Meteorology and Atmospheric Physics
https://doi.org/10.1007/s00703-019-00703-7

ORIGINAL PAPER

Intense rainfall conditions over Indo-Gangetic Plains under the influence of Madden–Julian oscillation

Madhu Singh[1,3] · R. Bhatla[1,2]

Received: 17 July 2018 / Accepted: 11 October 2019

Abstract
The Indo-Gangetic Plains (IGPs) are densely populated and agriculturally productive areas with strong interannual and intraseasonal rainfall variability. The intraseasonal rainfall variability over IGPs is due to variation in sea surface temperature in the equatorial Indian Ocean. The intense rainfall activity over IGPs is mainly convection-driven, which may be linked with Madden–Julian Oscillation (MJO). The threshold for exceptionally heavy rainfall during the period 1979–2012 is based on the analysis of heavy rainfall episodes (percentage departure in daily rainfall (PDR ≥ 700%). The thresholds for extremely strong MJO events show highest departure in MJO amplitude (PDA ≤ 200%). The present study aims to find the simultaneous relationship between 60 and 30-day cycles of rainfall variability over IGPs and linked with MJO amplitude variability for the period 1979–2012. Further, the 30-day cycle of rainfall variability is elaborately studied for different phases of MJO. The monthly and daily variability of IGPs rainfall as well as MJO amplitude is analysed to find important intense rainfall and MJO events. The results suggest that the monthly rainfall variability is caused due to synoptic scale weather systems like monsoon trough oscillation and corresponding pressure fluctuations over IGPs. The exceptionally intense rainfall activity during onset and retreat phases is observed to be associated with MJO phases 6–8. The intense rainfall activity during active-break phase is observed to be associated with MJO phases 3–5. The intense rainfall events during break phase are observed along foothills of Himalaya. The day-to-day rainfall variability is due to interaction between monsoon circulation and MJO.

1 Introduction

The climate of IGPs is subtropical humid (wet) with dry winters. The rainfall is mostly received in summer and is about 65 cm in west and increases to 250 cm annually to east and near Himalaya (Singh and Sontakke 2002). The monthly and day-to-day summer monsoon rainfall variability over India has linkage to regional scale energetic. The monthly and day-to-day rainfall variability over IGPs is dependent on the important rain bearing systems like formation of monsoon depressions in Bay of Bengal region, strength of monsoon current and strength of Tropical Easterly Jet stream. The dominant modes of interannual rainfall variability are manifestation of drought and flood events, while the dominant modes of intraseasonal rainfall variability are manifestation of active and break events (Krishnamurty and Shukla 2000). The dominant mode of daily rainfall anomalies (leading empirical orthogonal functions) of the daily rainfall anomalies has a spatial pattern different from that of the dominant mode of seasonal anomalies. The monthly, seasonal and annual rainfall time series for the period 1871–1993 have been documented by Parthasarthy et al. (1994). Their results reveal that rainfall variability during June and September is highest and rainfall variability over India is least during July. Guhathakurta and Rajeevan (2008) have constructed seasonal and annual rainfall time series of 36 meteorological subdivisions of India using monthly rainfall data for the period 1901–2003 (for fixed network of 1476 rain gauge stations, i.e. one rain gauge for every 3402 square km area). Several studies have been done on the synoptic analysis of extreme hourly precipitation events (Chang et al. 2015; Luo et al. 2016; Zheng et al. 2016; Wu et al 2017).

Responsible Editor: A.P. Dimri.

✉ R. Bhatla
rbhatla@bhu.ac.in

1 Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India

2 DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India

3 Indian Institute of Tropical Meteorology, Pune, India

Published online: 04 November 2019

The rainfall variability over IGPs during different epochs of monsoon is different. The intense rainfall activity is observed over IGPs during onset and withdrawal phases of monsoon. However, the major contribution to seasonal rainfall is observed during active-break phase of monsoon. The Ganga Plain is domain of monsoon trough oscillation during southwest monsoon. The intense rainfall over IGPs occurs during active phase of monsoon on rare occasions. The intense rainfall events are observed along foothills of Himalaya during break phase of monsoon. Singh and Bhatla (2018) have shown slow retreat of monsoon over India under the influence of MJO.

The climate change related variations in precipitation pattern over IGPs are the most widely studied events (Murari et al. 2001; Srivastava et al. 2009). Kaskaoutis et al. (2014) have shown the influence of different synoptic weather conditions on aerosol concentration over Gangetic Plains. The aerosol concentration over IGPs also determines the incidences of intense rainfall events. The increase in greenhouse gases and aerosol concentration over IGPs play the major role in the ISVs over Gangetic Plains. The rise in sea surface temperature shows substantial positive feedback (0.5–2%/K) to the rise in intense precipitation events over IGPs. In view of the above, the purpose of the present study is to prepare daily time series of rainfall of IGPs and to determine dominant mode of day-to-day rainfall variability over IGPs. Further, the 60 days and 30 days rainfall variability over IGPs is analysed to find its association with the 60 days and 30 days MJO amplitude variability. The main objective of the present study is to explore and understand the possible mechanism of MJO responsible for heavy to very heavy rainfall activity over IGPs.

