Differences in the Climatological Characteristics of Precipitation between Active and Break Spells of the Indian Summer Monsoon

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ABSTRACT

Climatological characteristics of precipitation during the active and break spells of the monsoon are studied using 15 years of TRMM measurements. The spatial variation of rain fraction suggests that most of the seasonal rainfall occurs in spells of active monsoon over India, except for the zones along the east coast. The broader reflectivity distribution at higher altitudes and larger average storm height during active spells indicate the high prevalence of deep systems during this spell. The spatial distribution of the occurrence and fraction of different types of rain exhibits large variability from land to ocean and between the spells. The higher occurrence and fraction of stratiform rain during the active spell, particularly over the core monsoon zone, is due to the prevalence of organized mesoscale systems with large stratiform portions. The break spells are characterized by higher occurrence of shallow rain and larger fraction of convective rain. While an evening peak is observed over land during the break spell, the phase of the diurnal cycle exhibits large spatial variability during the active spell. The rainfall peaks from late night to midnight in southeastern India and in the morning near the foothills of the Himalayas during the active spell. The diurnal and semidiurnal components together explain more than 90% of total variance over many of the zones during both spells. The observed differences in precipitation between the spells are discussed in light of the differences in synoptic- and mesoscale mechanisms responsible for the production of precipitation.

1. Introduction

During the southwest monsoon (SWM) season, the rainfall in the Indian subcontinent exhibits vigorous intraseasonal oscillations (ISOs), with rainfall occurring in chaotic epochs, called active spells (copious rainfall), separated by spells of scant or no rainfall (break spells) (Ramamurthy 1969; Raghavan 1973; Webster et al. 1998; Gadgil and Joseph 2003; Goswami 2005; Waliser 2006; Rajeevan et al. 2010, and references therein). Detailed knowledge of these epochs is highly essential as not only do they dictate the interannual variability of monsoon rainfall (Pai et al. 2011; Kulkarni et al. 2011) but also their untimely occurrence with long duration will substantially reduce the crop yield (Kumar et al. 2004; Prasanna 2014). The ISO of precipitation is therefore regarded as one of the most important sources of weather variability in India (Webster et al. 1998; Hoyos and Webster 2007). The characteristics of the active and break spells have been elucidated by several authors: their identification (Rajeevan et al. 2006), duration (Rajeevan et al. 2010; Singh and Ranade 2010), spatial heterogeneity (Ramamurthy 1969; Goswami 2005; Rao et al. 2009; Kulkarni et al. 2009; Rajeevan et al. 2010; Chakraborty and Nanjundiah 2012; Ratan and Venugopal 2013), year-to-year variability (Hoyos and Webster 2007), circulation patterns during these epochs (Ramamurthy 1969; Goswami and Ajaya Mohan 2001; Rajeevan et al. 2010), causative dynamical
mechanisms and linkages with northward- and westward-propagating ISOs (Krishnamurti and Bhalme 1976; Sikka and Gadgil 1980; Krishnan et al. 2000; Annamalai and Slingo 2001; Goswami 2005; Waliser 2006; Sharmila et al. 2013; Pillai and Sahai 2014), diurnal variation of rainfall (Deshpande and Goswami 2014), and trends (Singh and Ranade 2010; Singh et al. 2014). Also, there is considerable progress in recent years in predicting these epochs up to three weeks in advance (Goswami and Xavier 2003; Abhilash et al. 2014). While the abovementioned studies have advanced our understanding of complex space–time variability of the active and break spells, the other important characteristics, such as the vertical structure of precipitation, the type of rainfall, rain fraction by different types of rainfall, and diurnal variation, during these epochs are not fully explored, mainly due to the lack of suitable observations covering the entire country (Pokhrel and Sikka 2013; Saha et al. 2014).

