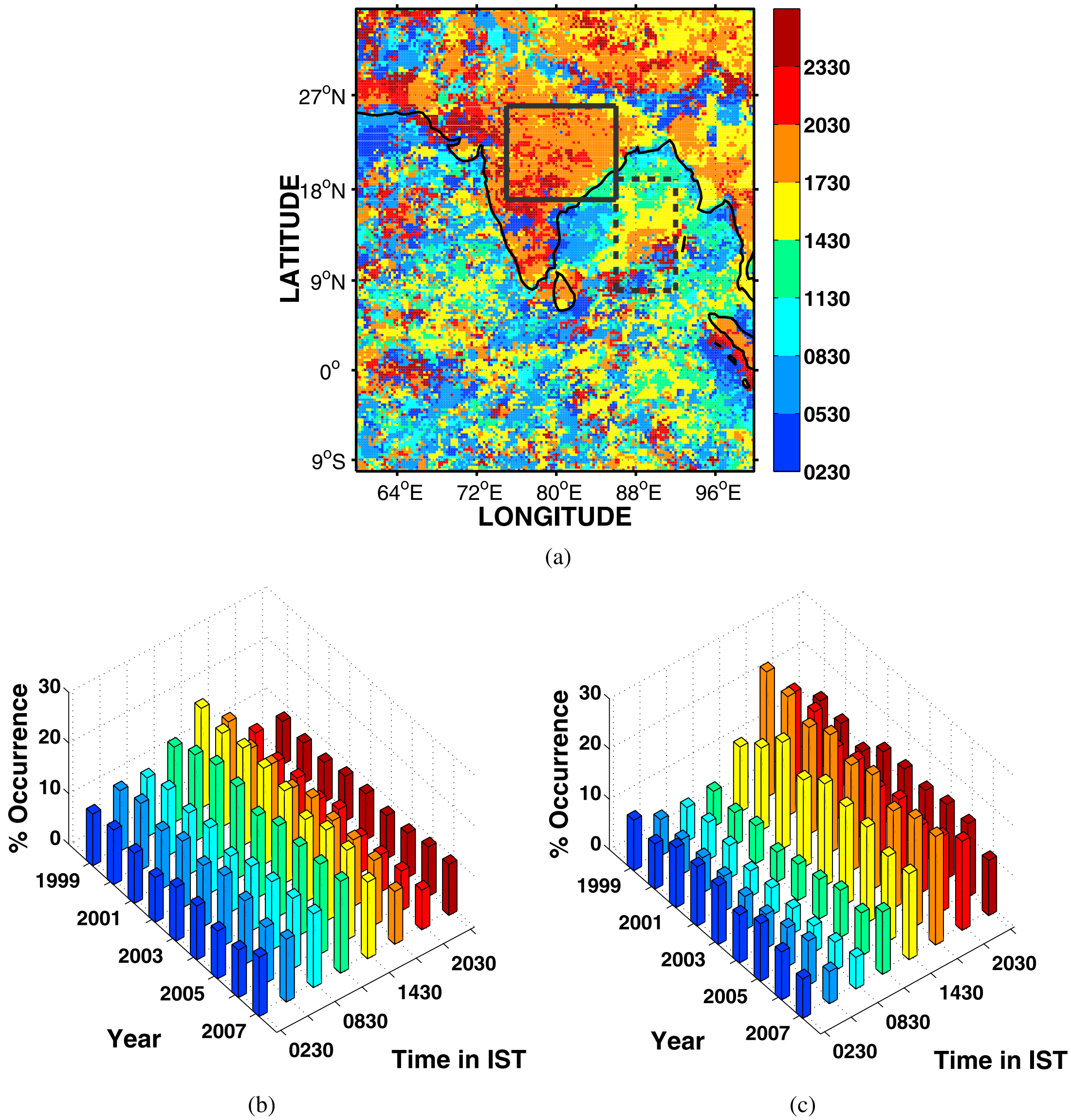