2 Data and methodology

The gridded rainfall data of IGPs ($0.25° \times 0.25°$) are obtained from IMD (India Meteorological Department). The daily rainfall time series is categorised into different rainfall categories. The different rainfall categories are listed in Table 1, as it shows the percentage departure in daily rainfall (PDR); it gives different intensity of rainfall events over IGPs. The MJO data are obtained from the website (https://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt). The daily MJO phase and amplitude time series is prepared for summer season (June–September). The MJO phase and amplitude time series is extracted for above four different categories of rainfall event. Further, the strong and weak MJO phase time series is prepared to find the difference in MJO activity during different rainfall events. Further, the percentage departure in MJO amplitude (PDA) is derived to find extreme MJO amplitude events. The extreme MJO phases are delineated depending on the PDA ≤ 200% and the weak MJO phases are delineated depending on the PDA ≤ 100%.

Table 1 The classification of daily rainfall events over IGPs during 1979–2012

Rainfall categories	Percentage departure
No rainfall	PDR < − 100
Light rainfall	− 100 ≤ PDR ≤ 100
Moderate rainfall	100 < PDR ≤ 200
Intense Rainfall	200 < PDR ≤ 300
Very intense rainfall	300 < PDR ≤ 400
Extremely intense rainfall	400 < PDR ≤ 500
Exceptionally intense rainfall	500 < PDR ≤ 700

3 Results and discussion

The rainfall rate over IGPs is 67.2 mm/day (Table 2), while the seasonal mean rainfall over IGPs is found to be 862.92 mm (Bhatla et al. 2015). The coefficient of daily rainfall variability over IGPs is 94.3%, while the coefficient of seasonal rainfall variability is 12.2%. It attributes due to heavy to very heavy rainfall activity over IGPs during 1979–2012. The exceptionally heavy rainfall event (588 mm in a day) occurred on September 29, 1981.The seasonal rainfall extreme is found to be 1119.56 mm and that observed in the year 1971. The frequency of no rainfall activity (recorded zero rainfall over many stations of IGPs) is highest in the year 1979. The day-to-day fluctuations in SMR are more as compared to seasonal fluctuations as defined in Bhatla et al. (2015). The observed rainfall variability over IGPs must be due to intraseasonal

Table 2 Month wise distribution of monsoon rainfall over IGP sand MJO events during 1979–2012

Month	Maximum rainfall (mm)	Rain rate (mm/day)	Strong days	Weak days	Total days
June	481.24	39.58	611	409	1020
July	475.24	91.75	559	495	1054
August	468.7	78.19	568	486	1054
September	588	58.55	609	411	1020
JJAS	588	67.2	2347	1801	4148

variability of SMR over IGPs. The intraseasonal variability of SMR over IGPs is defined in the following sections.

3.1 Monthly rainfall variability over Gangetic Plains

The monthly rainfall variability over IGPs during 1979–2012 is listed in Table 2. The highest rainfall rate (91.57 mm/day) is observed in July month, while the lowest rainfall rate (39.58 mm/day) is observed in June month. The rainfall rate during July (91.57 mm/day) and August (78.19 mm/day) months are greater than that during June (39.58 mm/day) and September (58.55 mm/day) months. However, highest rainfall is observed during June (481.2 mm in day) and September (588 mm in a day) as compared to that during July (475.2 mm in a day) and August (468.7 mm in a day). It may be concluded that IGPs receive highest rainfall in a day during onset and retreat phases of monsoon. However, the rainfall rate is highest during active-break phase of monsoon for the period 1979–2012. The rainfall rate over IGPs for a defined period is in inverse relation to the observed rainfall extreme value in a single day. The monthly rainfall variability over IGPs may show tele connection with the evolution of MJO in the equatorial Indian Ocean and its propagation to the west Pacific Ocean. The monthly analysis of MJO state reveals that the strong MJO events are more frequent during June and September as compared to that during July and August. The weak MJO events are more frequent during July and August. The results suggest that the strong MJO events are more frequent during onset and retreat phases, while the weak MJO events are more frequent during active-break phase of monsoon. Several studies have reported weak MJO phase 1 and phase 2 to be linked with the break phase of monsoon (Pai et al. 2011; Singh et al. 2017; Mishra et al. 2017; Singh and Bhatla 2019; Karmakar and Krishnamurti 2019). The monthly rainfall variability over IGPs corresponding to monthly MJO amplitude variability is shown in Fig. 1a–d. The highest departure (PDR ≥ 1125%) in rainfall occur during June. The results show that the highest rainfall variability is seen during June and September, while the lowest rainfall variability over IGPs is seen during July. The extreme rainfall events are mainly observed during June (Fig. 1a) and September (Fig. 1d). However, the frequency of heavy to very heavy rainfall events is highest during August (Fig. 1c). The 30 days rainfall variability is highest during August (Fig. 1c) and 30 days rainfall variability is least during July (Fig. 1b). The 30 days rainfall variability during July gives break-like situation over IGPs. The 30 days rainfall variability over IGPs is associated with the 30 days MJO amplitude variability. The 30 days MJO amplitude variability is highest during August and September, while the 30 days MJO amplitude variability is least during June and July.