The Precipitation Radar (PR) on board the Tropical Rainfall Measuring Mission (TRMM) with a unique capability of providing three-dimensional structure of precipitation and rain type information would be an ideal instrument for addressing the issues mentioned above (Liu et al. 2012). TRMM, indeed, has contributed significantly to our understanding on several aspects of monsoon precipitation, particularly the role of stratiform rain in northward propagation of episodes associated with ISO (Chattopadhyay et al. 2009), invigorating the monsoon flow, and also deepening the vertical extent of cyclonic circulation (Choudhury and Krishnan 2011). Several studies elucidated the complex spatiotemporal variability of different types of precipitation and associated latent heating in India and the surrounding ocean (Houze et al. 2007; Zuluaga et al. 2010; Romatschke et al. 2010; Romatschke and Houze 2011; Saikranthi et al. 2014; Saha et al. 2014; Bhat and Kumar 2015; Rasmussen et al. 2015; Houze et al. 2015). Houze et al. (2007) observed deep intense (40 dBZ for >10 km) and wide intense (40 dBZ over 1000 km²) precipitation in northwestern India and broad stratiform rain in the central and eastern Himalayan region resulting from Bay of Bengal (BOB) depressions. Zuluaga et al. (2010) noted that the peak in the latent heat (LH) profile varies spatially (between 7 and 3 km) and attributed this variability to preferential occurrence of stratiform and convective rain in those regions. Houze et al. (2015) noticed two distinctly different types of precipitation being identified as stratiform by the TRMM algorithm over the BOB. While the first type, a relatively more intense one, is associated with active monsoon conditions, the second type consists of weak and vertically oriented shallow cells. Pokhrel and Sikka (2013) used TRMM PR level 3 data (3A25) to quantify rain fractions of stratiform and convective rains in deficit and excess monsoon years and also to understand the interaction between tropospheric circulation regimes and precipitation (or LH) in those years. Saha et al. (2014) reported that most significant differences in stratiform and convective fractions between active and break spells occur in the monsoon trough region. The spatial, seasonal, and vertical variability of different types of precipitation (including virga rain) over India and the adjoining oceans has been studied comprehensively by Saikranthi et al. (2014). They noted significant regional differences in both the occurrence and vertical structure of different types of precipitation. Bhat and Kumar (2015) focused on the variability of deep convective clouds and reaffirmed the large regional variability in their occurrence. The diurnal variation of precipitation also shows significant spatial variation over India. Sahany et al. (2010) have shown that the phase of the diurnal cycle over inland orography is significantly different from coastal orography.

Two points are noteworthy from the above discussion:
1) None of the above studies that used TRMM data discussed the vertical and spatial structure of different types of precipitation during the active and break spells of the SWM.
2) The studies that dealt with the active and break spells, mostly using rain gauge data, also identify these epochs using the average rainfall data over the core monsoon zone (Rajeevan et al. 2010). It is now well known that the active and break spells exhibit complex spatial heterogeneity within India (Ramamurthy 1969; Gadgil and Joseph 2003; Rao et al. 2009; Kulkarni et al. 2009; Rajeevan et al. 2010; Singh and Ranade 2010).

During the active phase of the monsoon (as defined by the above studies), there is a widespread occurrence of rainfall over the monsoon trough zone, but the rainfall is scant over the foothills of the Himalayas (FHH) and the southeastern and northeastern parts of India. Given such large spatial heterogeneity in active and break spells, it is more logical to define active and break spells over smaller homogeneous regions rather than defining them for the whole of India or using rainfall over the monsoon trough region. Moreover, understanding precipitation characteristics on a subregional scale is crucial for the effective modeling of the local rainfall patterns and agriculture, hydrology, and water resources applications (Singh and Ranade 2010). Recently, Saikranthi et al. (2013) divided India into 26 coherent rainfall zones, within which the rainfall is homogeneous over different temporal scales, using daily rainfall data collected over 51 years at 1025 stations scattered across the country. These zones would be ideal for identifying active and break spells for smaller
regions. The active and break spells are, therefore, identified separately for each coherent zone from TRMM’s daily rainfall data. Making use of TRMM data products during the identified spells, this study aims to bring out, comprehensively, important differences in (i) the vertical structure of precipitation, (ii) the spatial variability of different types of rain, and (iii) the diurnal variation of precipitation between active and break spells of the SWM.

The organization of this paper is as follows. The description of data, procedure for identifying the active and break spells for each coherent zone, and statistics of active and break spells (number of spells, duration of each spell, etc.) are given in section 2. A description of prevailing synoptic features and spatial distribution of rain fraction by active and break spells is provided in section 3. The major differences in the vertical structure of precipitation, including storm height (SH), between active and break spells are highlighted in section 4. The spatial variability in the occurrence and rain fraction of different types of rain during active and break spells over India and the surrounding ocean is discussed in section 5. The diurnal variability of precipitation (in both occurrence and rain fraction) during active and break spells is presented in section 6. Section 7 summarizes the important findings of this paper.

2. Data description

TRMM rainfall data (2A25 and 3B42 version 7) during 1998–2012 are used here to describe the characteristics of precipitation during the active and break spells of SWM. To identify the active and break spells and also to quantify the seasonal rain fraction by these spells, overpass data may not be sufficient. Therefore, merged data product of 3B42, which is available at a spatial resolution of 0.25° and a temporal resolution of 3 h, is used for this purpose. TRMM PR 2A25 data are used to study the vertical structure of rainfall and to describe the spatial variation of different types of rain during the active and break spells. Houze et al. (2015) interpolated TRMM reflectivity data onto a 3D Cartesian grid based on the methodology proposed by Houze et al. (2007). They reprocessed all the data (available at http://trmm.atmos.washington.edu). These 3D gridded reflectivity data are used for the present analysis.