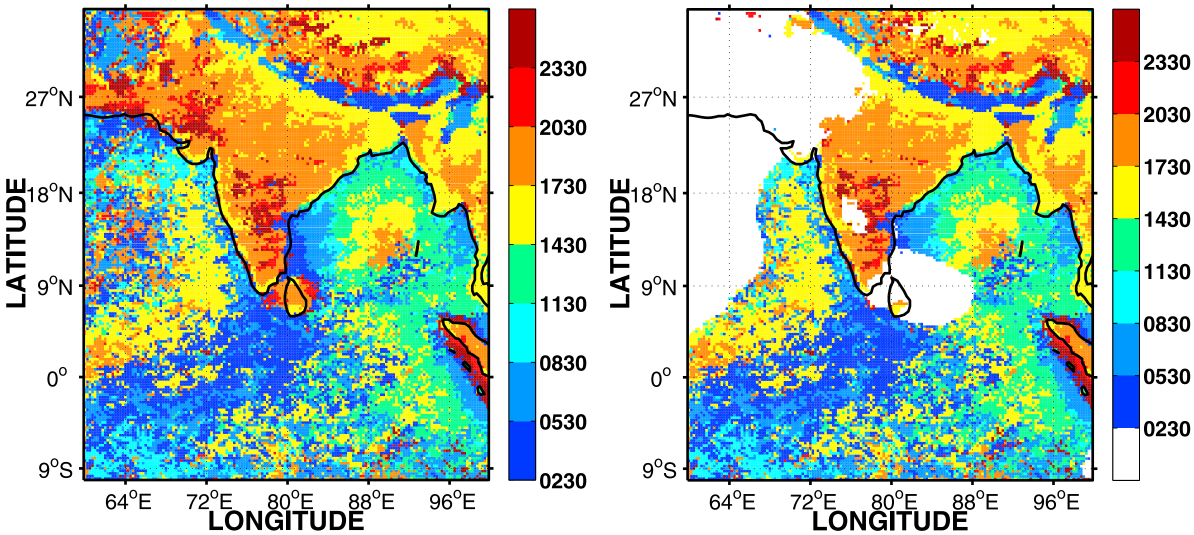