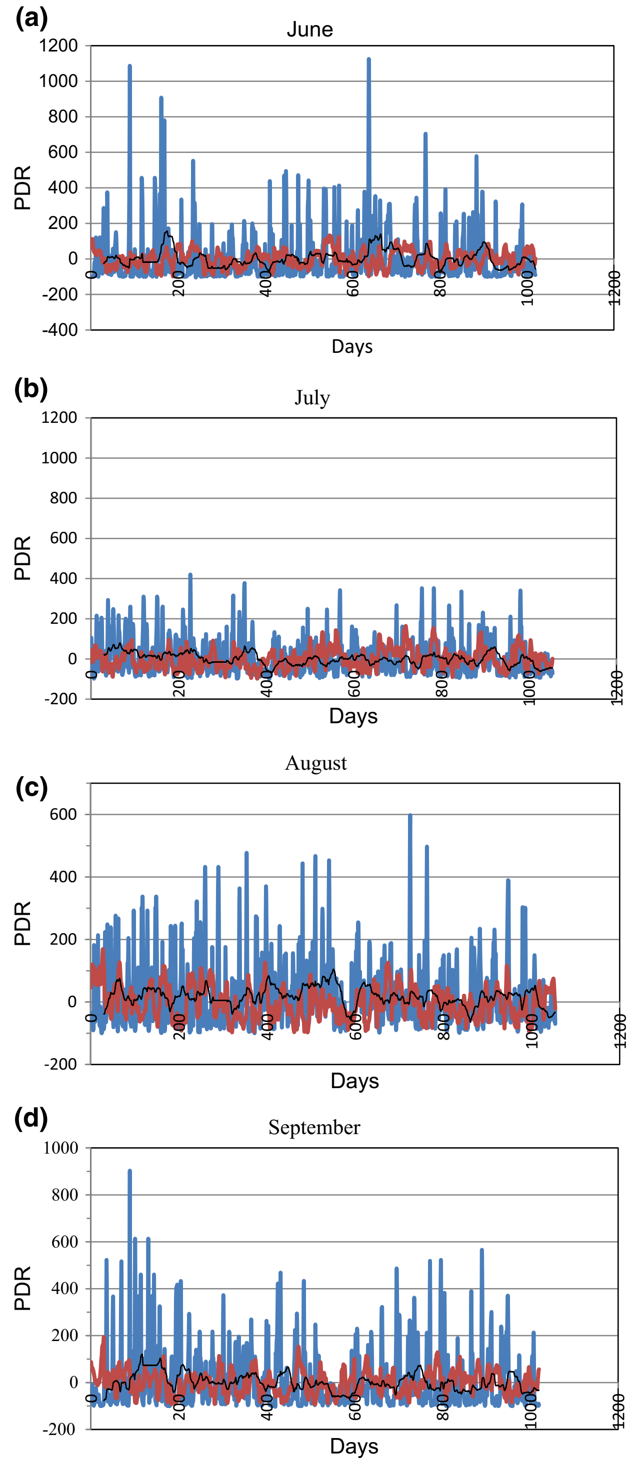

Fig. 1 The month wise rainfall variation (blue bars) corresponding to 60 day rainfall variability (black curve) and 30 day rainfall variability (brown curve) during June–September (**a**–**d**) for the period 1979–2012

3.2 Daily rainfall variability over Gangetic Plains

The day-to-day rainfall variability over IGPs corresponding

Table 3 MJO phase wise distribution of monsoon rainfall over IGPs during 1979–2012

Phase	Maximum rainfall (mm)	Rain rate (mm/day)	Strong days	Weak days	Total days
Phase 1	433.7	75.13	447	281	728
Phase 2	418	73.84	402	304	706
Phase 3	475.2	61.11	211	237	448
Phase 4	418	61.07	249	228	477
Phase 5	468.7	65.09	347	173	520
Phase 6	588	67.85	280	193	473
Phase 7	398.3	65.14	185	184	369
Phase 8	481.2	59.28	226	201	427
Total	588	67.2	2347	1801	4148

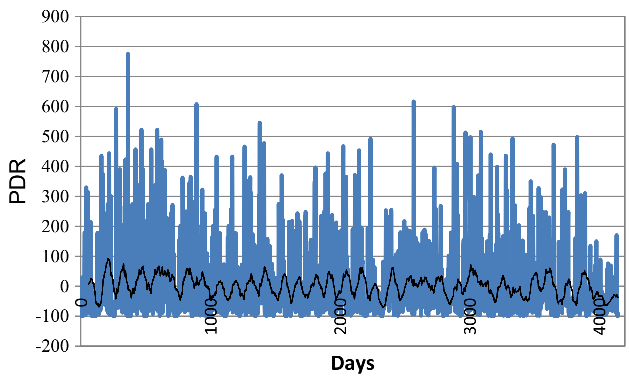

Fig. 2 The 60 days moving average (black curve) of daily rainfall (blue bars) over IGPs during 1979–2012