To understand prevailing synoptic features during the active and break spells, state meteorological parameters like pressure, temperature, and relative humidity (RH) obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) (Dee et al. 2011) have been used. The above parameters are collected at a spatial resolution of 0.5° × 0.5° during 1998–2012.

a. Discerning coherent rainfall zones

A complete description and validation of coherent zones are given in Saikranthi et al. (2013) in a comprehensive manner. As these zones are based on station rainfall data, they are available only over land. Since the present study aims to characterize precipitation features over the ocean also, three more zones are identified over the ocean (one over the Arabian Sea and two over the BOB) (Fig. 1a). The rationale for dividing the BOB into two zones lies in the fact that these zones exhibit different seasonal rainfall cycle and depression or cyclone occurrence. During the SWM, the low pressure systems or depressions that originate in the head of BOB pass through central and northern India, forming a quasi-stationary low pressure zone (called a monsoon trough) (Rajeevan et al. 2010). Figure 1b clearly shows the tracks of cyclones, depressions, and low pressure systems in the last 100 years, which are clustered and confined to the monsoon trough region. The majority of the storm tracks over the BOB are north of 15°N and west of 90°E. On the other hand, the cyclones generally form and intensify in the southern BOB and move west-northwest (and a few of them take recurvature and move eastward) during the northeast monsoon (NEM; October through December) (Fig. 1c). Therefore, the northern and southern BOB regions, with 15°N as the boundary, are considered as two different homogeneous regions.

b. Identification of active and break spells

A variety of techniques are available to identify the active and break spells in the literature (Ramamurthy 1969; Webster et al. 1998; Krishnan et al. 2000; Goswami and Ajaya Mohan 2001; Annamalai and Slingo 2001; Gadgil and Joseph 2003; Singh and Nakamura 2009; Rajeevan et al. 2010; Mohan and Rao 2012; Ratan and Venugopal 2013). Even though several parameters like wind, circulation patterns, and proxies of rainfall (outgoing longwave radiation) are used in some of the above studies, the majority of them employed rainfall, as it is the most important facet of the monsoon (Gadgil and Joseph 2003; Singh and Nakamura 2009; Ratan and Venugopal 2013). Rajeevan et al. (2010) developed a robust method to identify active and break spells, which the India Meteorological Department (IMD) also follows operationally, using 1° × 1° gridded rainfall data generated by IMD (Rajeevan et al. 2006). The present study adopts the same methodology to define the active and break spells but deviates in four aspects. 1) Since 1° × 1° rainfall data are available only over land, TRMM 3B42 version 7 data are used in the present study. 2) The
threshold for normalized rainfall anomaly is reduced to 0.5 in the present study, following Singh and Nakamura (2009). 3) Instead of confining to the core monsoon trough region, the regional averaged rainfall is considered for identifying active/break spells for that region. 4) Most of the above studies identified active/break spells only during the peak monsoon months of July and August. Since the present study includes regions in southern peninsular India, where the duration of the monsoon season is long, the rainfall during the whole season (June–September) is considered here.

A typical example for the identification of active and break spells is depicted in Fig. 2. Figure 2 shows the time series of standardized rainfall anomaly (bars) for region 18 during 2002 along with threshold values (±0.5). The active (break) spells are defined as periods in which the standardized rainfall anomaly exceeds +0.5 (is less than −0.5) continuously for 3 or more days. In an extended active (break) spell, for example in June (end of September), even if the standardized rainfall anomaly of any day in the middle of the spell is less than 0.5 (more than −0.5), it is included in the active (break) spell. Following the above criteria, Fig. 2 shows a total of four active (filled diamonds) and seven break spells (open squares) identified from the case study.

c. Statistical characteristics of active and break spells

The statistics of active and break spells for each region, identified following the procedure outlined in section 2b, are depicted in the form of joint probability distributions for spell duration (Figs. 3a,b). It is clearly evident from Fig. 3 that the active spells are of shorter duration with nearly 70% of them lasting ≤4 days. The same pattern is seen in all regions. Only 5% of the total spells are long lasting (>10 days) during the active spell. The average duration of active spells is nearly equal (i.e., 4–5 days) for all the regions. On the other hand, the distribution for break spells is much wider with 20%–30% of the spells having duration >10 days, indicating that the breaks tend to have a longer life-span than active spells, consistent with the results of Rajeevan et al. (2010). Further, the short-duration spells (≤4 days) occur only for 40% of total break spells. The average duration for breaks (5–9 days) is higher than that for active spells in almost all regions. In contrast to the active spells, where the average duration is nearly equal in all regions, the duration of break spells varies spatially in a systematic way. The duration is found to be shorter (longer) in regions lying along the east coast (in western India).

The number of active and break spells also varies spatially (Fig. 3c). In general, there are more break spells in regions along the east coast and relatively fewer
in western India. Even though their occurrence is less frequent, break spells persist for a longer period in western India, increasing the number of break days. Singh and Ranade (2010), using a different set of sub-regions, noticed a spatial pattern similar to the present study with more break spells in extreme southeastern peninsular India and fewer in northwestern India.