Figure 5. (a) Spatial distribution of the mode of the peak octet for JJAS 1999. For each grid point, the time of day (in 1999) at which the maximum rainfall is observed in the 3-hourly filtered rainfall anomalies (6 h to 1 day) is estimated after accounting for spurious Gibbs oscillations (see Figure 2 and the text for further details). These peak octet estimates, for each grid point, are pooled together into one frequency distribution, its mode is estimated, and its spatial distribution is plotted. Also shown is the three-dimensional behavior of the frequency distribution of the mode for (b) the Bay of Bengal (dashed rectangle) and (c) central India (solid rectangle).

3.3. Mode of the Peak Octet

[27] In order to obtain a spatial distribution more coherent than that illustrated in Figure 5a, we study the climatological behavior of the diurnal-scale signature. Toward that end, for each grid point, we pool together the estimates of the peak octet for all years (1999–2007) into a single-frequency distribution and estimate the corresponding mode. This estimate of the mode is called the ''climatological'' peak octet mode. Note that one could also use the mean peak octet as a measure of characterization of the diurnal-scale signature; however, this is fraught with complications owing to the cyclicity of the 0 to 21 or 24 h time cycle.

[28] Figure 6a shows the spatial distribution of the climatological peak octet mode. As expected, this spatial distribution is smoother than the distribution for a single year (Figure 5a). It is obvious from Figure 6a that a significant part of central India tends to receive maximum rainfall around 1730–2030 IST (i.e., early to late evening). Rainfall over the Himalayan foothills shows a mode of peak octet corresponding to 0230 IST [e.g., see *Sen Roy and Balling*, 2007], whereas over the Burmese mountains the rainfall peaks at 1430–1730 IST (late afternoon/early evening). It is also interesting to note that over the Gangetic plains and the Tibetan Plateau, the mode of the peak octet is around 1430 IST (early afternoon), separated by the late



(a) (b)

Figure 6. (a) Spatial distribution of the "climatological" mode of the peak octet for JJAS. The peak octet is estimated for each grid point for each of the 9 years (1999–2007) and is pooled together into one frequency distribution, and its mode is estimated. (b) Same as Figure 6a except those grid points which have rainfall occurring less than 30% of the time (see Figure 1b) have been masked out.

night/early morning maximum over the Himalayas. Around the Sumatra region, over land, one can clearly see a mode of the peak octet at 1730 IST, while in the ocean surrounding Sumatra, one can see multiple modes of the peak octet at 2330, 0230, and 0530 IST, suggesting a westward migration of the diurnal features [e.g., *Mori et al.*, 2004].

[29] Over the Bay of Bengal, the region closest to land shows an early morning (0530 IST) peak. This matches the finding of *Zuidema* [2003], who analyzed the brightness temperature data for 1988 and 1999 and reported a 0600 LT maximum in very cold cloud tops. However, over the rest of the BOB we observe modes at 1130, 1430, and 1730 IST from the north central to south bay. In order to check if this is a by-product of a southward propagation, we constructed Hovmoller diagrams of the 3-hourly diurnal rainfall. Figure 7a shows the Hovmoller diagram of 3-hourly reconstructed (consisting of only the diurnal and subdiurnal variability) rainfall for JJAS of 2007, averaged over 91.5°E–92.5°E. An active rainfall period which occurred around the first week of July is selected from Figure 7a and is shown in Figure 7b. From Figure 7b the diurnal rainfall can clearly be seen to propagate south, from around 22°N to 14°N in approximately 24 h, at an effective speed of around 10 m/s. *Liu et al.* [2008] studied the propagating rainfall episodes over the BOB using the TRMM Real-Time Multi-Satellite Precipitation Analysis (MPA-RT) product for May–September 2002–2004 and found that a majority of the precipitation episodes translate southward and, on average, these systems have a latitudinal span of 5° and a 1-day duration with a meridional propagation speed of around 8 m/s.

[30] Over the equatorial Indian Ocean, while most of the western part shows an early morning/late night peak, the eastern part does not show any striking spatial coherence in the mode of the peak octet, owing to the occurrence of a dual maxima. Specifically, we find a coexistence of early/late afternoon and early morning peaks. By using a threshold linked to the percentage of rainy days, one can visually eliminate the low-rain regions, and spatially more coherent patterns of the diurnal-scale signature emerge. This is shown in Figure 6b. For instance, the region over the Arabian Sea which shows a spatially coherent pattern of 1430–1730 IST can now clearly be seen as that region where it rains at least 30% of the time (compare with Figure 1b). Another example depicting the usefulness of the thresholding is the region in and around Sri Lanka. For instance, in Figure 6a, the Sri Lankan land region shows a 1730 IST peak, although it hardly rains there during this time of the year (e.g., see Figure 1a). On applying a threshold, it can be clearly seen from Figure 6b that most of the Sri Lankan land region does not show any diurnal signature. *Dai et al.* [2007] found that the spatial patterns of precipitation in midlatitudes depend more on the frequency than on the intensity of rain. In the tropics, we find a similar behavior, although most of the regions of heavy rain in the tropics also seem to be the regions where it rains frequently (compare, for instance, Figures 1a and 1b).