to different phases of MJO is listed in Table 3. The rainfall rate is highest during MJO phase 1 (75.13 mm/day) and phase 2 (73.84 mm/day), while the rainfall rate is least during MJO phase 3 (61.11 mm/day), phase 4 (61.07 mm/day) and phase 8 (59.28 mm/day). The moderate rainfall rate is observed during MJO phase 5 (65.09 mm/day), phase 6 (67.85 mm/day) and phase 7 (65.14 mm/day). The highest rainfall is observed during MJO phase 6 (588 mm in a day) and MJO phase 8 (481.2 mm in a day). However, the MJO phase 7 is associated with least rainfall (383.3 mm in day). The rest phases show ≥ 400 mm rainfall over IGPs in a day. The analyses of MJO state reveal that strong MJO events are frequent during MJO phase 1, phase 2, phase 5 and phase 6. The weak MJO events are more frequent during MJO phase 2 and weak MJO events are less frequent during MJO phase 5. The MJO phase 1, phase 2, phase 5 and phase 6 are more frequent, while MJO phase 7 and phase 8 are less frequent during 1979–2012.

3.3 Impact of MJO on intraseasonal rainfall variability over IGPs

The 60-day cycle of rainfall variability over IGPs gives period of heavy to very heavy rainfall activity over IGPs (Fig. 2). The 60-day cycle of rainfall variability over IGPs show PDR in rainfall in the range $-100 \leq PDR \leq 100$. The results suggest normal rainfall activity on 60 days cycle of rainfall variability. However, the peaks of 60-day rainfall variability gives extreme rainfall events over IGPs. There occur 33 events of positive departure and 30 events of negative departure on 60-day cycle of rainfall variability. The day-to-day rainfall variability shows large fluctuation in different rainfall categories. The results suggest that moderate rainfall events show percentage departure in rainfall in the range $100 < PDR \leq 200$ and heavy rainfall events show percentage departure in rainfall in the range $200 < PDR \leq 500$. It is observed that exceptionally heavy rainfall events show percentage departure in rainfall $PDR \geq 700$. The 30 days running mean of daily IGPs rainfall is comparable to MJO-related changes in rainfall pattern over IGPs (Fig. 3). The 30-day cycle of rainfall variability over IGPs (Fig. 2) shows more fluctuations in rainfall as compared to 60-day cycle

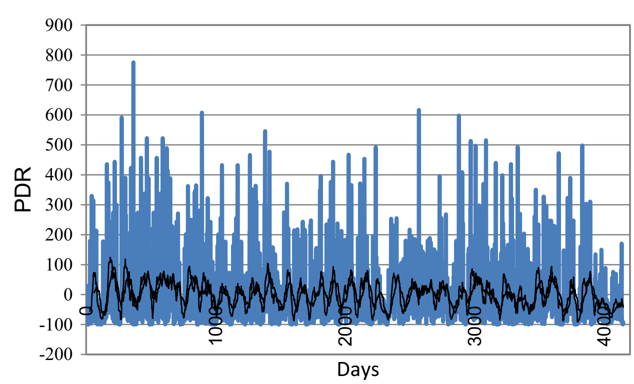

Fig. 3 The 30 days moving average of daily rainfall over IGPs during 1979–2012

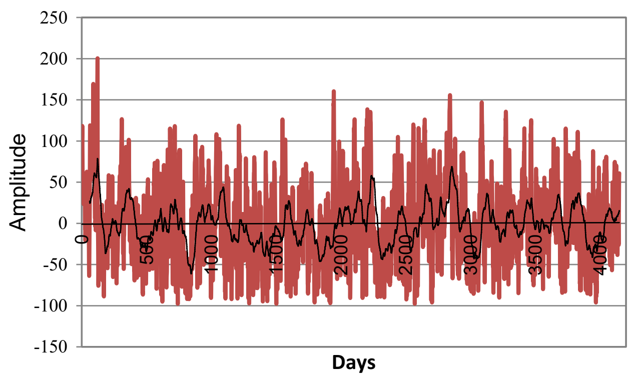

Fig. 4 The 60 days moving average (black curve) of daily MJO amplitude (red bars) during 1979–2012