Further, more active spells are found over the BOB and Arabian Sea. Since the area considered in the present study for these regions is also large, the number of rain pixels (Fig. 3d) is quite large. Except for the regions in the extreme southeastern India, the number of rain pixels in all other regions is quite large ($>10^4$). Even though the rainfall in a break spell is meager, more spells with longer duration make the number of rain pixels nearly equal to that of an active spell.

### 3. Differences in prevailing synoptic conditions between active and break spells

Figure 4 shows the composite wind pattern and wind anomalies at the 850-hPa level, obtained from ERA-Interim, for active and break spells, depicting the synoptic situation during these spells. Figure 4 is somewhat different from figures presented in earlier studies. Past studies have shown the synoptic situation over the whole of India, when central India (CI) (or the monsoon trough region) experiences an active or break spell. On
the other hand. Fig. 4 shows the average wind pattern for the active (and break) spell of the corresponding homogeneous region. In other words, wind vectors for active spells shown in each homogeneous zone represent the active spell winds of that region. The wind anomalies are computed by subtracting the average winds for the active (or break) spell from the seasonal mean.

Clearly, the wind magnitude (shading) shows distinct variation between the spells. Over land, the highest variation between the spells is seen over peninsular India, where the winds during the break spell are stronger than during the active spell. Quantitatively, the largest difference in wind magnitude (≈5 m s⁻¹) between the spells is found along the mean axis of the low-level jet (LLJ) (i.e., along ≈15°N). Many earlier studies used strong LLJ as an indicator for active spell (Webster et al. 1998; Goswami and Ajaya Mohan 2001). The active spell in those studies is for CI or the monsoon trough region. It suggests that not all regions in India experience an active monsoon, when the LLJ is strong. In general, the active spell prevails in regions on the cyclonic shear side of strong wind (Joseph and Sijikumar 2004).
Two features are prominently seen in the monsoon trough region. 1) Although not much difference is seen in the wind magnitude over the eastern part of the monsoon trough region between the spells, a closed circulation pattern is clearly apparent during the active spell. The wind anomaly plot shows this cyclonic circulation much more clearly (Fig. 4c) during active monsoon spells, consistent with Houze et al. (2007, 2015). Such a distinct closed circulation is not clearly apparent during the break phase of the monsoon. Rather an anticyclonic circulation is observed during the break spells over the eastern part of the monsoon trough. 2) Large difference is seen in the wind magnitude over the western part of the monsoon trough. Figure 4 clearly depicts large wind differences between the spells in semiarid regions of India [northwestern India (NWI) and southeastern peninsular India (SEPI)], whereas the wind difference is small in the wettest regions (west coast, CI, and FHH).

The winds are stronger over the ocean than land during both active and break spells. The LLJ is strongest over the Arabian Sea (western side of the Arabian Sea, precisely) during both spells, with magnitude in excess of 15 m s\(^{-1}\). In contrast to the variation over land, winds are stronger during the active spell than break spell over the ocean (in the Arabian Sea and BOB). Over the Arabian Sea, the axis of peak wind (or LLJ) shifts northward, from 12° to 15°N, during the break monsoon.

Figure 5 shows the spatial distribution of pressure, temperature, and RH differences between the spells. The monsoon trough is strikingly apparent in the pressure difference plot as a large negative pressure anomaly stretching from the northern BOB through CI to NWI (Fig. 5a). Large negative pressure difference (>2 hPa) is also apparent over the Arabian Sea. The pressure difference between spells is small over SEPI and northern parts of India (white patches). Even in other regions, the pressure difference is not as pronounced as in the monsoon trough region. It clearly suggests that the pronounced pressure difference between spells exists only over the monsoon trough region, primarily resulting from the passage of low pressure systems and depressions (Goswami 2005; Houze et al. 2007). In other regions, the precipitating systems during the active spells may not be as organized as in the monsoon trough region to produce pronounced pressure differences between spells.

The temperature (Fig. 5b) and RH (Fig. 5c) differences are large in regions where the pressure difference between the spells is negligible (<0.5 hPa) (i.e., in NWI and SEPI). The RH difference between spells is small, as expected, not only over the ocean but also along the west coast of India and the eastern side of the monsoon trough region.
trough region. In other words, the differences are large in semiarid regions and small in rainy and oceanic regions.