[31] We briefly compare our results with two recent and relevant studies which have comprehensively analyzed the diurnal structure of rainfall in the Asian region [*Hirose and Nakamura*, 2005; *Kikuchi and Wang*, 2008] (hereafter referred to as HN05 and KW08, respectively). Using TRMM 3B42 and 3G68 annual rainfall, KW08 identified three primary rainfall diurnal cycle regimes: oceanic, continental, and coastal (landside and seaside). Interestingly, a substantial part of Indian land, which receives rain during the summer monsoon season, does not form a part of any of the aforementioned regimes. On the other hand, the Indian land region which appears to show up in their analysis is peninsular India, which in fact receives most of its rain

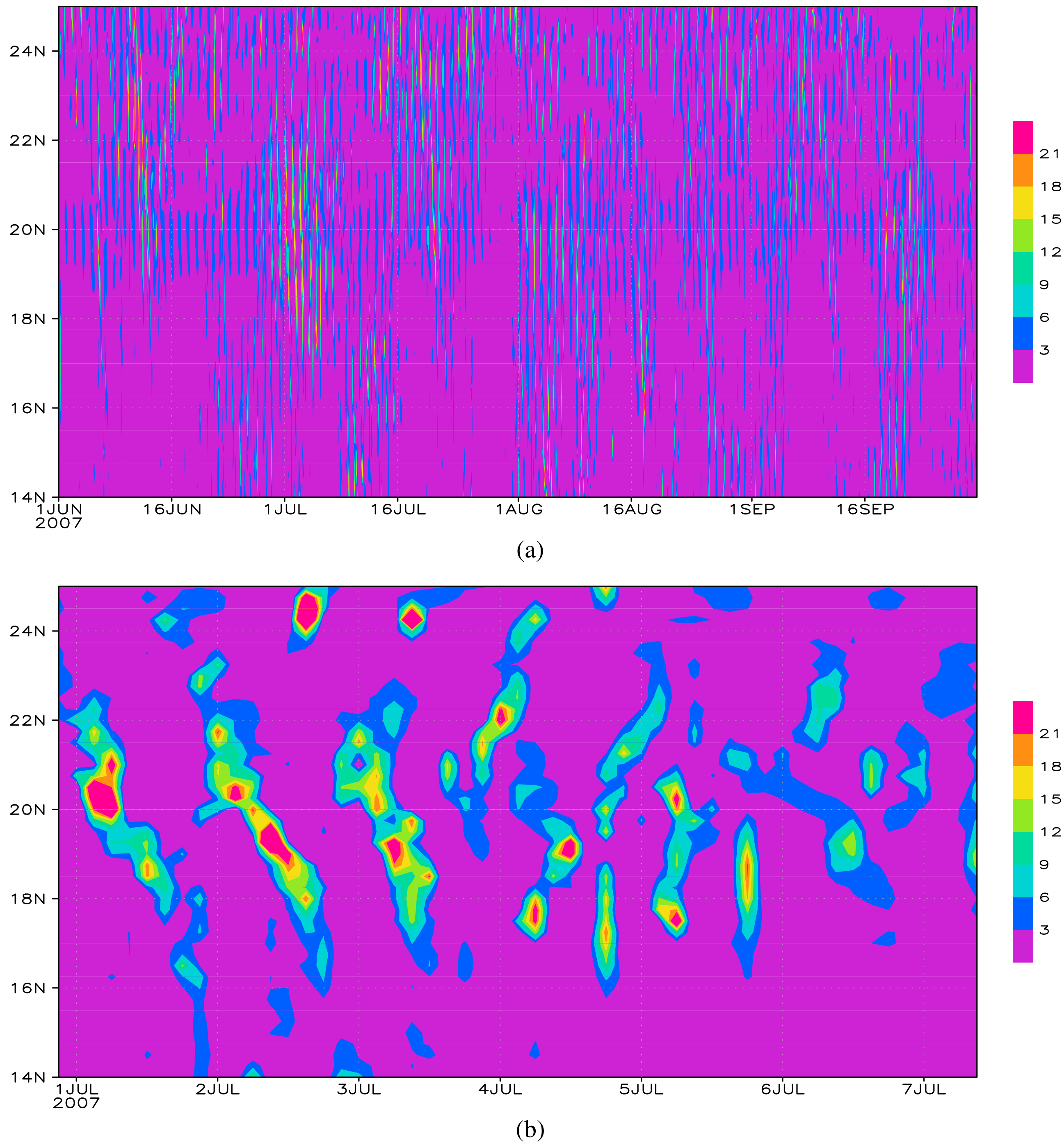


Figure 7. (a) Hovmoller diagram of 3-hourly reconstructed rainfall for JJAS of 2007, averaged over 91.5°E–92.5°E. The reconstructed rainfall consists of only diurnal and subdiurnal variability. (b) Active rainfall period during 1–7 July. The color bar shows intensity in mm/h.