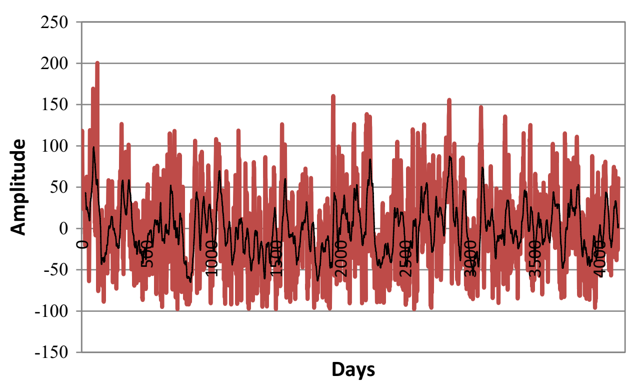

Fig. 5 The 30 days moving average of daily MJO amplitude during 1979–2012

of rainfall variability over IGPs. The period of above normal rainfall activity, i.e. PDR > 100, is greater in the case of 30-day cycle of rainfall variability. The period of below normal rainfall activity is lesser in the 30-day cycle of rainfall variability. The 60-day and 30-day cycles of rainfall variability observed over IGPs may be due to 60-day (Fig. 4) and 30-day (Fig. 5) cycles of MJO amplitude variability. The 60-day cycle of MJO amplitude variability shows percentage departure in MJO amplitude in the range $-100 \leq \text{PDA} \leq 100$. The day-to-day departure in MJO amplitude is greater than the 60-day cycle of MJO amplitude variability. The MJO events with departure in amplitude greater than 100% are defined as intense MJO events. It is observed that most of the MJO events show ± 100% departure and few events show departure in MJO amplitude ≥ 200%. These events are defined as anomalous MJO events. The 30-day cycle of MJO amplitude variability is more as compared to 60-day cycle of MJO amplitude variability. The day-to-day variability in MJO amplitude is even greater than the 30-day cycle of MJO amplitude variability. The 30 days rainfall variability over IGPs corresponding to different phases of MJO are shown in Fig. 6a–h. The MJO phase 1 and phase 2 are associated with less-intense rainfall events and greater MJO amplitude departure. The results suggest that MJO phases 1–2 are associated with moderate rainfall activity over IGPs with strong day-to day MJO amplitude variability. The 30 days rainfall variability over IGPs is highest during MJO phases 3–5. Thus, the extreme events are more frequent during MJO phases 3–5. The highest departure in MJO amplitude is observed during MJO phase 3 and phase 5. The rainfall pattern during MJO phases 1–2 is similar to break monsoon conditions, whereas the rainfall pattern during MJO phases 3–5 is similar to active monsoon conditions. The MJO phases 6–8 are associated with moderate rainfall activity over IGPs with intense rainfall events on rare occasions. The MJO amplitude is highly variable during MJO phases 7–8. The MJO phase 6 is associated with least variation in MJO amplitude. The 30-day cycle of rainfall variability shows highest variation during MJO phase 8 and least during MJO phase 6.

3.4 Mechanism of intense rainfall conditions over Gangetic Plains

The month wise and MJO phase wise distribution of intense rainfall events over IGPs during 1979–2012 is listed in Table 4. The intense rainfall events are identified based on the highest departure in day-to-day rainfall during 1979–2012. The particular dates of intense rainfall events are listed to find some threshold value of intense rainfall events over IGPs during different months and different phases of MJO. The results suggest that extremely intense rainfall event (588 mm in a day) occurred over Gangetic Plains on September 29, 1981 during MJO phase 6. The departure in day-to-day rainfall is found to be 775% and departure in day-to-day MJO amplitude is found to be 67%. The month wise departure in rainfall and MJO amplitude matches with the phase wise departure in rainfall and MJO amplitude. Another extremely intense rainfall event (481.2 mm in a day) over Gangetic Plains is observed on June 8, 2000 during MJO phase 8. The rainfall departure in June is 1125% and that during MJO phase 8 is 712%. The departure in MJO phase 8 amplitude is negative (− 98%). The mismatch of daily departure in rainfall during June and that during phase 8 is due to low rainfall rate in June (39.28 mm/day) and high rainfall rate (59.28 mm/day) during phase 8 for the period 1979–2012. The intense rainfall event during July (475.2 mm in a day) and August (468.7 mm in a day) shows less departure in day-to-day rainfall and day-to-day MJO amplitude. During the month of July, intense rainfall events are observed on July 10, 1986 corresponding to the MJO phase 8. The day-to-day departure in rainfall during July is observed to be 607% and day-to-day departure in amplitude is observed to be − 31%. There is slight mismatch of