4. Differences in characteristics of precipitation

The general characteristics of precipitation, like spatial variation of its intensity and rain fraction, its vertical variation, and SH distribution, during the active and break spells are discussed in this section. Figure 6 shows the spatial distribution of rain fraction and average daily rainfall obtained from TRMM 3B42 for active and break spells. The rain fraction for the active (break) spell is nothing but the fraction of rainfall during the active (break) spell in the seasonal rainfall (in terms of percent). One would expect larger rain fractions during active spells as these spells are defined based on rainfall, but the percentage of rain fractions is not predetermined and therefore useful. Clearly, as expected, the rain fraction for the break spell is small and is less than 10%. Most of the seasonal rainfall occurs during the active spell with a rain fraction of 40%–75%. Large rain fraction values are seen during the active spell over the ocean and also in NWI and CI, indicating that most of the rainfall in these regions occurs during active spells. The rain fraction along the east coast and in FHH is relatively small (~30%) during the active spell. It implies that most of the rainfall in the above regions occurs sporadically (not in spells of active or break monsoon). The rain fraction values reported by Singh and Ranade (2010) for different subregions across India are within the

Fig. 6. Spatial variation of rain fraction by (a) active and (b) break spells. Spatial variation of unconditional daily rainfall rate during (c) active and (d) break spells.
range obtained in the present study, but they are clustered at the higher end of the range.

The average daily rainfall (unconditional) maps for active and break spells also show distinct differences between the spells. The average daily rainfall for an active spell is higher by a factor of about 2–4 than for a dry spell. The principal rainy regions in India, like the west coast of India, the eastern side of the monsoon trough region, and BOB, show large values of daily rainfall. The regions over land where the rain fraction is high have weak daily rainfall. This means that these semiarid regions receive most of the seasonal rainfall in spells but with lower seasonal rainfall (and therefore lower daily rainfall). It does not mean that the storms in these regions are weak. These regions, like NWI, are the preferred regions for the deepest storms (Zipser et al. 2006; see also Fig. 8).

The differences in vertical structure of precipitation between active and break spells are depicted in the form of contour frequency by altitude diagrams (CFADs) for reflectivity $Z$ corresponding to active and break spells (Figs. 7a,b) and the difference between them (Fig. 7c). CFADs are normalized probability distributions that can reveal the vertical structure of precipitation in a much better way than the mean profiles. Here, the bins are normalized by the maximum frequency, following DeHart et al. (2014). The data from all regions are combined to depict the major differences between the spells. The $Z$ distribution during the active spell is wider and has larger values than the break spell above the melting layer, indicating that the precipitating systems are deep and strong during the active spell. At lower heights (<4 km), the occurrence of weaker reflectivity is more strikingly apparent during the break spell. The CFAD for $Z_{\text{active}} - Z_{\text{break}}$ (Fig. 7c) reveals these differences much more clearly than individual CFADs. It shows the $Z$ distribution prominently at higher altitudes and at larger reflectivities during the active spells. These differences are primarily due to the preferential occurrence of cold rain (stratiform, convective, and transition) during the active spell and shallow rain (with weaker intensities) during the break spell (shown later in Figs. 9 and 10).

The average SH distribution during the active and break spells depict large variation in space and also between the spells (Fig. 8). In general, the SHs are higher over land than ocean in both spells. This land–ocean difference is not unique to the monsoon region but rather a manifestation of a general behavior of convection throughout the tropics (Houze et al. 2015). Between the BOB and Arabian Sea, the storms are shallower in the Arabian Sea in both spells. The reasons for higher storm height over land and the BOB are discussed at length in Saikranthi et al. (2014) (i.e., higher occurrence of shallow rain over the Arabian Sea and
deep low pressure systems over land and the BOB with good spatial correspondence with CAPE). The spatial variability is relatively weak during the active spell compared to that of the break spell. During the break spell, the average storm height varies from 8–10 km in the northwest dry province (region known for the deepest storms) to 2–4 km in the Arabian Sea and west coast (ASWC; where shallow rain dominates). Such small average storm heights in ASWC during the break spell indicate that the storms are predominantly shallow in nature in that region. Both over the land and ocean, the average storm height is higher during the active spell than break spell by 2–3 km. The next section provides a detailed description of the type of rainfall and its spatial variability and corroborates the inferences drawn in this section.

5. Spatial variability of different types of precipitation

The precipitation data during the active and break spells are segregated separately into three rain types as stratiform, convective, and shallow, following the TRMM 2A23 (version 7) algorithm. The occurrence and rain fraction of different types of precipitation are estimated and presented in Figs. 9 and 10, respectively. It is clearly evident from Fig. 9 that stratiform rain prevails most of the time (50%–80%) during the active spell. The highest occurrence of stratiform rain is in the CI, while the lowest is seen in the Arabian Sea. Although other types of rain occur infrequently over most of India, there are some preferred regions where their occurrence is considerable. For example, convective rain occurs for 20%–40% over the northwest dry province and SEPI, the two semiarid regions. Also, shallow rain occurs preferentially over the ASWC 40% of the time.