during the northeast monsoon (October through December). However, as we have shown, the entire central Indian region (16°–26°N, 76°–86°E) has an early evening (1730 IST) maximum during the summer monsoon season (e.g., see Figure 6).

[32] The features that we find in our study which differ from those reported by HN05 or KW08 are the following. (1) A spatially coherent pattern in diurnal peak occurs over the Arabian Sea along a region where it rains at least 30% of the time. Moreover, this is clearly different from the oceanic regime suggested by KW08. (2) KW08 suggest that the equatorial Indian Ocean (EIO) forms a part of the oceanic regime. Interestingly, our study suggests that while the western EIO (predominantly 0230–0530 IST) conforms to the oceanic regime, the eastern EIO (0530 and 1430 IST) does not. (3) Over the Indian land region, the Western Ghats show a prominent diurnal signature corresponding to 1430–

1730 IST, while the Gangetic Plains show a 1430 IST maxima.

[33] Our findings are based on the implicit assumption that TRMM 3B42 is a suitable product for studying the diurnal cycle of rainfall. KW08 emphasize in their study that TRMM 3B42 lags 3G68 by 3 h and claim that 3G68 yields an "arguably" more accurate diurnal phase. We contend that the lagging is not needed, and, in fact, we have verified our results for several subregions with some previous studies which used a sparse network of rain gauges [e.g., *Pathan*, 1994; *Barros et al.*, 2004; *Sen Roy and Balling*, 2007]. Hence, we have reason to believe that the diurnal phase depicted by TRMM 3B42 seems to be accurate, at least over the land region of our study.

3.4. Validation of TRMM With Buoy Data

[34] In order to validate our results over the ocean, three locations (12°N, 0°N, and 1.5°S) along 90°E have been selected for comparison on the basis of the availability of data. Data from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoy array [*McPhaden et al.*, 2009] has been analyzed for the summer season (JJAS) of the following years: (1) 2008 (12°N, 90°E), (2) 2005 (0°N, 90°E), and (3) 2002–2003 (1.5°S, 90°E). Separate years have been used for the three stations because of lack of data for the same period over the three locations. The temporal resolution of the original buoy data is hourly at 1.5°S and 10 min at 12°N and 0°N. Since TRMM 3B42 has a 3-hourly temporal resolution, as a first step, we convert the buoy data to 3-hourly means corresponding to the same times of day as those of TRMM (i.e., 0000–2100 UTC at 3-hourly intervals). Then we compare the corresponding rainfall time series over the three locations. For the buoy located at (12°N, 90°E), the data for September had a large number of missing values, and hence, only June–August rainfall has been considered for our analysis. Given the fact that TRMM 3B42 is a satellite product and the horizontal resolution is 0.25° × 0.25°, it is highly unlikely that the 3B42 rainfall amplitudes would match those of the in situ buoy data. Furthermore, there are sampling issues involved in any satellite-based measurement, unless the satellite is geostationary. Taking into account the above facts, there seems to be a good agreement between TRMM 3B42 and buoy observations, thus adding credibility to the product, as can be seen in Figures 8a, 8c, and 8e.