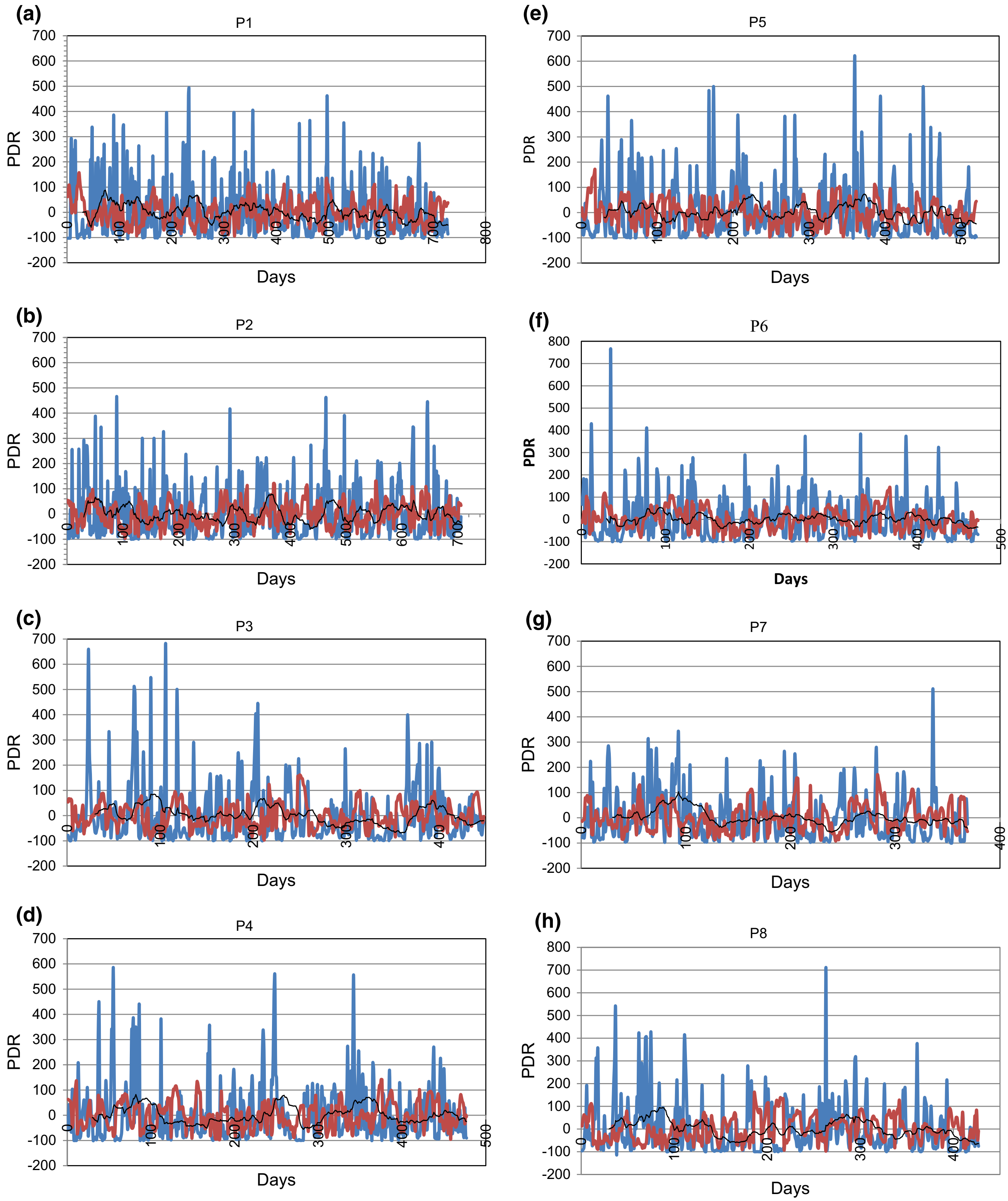

Fig. 6 The phase wise 1–8 (**a**–**h**) rainfall variations (blue bars) corresponding to 60 day rainfall variability (black curve) and 30 day rainfall variability (brown curve) during 1979–2012

departure in rainfall (678%) and amplitude (− 23%) during phase 3 with the observed departure during July month. It may be due to different rainfall rate during July and that during phase 3. The intense rainfall event during August is

Table 4 Intense rainfall events distribution over IGPs during 1979–2012

Month wise distribution	Maximum rainfall (mm)	Date	MJO phase	Percentage departure (%)	
				Rainfall	Amplitude
June (J)	481.2	8J, 2000	8	616	−98
July (JY)	475.2	10JY, 1986	3	607	−31
August (A)	468.7	12A, 2002	5	598	49
September (S)	588	29S, 1981	6	775	67
MJO phase wise distribution					
Phase 1	433.7	10JY, 1990		546	55
Phase 2	418	11S, 1983		466	26
Phase 3	475.2	10JY, 1986		678	−23
Phase 4	418	11S, 1982		584	−84
Phase 5	468.7	12A, 2002		598	49
Phase 6	588	29S, 1981		775	67
Phase 7	398.3	9JY, 2006		493	−4
Phase 8	481.2	8J, 2000		712	−98

observed on August 12, 2002 associated with MJO phase 5. The departure in day-to-day rainfall during August is 598% and departure in amplitude is 49%. The match of departure in rainfall and MJO amplitude during August and that during phase 5 is due to comparable rain rate and mean MJO amplitude. Thus, it may be concluded that intense rainfall conditions prevail over Gangetic Plains during MJO phase 3–5 (July and August) and 6–8 (June and September). The possible reason could be intense rainfall events during active-break phase is associated with MJO phases 3–5. The moisture incursion from MJO phases 3–5 regions is responsible for intense rainfall events over Gangetic Plains during