High occurrence of stratiform rain is seen only sporadically during the break spell. Its occurrence is lowest over the Arabian Sea, where it only occurs less than 30% of time, probably the lowest among the reported values in the literature, not only over India but also anywhere in the world. During the break spell, the synoptic situation is not in favor of the formation of clustered systems with large fractions of stratiform rain (Goswami 2005; Houze et al. 2007). The shallow rain occurrence is highest (>60%) over this region and along the west coast of India. Even in other regions, the shallow rain occurrence is high, varying from 20% in the NWI and SEPI to 40% in the monsoon trough region. Mohan and Rao (2012) studied the differences in background meteorological parameters over Gadanki (13.45°N, 79.18°E), between active and break spells. They noted intriguing differences in the occurrence of stable layers and instability between the active and break spells. The higher occurrence of strong stable layers near the top of the atmospheric boundary layer and at the freezing-level height (FLH) limits the growth of clouds and increases the occurrence of shallow rain, as observed in this study. Further, Mohan and Rao (2012) have shown that the convective available potential energy (CAPE) is higher during the active spell than the break spell. It means that the clouds may grow deep during the active spell, consistent with the present results. The average storm height is found to be larger during the active spell than the break spell (Fig. 8).
As expected, the convective rain fraction during the active spell is high over the NWI and SEPI, where its occurrence is considerable. Interestingly, the CI receives 60%–70% of total rain in the form of stratiform rain, mainly because of the higher occurrence of stratiform rain (even though its rain rate is small). Even in other regions, its contribution to the total rain is substantial (~40%). As seen in Saikranthi et al. (2014), the shallow rain fraction over the Arabian Sea and convective rain fraction over the BOB are also substantial. The break spells, on the other hand, receive 80% of rainfall in the form of convective or shallow rain. Shallow rain dominates over the ASWC, and convective rain dominates the rest of India. The stratiform rain fraction is lowest during the break spell with many regions having less than 20%.

Saha et al. (2014) noted that the most significant differences between spells in convective and stratiform cloud amounts occur in central India. Note that they used the spells identified for core monsoon zone (Rajeevan et al. 2006). On the other hand, the present study, which groups the database on active and break spells identified for small homogeneous regions, clearly shows that the shallow and stratiform rain occurrence and fractions are significantly different not only in central India but also over most of India.

6. Diurnal variability of precipitation

The diurnal variation of precipitation is one of the fundamental modes of variation and is least explored in the Indian region, particularly during active and break spells. This section aims to describe the variation of precipitation at diurnal and semidiurnal scales in terms of their amplitude and phase (time of rain peak occurrence). TRMM 2A25 data in each homogeneous region are, first, segregated into 24-hourly bins [Indian standard time (IST)]. The frequency and rain amount in each hour are estimated. The occurrence percentage (rain fraction) at each hour is estimated by dividing the frequency (rain amount) of that hour with the total

![Figure 9](http://journals.ametsoc.org/jcli/article-pdf/29/21/7797/4073490/jcli-d-16-0028_1.pdf)
number of occurrences (total rain amount) from 24 h and then multiplying this fraction by 100. Harmonic analysis is performed on both the occurrence and rain fraction data to obtain the amplitude and phase of diurnal and semidiurnal components. The basic form of the harmonic equation is as follows:

$$P(x) = P_0 + \sum_{k=1}^{N/2} A_k \cos(k\theta - \Phi_k),$$  \hspace{1cm} (1)

where $P(x)$ is the frequency in the hourly interval $x$, $P_0$ is the mean hourly frequency, $A_k$ is the amplitude of the $k$th harmonic, $\theta = 2\pi x/N$, $N$ is the number of intervals ($=24$), and $\Phi_k$ is the phase angle of the $k$th harmonic. A Fisher test is performed to know whether the retrieved amplitudes are significant (Anderson 1971).

Figure 11 shows the amplitude (color) and phase (arrow) of the diurnal component for the rain occurrence and rain fraction during the active and break periods. The diurnal cycle of rain occurrence (and rain fraction) reveals several interesting features. The phase of the diurnal cycle exhibits distinct spatial variability (land vs ocean and also within the land region) during the active spell, whereas such variability is seen only between the land and ocean during the break phase. The pattern of diurnal cycle appears to be different over the Arabian Sea and BOB. While the diurnal cycle in the northern BOB is nearly the same during both active and break spells, it is different over the Arabian Sea and southern BOB. The rainfall peak shifts from noon during the active spell to midnight–early morning (0300 IST) during the break spell over the Arabian Sea. The early morning peak is generally expected over the open ocean as a result of nocturnal convection triggered by cloud-top longwave cooling (Dai 2001; Nesbitt and Zipser 2003). In the absence of any strong synoptic forcing, this could be the reason for the peak at 0300 IST during the break spell. The shift in the phase of diurnal cycle from 1000 IST in the north to noon in the southern BOB during the active spell is consistent with southward propagation rainfall episodes reported by earlier studies (Liu et al. 2008; Sahany et al. 2010). The
observed noon peak in the BOB is consistent with the diurnal cycle reported by Romatschke and Houze (2011).