[35] The same methodology as described in section 2 is applied to the buoy data to estimate the peaks of the diurnal cycle of rainfall. It can be seen in Figures 8b, 8d, and 8f that there is a very good agreement between the two data sets as far as the peak octet is concerned. For example, in Figure 8b, it can be seen that for buoy observations (0°N, 90°E) the diurnal cycle of rainfall peaks at around 1800 LT, and TRMM also shows the peak to be occurring around the same time, i.e., 1800 LT. Figures 8d and 8f also show a good match between the buoy and TRMM estimates of the phase of the diurnal cycle of rainfall at the respective locations. Thus, from the above comparison of the rainfall time series and the peak octets for three locations over the Bay of Bengal, it appears that the conclusions drawn from the analysis of the TRMM 3B42 product regarding the peak octet of the diurnal cycle of rainfall are robust.

3.5. Discussion

[36] We discuss in this section some possible mechanisms that might dictate the diurnal cycles over various regimes.

3.5.1. Land

[37] The late afternoon/early evening peak in the central Indian region (plains) can be attributed to the local convection due to the solar heating cycle of the land surface. The study of winter (January and February) precipitation over the Indian land suggests that the maxima of rainfall are around midnight to predawn hours [e.g., *Sen Roy*, 2008]. Thus, there is a strong likelihood that the southwestern monsoonal flow, prevailing during summer monsoon season, forms an essential driving component of the diurnal cycle of rainfall over the plains.

3.5.2. Orography

[38] The region over which we have analyzed the diurnal signatures consists of two different kinds of orography, namely, coastal (Western Ghats and the Burmese mountains) and inland (Himalayas). Our analysis suggests that while the coastal orographic precipitation peaks during the day (early to late afternoon), the maximum rainfall occurs over inland orography in the early morning (predawn) hours. For the coastal orography, the land-sea breeze circulation, in combination with the prevailing monsoonal flow, could be one of the probable reasons behind the observed peak time. The local onshore breeze and the monsoonal flow move along the same direction during the afternoon hours, thus causing strong winds. The orographic lifting of these strong moisture-laden winds can act as a potential trigger for deep convection and its associated rainfall.

[39] The late night/early morning peak over the Himalayas can be associated with the convergence of the katabatic winds moving downslope and the southwesterly winds blowing onshore during the Indian summer monsoon season. *Barros et al.* [2004] reported strong nighttime activity along the south facing slopes of the Himalayan range, characterized by the development of short-lived convection of duration 1–3 h, aligned with protruding ridges between 1:00 and 3:00 a.m. Also, *Sen Roy* [2008] reported that the late night peak hour is observed over the Himalayas in the winter season as well, suggesting that perhaps the southwesterly winds may not be an essential condition for the observed late night/early morning peak. In addition, the differences in diurnal rainfall characteristics may also be attributed to the differences in physical dimensions of the mountain ranges (the Himalayas being much higher and wider compared to the Western Ghats and Burmese mountains).

3.5.3. Ocean

[40] The most striking observation over the Bay of Bengal is the presence of multiple modes of the peak octet, suggesting a southward propagation of the diurnal rainfall patterns. Several other studies have also reported similar behavior. For instance, *Yang and Slingo* [2001] analyzed brightness temperature and hypothesized that the observed spatial structure in brightness temperature, suggesting southward propagation of convection, could be due to the diurnally generated gravity waves. *Miyakawa and Satomura* [2006] reported that the southward propagating mesoscale convective systems over the BOB tend to occur when a trough exists over the bay at around 600 hPa, and the wind shear between the surface and the 600 hPa height has a

