https://doi.org/10.5194/egusphere-2024-2219
Preprint. Discussion started: 13 August 2024

RELATIONSHIP BETWEEN INTRASEASONAL OSCILLATIONS AND ABNORMAL RAINFALL IN VIETNAM

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https://doi.org/10.5194/egusphere-2024-2219
Preprint. Discussion started: 13 August 2024

Abstract

Vietnam's summer monsoon season are charaterised by intense rainfall, driven by dynamic intraseasonal oscillations such as the Madden-Julian Oscillation (MJO) and the Boreal Summer Intraseasonal Oscillation (BSISO). Located near the equator with diverse terrain, the country presents a unique case for studying how these atmospheric mechanisms interact with local geography, influencing both the timing and spatial distribution of extreme rainfall events. Despite this, gaps remain in understanding the detailed coupled impact mechanisms that hinder the accurate prediction of abnormal rainfall over the region. This study pioneers an exploration into the interconnected dynamics of abnormal rainfall occurrences and coupled activities of BSISO and MJO in Vietnam. Using association analysis of abnormal events, detected from remote sensing gridded rainfall database, within conditional probability analysis framework, our findings reveal distinct seasonal patterns: during summer, North and South Vietnam experience primary impacts, whereas Central Vietnam becomes more susceptible during autumn. Notably, BSISO phases 3 and 5 dominate the summer landscape, while MJO phases exhibit balanced occurrence frequencies throughout the season. Probability assessments highlight phase 7 of BSISO in July and phases 6-7 in August as periods of heightened extreme rainfall probability in North and South Vietnam, contrasting with phases 5-8 in Central Vietnam. Additionally, MJO phase 5 emerges as a focal point for intensified extreme rainfall in October, alongside notable increases in phases 3-4 during September. This comprehensive analysis enhances our understanding of the complex interactions shaping Vietnam's monsoonal rainfall dynamics, offering valuable insights for future studies levaraging the two intraseasonal osciliations mechanisms to explain and predict abnormal heavey rainfall in Vietnam.

Keywords: BSISO, MJO, CMORPH, heavy rainfall, intraseasonal oscillations, monsoon rainfall

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1. Introduction

Vietnam, located in the Asian summer monsoon belt, exhibits a distinct climate marked by significalt regional variation caused by multiple-scale atmospheric dynamics mechanisms interacting with the country's elongated north-south mountainous terrain. The rainy season in the North and South Vietnam is associated with the development of the tropical westerly winds, beginning around mid-May and ending around September (Nguyen and Nguyen 2004; Nguyen et al. 2014; Nguyen-Le et al. 2014). In contrast, due to the Foehn effect induced by the Truong Son mountain range, theCentral Vietnam experiences oppositely dry season during the summer months (Nguyen-Le et al. 2014). The rainy season in the Central typically starts from August to September and ends around December, related to the development of the northeast monsoon and the strong activity of the tropical disturbances (Yokoi and Matsumoto 2007; Tuan 2019; Nguyen et al. 2023). Recent study (Nguyen et al. 2022) pointed out that North Vietnam experiences early rainfall in spring due to the influence of cold fronts.

Rainfall in Vietnam exhibits clear oscillations on an intraseasonal scale, including two main modes: 10–20 days and 30–60 days (Tuan 2019; Truong and Tuan 2018; 2019). The 10–20-day oscillations are caused by the southward movement of pressure anomalies from the extratropical region, interacting with the westward movement of tropical disturbances. The movements of these pressure anomalies are directed by developments of upper-level wavetrain along jet stream (Tuan 2019). On the other hand, the 30–60-day oscillations are primarily induced by the Madden-Julian Oscillation (MJO) and the Northern Hemisphere summer monsoon (BSISO). While the MJO typically appears apparently in the late summer and autumn, moving from west to east, the BSISO occurs frequently in summer and propagates northeastward (Madden and Julian 1972; Lee et al. 2012).

Heavy rainfall induces serious consequences for socioeconomic activities causing flooding and land slides. Accurate predicting these occurences or probability of occurences in intraseasonal context is crucial for mitigating associated risks across multiple societal sectors. Initial studies on the heavy rainfall occurences in Vietnam were based on analyzing a large number of their related synoptic patterns which were mainly conducted by experienced forecasters and researchers in National Center for Hydrometeorological Forecasting (Khanh 1993; 1998a, 1998b, Lanh 2012). These studies identified various synoptic patterns contributing to the occurrence of the heavy rainfall, varying with climatic subregion. Keys patterns include tropical cyclones, interactions between cold surge and tropical disturbances, the arrival of tropical convergence zones (ITCZ) and deepening of monsoon trough, and the

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intensification of high-level troughs associated with cold surge. However, these insights rely on forecasters experiences, there are lack of robust statistics ralationship have provided.