Over land, the rainfall peak occurs in the evening in almost all the homogeneous zones during the break spell. In the absence of large-scale synoptic forcing and organized convection during the break spell, the rainfall occurs mainly because of isolated evening convection triggered by daytime insolation (Dai 2001; Roy and Balling 2007). On the other hand, the phase of rainfall occurrence and rain fraction varies significantly in different climatic zones during the active spell. An evening peak is observed in the majority of the homogeneous zones, except for the zones on the lee side of the Western Ghats (zones numbered 4, 7, 8, 10, and 11) and near the foothills of the Himalayas (zone 26). The late night–midnight peak in the zones lying on the east of the Western Ghats is also noted by Mao and Wu (2012) and Sunilkumar et al. (2016) and is thought to be due to large-scale organized systems during the active spell (Romatschke and Houze 2011; Rao and Mohan 2016, manuscript submitted to *Climate Dyn.*). Eastward movement of these organized systems is seen only during the active spell in the presence of strong synoptic forcing (upper-air trough, large CAPE, and moderate low-level wind shear). Both the rain occurrence and rain fraction peak at 0600–0700 IST near the foothills of the Himalayas (zone 26), consistent with the nocturnal triggering of convection reported by earlier studies (Basu 2007; Sahany et al. 2010; Romatschke et al. 2010). The nocturnal triggering of convection is attributed to the low-level convergence of katabatic mountain winds and synoptic flow (Romatschke et al. 2010). In a

**Fig. 11.** The diurnal variation of precipitation occurrence in different regions of the study region during the (a) active and (b) break phases of the monsoon. The arrow length indicates the amplitude, whereas the arrow indicates the time of maximum rainfall. (c), (d) As in (a), (b), but for rain fraction.
subsequent study, Romatschke and Houze (2011) segregated the rainfall systems based on the size as small or medium and based on the intensity as strong or weak. They noted two peaks in the diurnal cycle and attributed them to the dominance of different sizes of systems at those times. Nevertheless, the strong systems (both small and medium size) clearly show a peak in the morning over the Himalayas. The diurnal cycle in the present study is also consistent with that of Romatschke and Houze (2011). The morning peak, however, exists only during the active spell but not during the break spell. The diurnal cycle of precipitation over the Western Ghats is quite different from that over the Himalayas, indicating the complex interplay of the synoptic flow with the orography and associated flows (Sahany et al. 2010). The zones in the northern plains also show a distinct diurnal cycle with a peak in the afternoon during the active spell, as opposed to the peak in the late evening in the zones south of them. Nevertheless, they show a similar diurnal cycle during the break spell as their neighboring zones.

The amplitude of the diurnal cycle is large in semiarid regions (NWI and SEPI), whereas the rainy regions possess smaller amplitudes. The rainy regions (west coast of India and CI) receive rainfall rather continuously because of organized large-scale systems like depressions and low pressure systems and orographic lifting of moist monsoonal air (Romatschke and Houze 2011). The higher occurrence of shallow and stratiform rain (Saikranthi et al. 2014) in the above regions supports the observed diurnal cycle. In the case of SEPI, the rainfall is not continuous, and it occurs mainly as a result of the propagating MCSs from the west coast (Rao and Mohan 2016, manuscript submitted to Climate Dyn.). Figure 12 also shows this propagation to some extent, where the phase of the cycle progressively shifts from the evening along the west coast to midnight along the east coast. Since the rainfall is not continuous and occurs in a preferred time period (because of either propagating systems or insolation), the amplitude of the diurnal cycle is large in this region. Even within the core monsoon zone, the amplitude of the diurnal cycle shows an east–west gradient with larger amplitudes over zones in the western part of the monsoon trough.

Among the spells, the diurnal cycle is weaker during the active spell than the break spell. During the break spell, the rainfall occurs mainly because of convection in the evening over land and midnight–morning over the ocean. Even though the rainfall is meager during this spell, its diurnal amplitude is large. On the other hand, large-scale systems with a higher fraction of stratiform rain are mainly responsible for the rain during the active spell, reducing the amplitude of the diurnal cycle.

The amplitude and phase of the semidiurnal variation of precipitation during the active and break spells are shown in Fig. 12, depicting their spatial variability. Clearly, the semidiurnal component is weak and significant in only some regions. The semidiurnal cycle is significant in more zones during the break spell than the active spell, and these zones are clustered in CI, along FHH, and in the southernmost parts of India. All these regions show an early morning peak. This peak occurs because of the interaction of valley winds with synoptic flow during the night near FHH (Houze et al. 2007; Deshpande and Goswami 2014) or advection of convective systems originated in the open ocean (Nesbitt and Zipser 2003).

The diurnal and semidiurnal components together explain more than 80% of the total variance over most parts of India during both the spells. The only exceptions are the zones along the east coast in peninsular India (south of 16°N), the southern BOB, the Arabian Sea, and the foothills of the Himalayas during active and break spells. These two components explain more than 90% of variance in zones in the interiors of peninsular India and NWI, where the diurnal amplitudes are large. Among these two modes, the first harmonic dominates the diurnal cycle and explains more than 70% of variance in many zones of India. The semidiurnal component explains more than 40% in zones located in the northern plains of India.