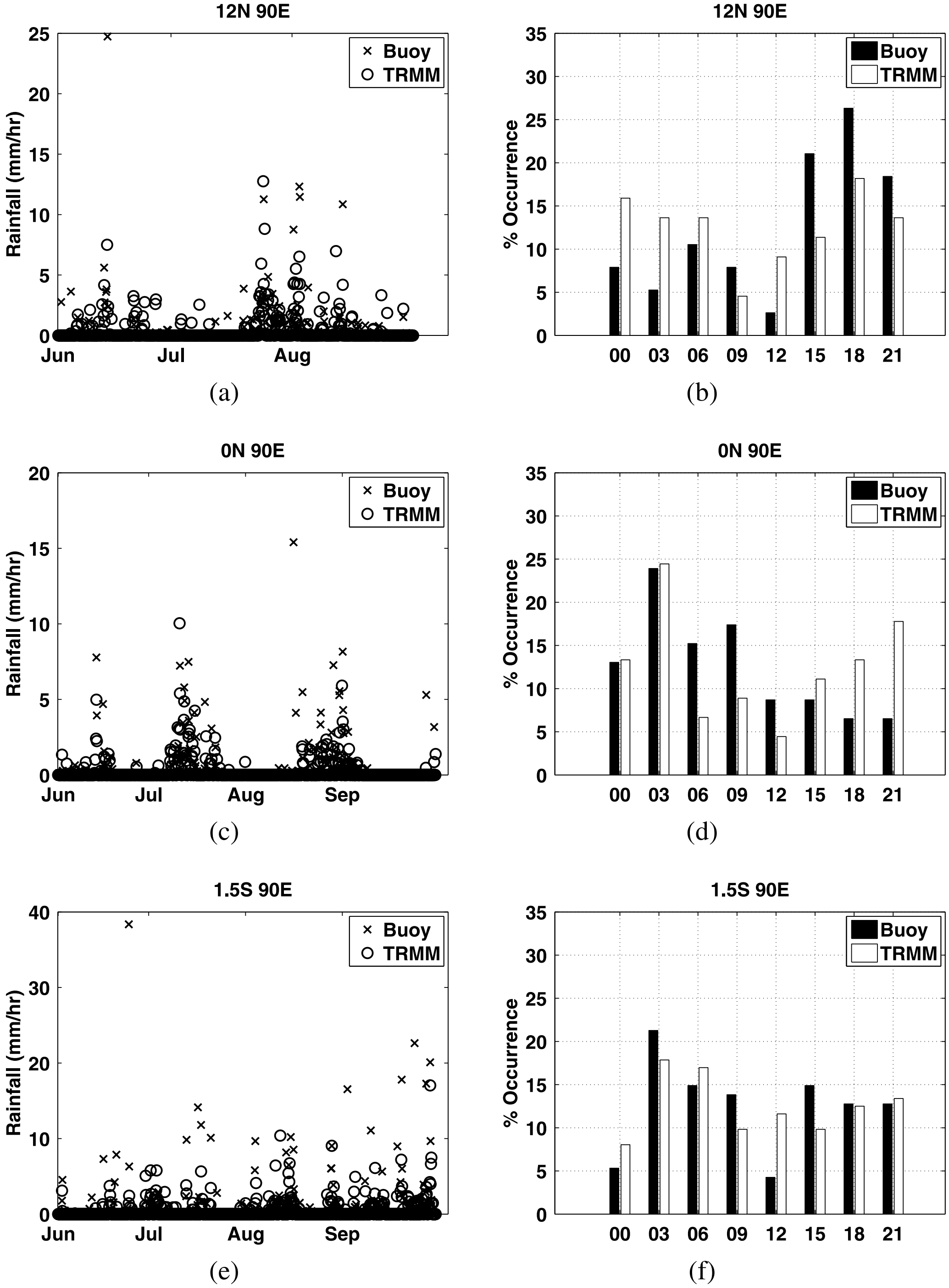


Figure 8. The JJAS time series of rainfall intensity in mm/h for TRMM 3B42 and buoy along 90°E at (a) 12°N (2008), (c) 0°N (2005), and (e) 1.5°S (2003). (b, d, and f) The histogram of the estimated peak octet (local time) of the diurnal cycle of rainfall at the corresponding locations for the two data sets. The peak octet histogram for the location (1.5°S, 90°E) is based on 2 years (2002 and 2003) of observations.

southward component. *Liu et al.* [2008], on the basis of their study of propagating rainfall episodes, hypothesized that the initiation of these convective systems could be attributed to the thermally induced diurnal circulations.