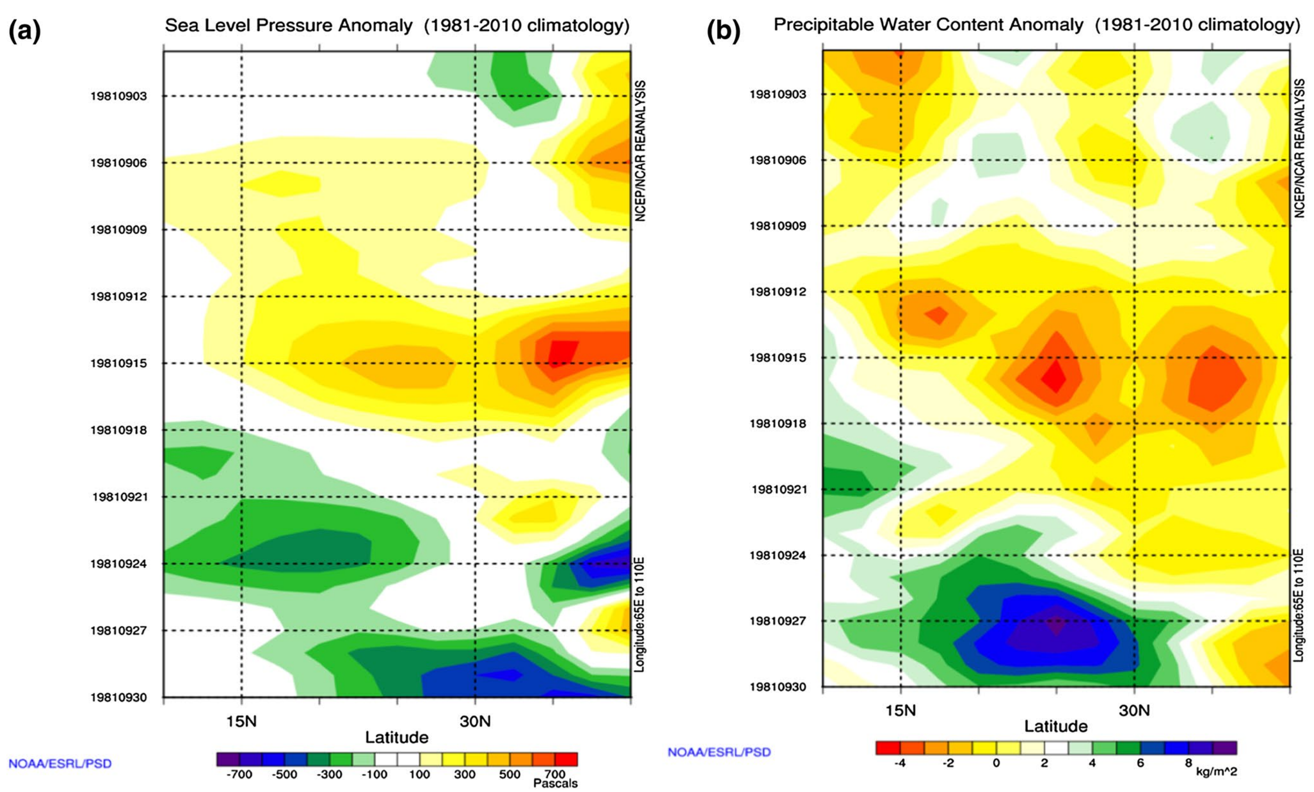

Fig. 7 The time-latitude diagram depicting intense rainfall conditions of **a** sea-level pressure anomaly, **b** precipitable water content anomaly over IGPs on September 29, 1981. (Source: NCEP/NCAR reanalysis)

active-break period. The moisture incursion from MJO phases 6–8 regions is responsible for intense rainfall events during onset and retreat phases of monsoon. The mechanism of intense rainfall conditions over Gangetic Plains could be explained by development of intense low pressure system and high perceptible water content. The anomaly of mean sea-level pressure (from climatology of 1981–2010) during September 1981 is shown in Fig. 7a. The time-latitude diagram depicts the daily evolution of intense low-pressure system during September 1981 that resulted in extremely intense rainfall event on September 29, 1981 associated with MJO phase 6. There is development of low-pressure system (pressure anomaly ≥ -7 hPa) onwards September 21, 1981 and it intensified on September 29, 1981. The perceptible water content matches with the intense low-pressure conditions during September 21–30, 1981 associated with MJO phase 6. The anomaly in perceptible water content (from climatology of 1981–2010) is shown in Fig. 7b. The perceptible water content anomaly is high during September 21–30, 1981 associated with MJO phase 6. The perceptible water content anomaly is highest ($\geq 8\,\mathrm{kg/m^2}$) on September 29, 1981. It is suggested to carry out simulation of these intense rainfall events to study the exact mechanism of intense rainfall events over IGPs.