7. Summary and conclusions

The spatial characteristics of precipitation—in terms of its occurrence frequency, rain fraction, vertical structure, type, and diurnal variability—during the active and break spells of the monsoon are compared and contrasted in a comprehensive manner. The approach adopted here is slightly different from that of earlier studies. Instead of defining the active and break spells for a particular region (e.g., monsoon core or central India), the spells are defined for small homogeneous rainfall zones and the data within a zone are segregated based on the active or break spell of that zone. The duration of active spells is found to be shorter than break spells in all homogeneous zones. The average duration of active spells in all homogeneous regions is nearly equal (i.e., 4–5 days), whereas it varies considerably during the break spell, from about 6 days along the east coast to 8–9 days in western India.

The synoptic situation, obtained from the composites of meteorological parameters, during the active and break conditions is distinctly different only in some preferred regions. The winds at the 850-hPa level are stronger during the break (active) spells than the active
(break) spells over land (ocean). Further, the wind anomaly plots clearly show acyclonic circulation in the eastern part of the monsoon trough during the active spell but not during the break phase. The surface pressure difference is quite large and seen only in the monsoon trough region, indicating that systems like depressions or low pressure systems, which are highly organized and quasi permanent, will only produce such large pressure differences. The pressure difference is almost negligible in semiarid regions. However, the temperature and humidity differences between active and break spells are large only in semiarid regions, whereas they are small in rainy regions and also over the ocean.

In general, most of the seasonal rainfall occurs during the active spells, but the rain fraction is not uniform over the entire country. It varies from 30% along the coast and FHH to 75% in the NWI and over the ocean. This means that most of the rainfall occurs in spells of active monsoon over NWI and over the ocean, whereas it occurs sporadically along the coast and FHH. The rain fraction for break spells is found to be small (<10%) in all regions.

The vertical structure of precipitation is quite different in active and break spells with wider distribution of reflectivity \( Z \) above (below) the freezing level during the active (break) spell. The difference in \( Z \) distribution between active and break spells clearly shows the predominant occurrence of \( Z \) at higher altitudes and at higher reflectivities during the active spell. The preferential occurrence of cold rain during the active spell and shallow rain during the break spell is thought to be
mainly responsible for the observed vertical structure. The general morphological features of storm height, like higher over the land than ocean and higher over the BOB than Arabian Sea, are seen in both spells; nevertheless, the magnitude of storm height difference in the above regions is different. The land–ocean difference in storm height is not unique to the monsoon region but rather observed throughout the tropics (Houze et al. 2007). The present study clearly shows that the storms are deeper (SH > 8 km) during the active spell than the break spell, in contrast to the variations noted in the Australian monsoon system (Cifelli and Rutledge 1998; Mohan and Rao 2012; Saikranthi et al. 2014).

The variability of rain type is quite significant spatially within a spell and also between the spells. The stratiform rain occurs predominantly over the entire country during the active spell, with the highest occurrence over CI (~80%) and lowest over the Arabian Sea (~50%). Such high occurrence of stratiform rain is seen only in some regions distributed sporadically during the break spell. The occurrence is lowest over the Arabian Sea (<30%), and such lowest values were not reported anywhere in the literature. The shallow rain occurrence is high during the break spell, in particular over the Arabian Sea, where it reaches more than 60%. The prevalence of organized large-scale systems during the active spell and the absence of such systems are mainly responsible for the observed rain type distribution (Houze et al. 2007; Romatschke et al. 2010; Saikranthi et al. 2014). The higher occurrence of strong stable layers and weak instability during the break spell seems to limit the growth of convective systems and increase the number of shallow systems (Mohan and Rao 2012).

The phase and amplitude of the diurnal cycle of precipitation exhibit distinct spatial variability during the active spell, whereas such variability is seen only between land and ocean during the break phase. In general, the amplitude of diurnal cycle is large during the break spells and in semiarid regions compared to that during active spells and in rainy regions. Highly organized and long-duration events, like low pressure systems and depressions that present in rainy regions during the active spells, generally weaken the diurnal cycle. While the phase of the diurnal cycle shows an evening peak over land during the break spell, it varies spatially during the active spell. The rainfall peaks during late night–midnight in southeastern India and in the morning near the foothills of the Himalayas during the active spell. The eastward-moving organized systems and low-level convergence of katabatic winds from the Himalayas and synoptic monsoon flow, respectively, are thought to be responsible for the observed diurnal cycle (Houze et al. 2007; Rao and Mohan 2016, manuscript submitted to Climate Dyn.). The diurnal and semidiurnal components explain more than 90% of total variance over many of the zones considered in the study during both spells. Among these components, the diurnal component is found to be dominant as it explains more than 70% of variance in a majority of the zones. The semidiurnal variation of precipitation is weak and confined to few regions, clustered in CI, in southern India, and along the FHH.

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