[41] Over the Arabian Sea, a spatially coherent pattern in the mode of diurnal rainfall peak over a region where it rains at least 30% of the time suggests well-organized local convection as a probable cause behind the observed peak. Finally, while there appears to be organized convection over the western equatorial Indian Ocean (as seen from the homogeneity of the peak octet), the lack of spatial coherence over the eastern equatorial Indian Ocean suggests the

dominance of locally triggered (unorganized) short-duration events [e.g., see *Ramesh Kumar et al.*, 2006].

4. Conclusions

[42] The statistical characteristics of the diurnal variations in the summer season (JJAS) rainfall over the Indian land and neighboring oceans (10°S–35°N, 60°E–100°E) have been systematically documented using the TRMM 3-hourly, 0.25° × 0.25° 3B42 rainfall product for 9 years (1999–2007). Over the Bay of Bengal, while the region closest to land shows an early morning (0530 IST) peak, there are multiple modes of the peak octet of diurnal rainfall at 1130, 1430, and 1730 IST from the north central to south bay. This spatial structure of the modes of the peak octet suggests a southward propagation of the diurnal-scale rainfall, verified through Hovmoller diagrams. In addition, using buoy data (TRITON) over the Bay of Bengal, we have validated the estimates of peak octet of rainfall from TRMM. The Burmese mountains and the Western Ghats were found to have a late afternoon maximum (1430–1730 IST), while the Himalayan foothills were found to have a nocturnal (0230 IST) maximum. It thus appears that the diurnal cycle of rainfall over inland orography is different from the coastal orography. A significant part of Indian land (central India) shows a mode of the peak octet at 1730 IST, confirming the conclusions of several previous studies. However, over the Gangetic plains, we find that the diurnal rainfall peaks at 1430 IST, a few hours earlier than over central India. We also find that over the Arabian Sea (to the east of 65°E and north of the equator, along a region where it rains for more than 30% of the time) the peak octet of diurnal rainfall is around 1430–1730 IST. This finding matches the broad conclusion of *Dai et al.* [2007] that the spatial patterns of precipitation in midlatitudes depend more on how often it rains rather than on how much it rains; however, in the tropics most of the regions with frequent rain are the ones with high seasonal mean. Another important finding from our analysis is that the peak octet in the equatorial Indian Ocean appears to behave differently over the western and eastern parts. While the western part appears to receive its maximum rain during the late night/early morning hours, the eastern part shows a coexistence of early/late afternoon and early morning peak octets. Finally, there is no significant interannual variation associated with the summer season diurnal cycle of rainfall over the Indian land and its neighboring oceans.

[43] Analyses of observations and modeling studies are further needed to explore the physical mechanisms that govern diurnal and subdiurnal variations in rainfall over the monsoon regions. On the analysis front, the relation between the diurnal cycle and the intraseasonal oscillations (ISOs) of the Indian monsoon needs to be explored. Broadly speaking, do ISOs modulate the diurnal-scale behavior, and what are the differences in diurnal variability of rainfall during the active and break phases of the monsoon? Also, for instance, the out of phase behavior between the Bay of Bengal and central India and its implication for larger-scale convective systems, such as depressions, need to be explored. Modeling studies [e.g., see *Mapes et al.*, 2003b; *Basu*, 2007; *Lau et al.*, 2007] are equally important for addressing mechanism issues. In order to investigate the physical mechanisms governing the observed characteristics of the diurnal cycle of precipitation over the Indian region, a modeling study is under way using the Weather Research and Forecasting (WRF) model, both in implicit as well as cloud-resolving modes. Preliminary results indicate that the spatial patterns of the diurnal anomalies obtained from the model runs broadly match those observed over the Indian region. We are currently performing sensitivity studies to investigate the impact of various cumulus, microphysics, and boundary layer schemes on the simulation of the diurnal cycle. Following that, we intend to use WRF in a cloud-resolving mode over central India and the Bay of Bengal to understand the physical mechanisms (e.g., diurnally generated gravity waves in the BOB) that drive the diurnal cycle over these regions.

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