4 Conclusions

The intraseasonal rainfall variability over IGPs has been investigated based on the impact of MJO on Indian summer monsoon. The results show that significant periodicities have been identified in the long-time series of observed IGPs monsoon rainfall data. The departure in 60 days and 30 days rainfall over IGPs reveals heavy to very heavy rainfall activity over IGPs. The day-to-day variability in SMR over IGPs is observed due to interannual variability in active and break days during the period 1979–2012. The day-to-day variability in SMR over IGPs is observed also due to interannual variability in MJO activity in the equatorial Indian Ocean. The 60 days and 30 days departure in MJO amplitude is analysed to find normal and anomalous MJO activities in equatorial Indian Ocean. The 60 days variability in SMR and MJO amplitude is lesser than the 30 days variability in SMR and MJO amplitudes. There occur considerable fluctuations on 30-day cycle of rainfall variability over IGPs. The departure in daily rainfall is analysed, which gives the simultaneous relationship between the rainfall variability over IGPs and MJO activity. The intense rainfall activity is observed over Gangetic Plains under the influence of MJO phases. The extremely intense rainfall events are observed over Gangetic Plains during onset and retreat phases of monsoon associated with prevailing atmospheric circulation and moisture incursion from MJO phases 6–8 regions. However, the intense rainfall conditions during active-break phase is observed to be associated with prevailing atmospheric circulation and moisture incursion from MJO phases 3–5 regions. The intense rainfall activity is observed during break phase along foothills of Himalaya. Several studies postulate the rainfall dynamics at regional scale (Anandh et al. 2017; Mishra et al. 2017; Bhatla et al. 2017) in linkage to distinct MJO phases, the present study examines the rainfall characteristics over IGPs region for distinct MJO phases. However, the numerical experiments are necessary to understand the underlying mechanism of intense rainfall events over IGPs region. The exceptionally intense rainfall events over IGPs identified in the present study may be used for forecasting extreme rainfall events over IGPs. The increase in extreme rainfall events may contribute to decrease in SMR variability over IGPs.

Acknowledgements The authors are very much grateful to Dr. DR Pattanaik, India Meteorological Department, New Delhi for his valuable suggestions that helped a lot in improving the quality of this paper. The Bureau of Meteorology (https://www.bom.gov.au/climate/mjo/) is thankfully acknowledged for providing real-time MJO data.

References

Anandh PC, Vissa NK, Broderick C (2017) Role of MJO in modulating rainfall characteristics observed over India in all seasons utilizing TRMM. Int J Climatol. https://doi.org/10.1002/joc.5339

Bhatla R, Singh M, Mall RK, Tripathi A, Raju PVS (2015) Variability of summer monsoon rainfall over Indo-Gangetic Plains in relation to El-Nino/La-Nina. Nat Hazards 78(2):837–853

Bhatla R, Singh M, Pattanaik DR (2017) Impact of Madden-Julian oscillation on onset of summer monsoon over India. Theor Appl Climatol 128(1–2):381–391

Chang WY, Lee WC, Liou YC (2015) The kinematic and microphysical characteristics and associated precipitation efficiency of subtropical convection during SoWMEX/TiMREX. Mon Weather Rev 143(1):317–340

Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. Int J Climatol 28(11):1453–1469

Karmakar N, Krishnamurti TN (2019) Characteristics of northward propagating intraseasonal oscillation in the Indian summer monsoon. Clim Dyn 52(3–4):1903–1916

Kaskaoutis DG, Houssos EE, Goto D, Bartzokas A, Nastos PT, Sinha PR, Kharol SK, Kosmopoulos PG, Singh Takemura T (2014) Synoptic weather conditions and aerosol episodes over Indo-Gangetic Plains India. Clim Dyn 43(9–10):2313–2331

Krishnamurthy V, Shukla J (2000) Intraseasonal and interannual variability of rainfall over India. J Clim 13(24):4366–4377

Luo Y, Wu M, Ren F, Li J, Wong WK (2016) Synoptic situations of extreme hourly precipitation over China. J Clim 29(24):8703–8719

Mishra SK, Sahan S, Salunke P (2017) Linkages between MJO and summer monsoon rainfall over India and surrounding region. Meteorol Atmos Phy 129(3):283–296

Murari L, Nozawa T, Emori S, Harasawa H, Takahashi K, Kimoto M, Numaguti A (2001) Future climate change: Implications for Indian summer monsoon and its variability. Curr Sci 81(9):1196–1207

Pai DS, Bhate J, Sreejith OP, Hatwar HR (2011) Impact of MJO on the intraseasonal variation of summer monsoon rainfall over India. Clim Dyn 36(1–2):41–55

Parthasarathy B, Munot AA, Kothawale DR (1994) All-India monthly and seasonal rainfall series: 1871–1993. Theor Appl Climatol 49(4):217–224

Singh M, Bhatla R (2018) Role of Madden–Julian oscillation in modulating monsoon retreat. Pure Appl Geophys. https://doi.org/10.1007/s00024-018-1788-y

Singh M, Bhatla R (2019) Modulation of active-break spell of Indian summer monsoon by Madden Julian Oscillation. J Earth Syst Sci 128(3):70

Singh N, Sontakke NA (2002) On climate fluctuations and environmental changes of the Indo-Gangetic Plains, India. Clim Change 52:287–313

Singh M, Bhatla R, Pattanaik DR (2017) An apparent relationship between Madden–Julian oscillation and the advance of Indian summer monsoon. Int J Climatol 37(4):1951–1960

Srivastava AK, Rajeevan M, Kshirsagar SR (2009) Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmos Sci Lett 10(4):249–254

Wu M, Wu CC, Yen TH, Luo Y (2017) Synoptic analysis of extreme hourly precipitation in Taiwan during 2003–2012. Mon Weather Rev 145(12):5123–5140

Zheng Y, Xue M, Li B, Chen J, Tao Z (2016) Spatial characteristics of extreme rainfall over China with hourly through 24-hour accumulation periods based on national-level hourly rain gauge data. J Atm Sci 33(11):1218–1232