On the other hand, mechanisms of heavy rainfall were also investigated for individual heavy rainfall events. Wu et al. (2011) pointed out that the heavy rainfall in Hanoi in October 2008 was caused by the interaction between cold surges and tropical disturbances. This disturbance was part of a synoptic-scale tropical wave developing from the warm Pacific Ocean to the East Sea. Van de Linden et al. (2016) demonstrated that the heavy rainfall in northern Vietnam in August 2015 was caused by a westward movement of a low-pressure system over the northern region combined with the strong activity of the southwest monsoon. The movement of the low-pressure system was associated with the westward movement of a high-level trough in the extratropical region. In another study, Chen et al. (2012) indicated that the heavy rainfall in Hanoi in 2008 was caused by the interaction of multiple processes at different scales, including 5-day oscillations, 12–24-day oscillations, and the MJO. In more spatially specific studies focusing the Central Vietnam, heavy rainfall is primarily attributed to interactions between cold surges, tropical disturbances, and topography (Yokoi and Matsumoto 2007; Yen et al. 2011; Chen et al. 2012). Meanwhile, in the Central Highlands and South Vietnam, the heavy rainfall be less frequent and less studied. Van de Linden et al. (2016) pointed out that heavy rainfall in this area often occurs more frequently during the activity phases of the MJO and tropical waves. Based on the analysis of large-scale synoptic patterns related to the historical heavy rainfall event in the subregion in August 2019, Wu et al. (2021) showed that this heavy rainfall event was caused by multi-scale interaction between the 10–60-day frequency oscillations and the 6–10-day frequency oscillations.

While these studies offer valuable insights into potential atmospheric mechanisms influencing the intraseasonal oscillations in local extreme events, there are lack of studies explicitly climatological relationships between these multiple oscillations – such as MJO or BSISO and these coupled effects – and abnormal rainfall occurrences in across subregions in Vietnam. Understanding how different subregions respond differently to these oscillations remains an important area for further investigation. Our study focus on understanding the influence of intraseasonal oscillations on the probability of abnormal rainfall occurrences across different regions of Vietnam. We aim to uncover how varying local terrains and geographical conditions responds differently with large-scale atmospheric oscillations, leading to diverse rainfall patterns throughout Vietnam.

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This paper is organized as following; the Section 2 presents the data and methodology used in the study. Section 3 presents the results of the analysis of the relationship between BSISO and MJO heavy rainfall in Vietnam. The conclusion and discussion are presented in Section 4.

2. Data and methodology

2.1. Data

In this study, high-resolution satellite rainfall data (CMORPH) are utilized to calculate the linkage of heavy rainfall occurrence over the Vietnam region. These data are provided at a spatial resolution of 8 km x 8 km and a temporal resolution of 3 hours. This dataset is estimated based on microwave observations from remote sensing satellites and employs the rainfall estimation algorithm developed by Ferraro (1997). To identify the activies of the BSISO and MJO, the BSISO and MJO index provided by the Asia-Pacific Economic Cooperation Climate Center (APCC) were employed. These indexes were constructed based on the analysis of the natural orthogonal functions of various atmospheric variables (Wheeler and Hendon 2004; Lee et al. 2013). Since the calculation of these indexes does not requires bandpass filtering, it can be applied to real-time forecast data to support forecasting.

2.2. Methodology

Since extreme rainfall exhibits seasonal variation (Tuan 2019), the extreme event thresholds were calculated for each month. In this study, a rainfall event is identified based on the 90th percentile of days with rainfall exceeding 0.3 mm in each respective month. This identification of rainfall events is conducted across all grid points from May to November, which is considered the rainy season in North and South Vietnam. The period from December to April is considered dry season in Vietnam (Nguyen-Le et al. 2014); therefore, it is excluded from our analysis.

Using 21 years of the BSISO, MJO and CMORPH rainfall data from 2000 to 2020, the empirical probability of extreme heavy rainfall occurrence in each phase of BSISO, MJO is calculated using the following formula:

$$\mathrm{P-dependent\ Pr\_O(\%) = P(Ext\ /\ BSISO_{XZ})},$$

In which, Pr_O represents the probability of heavy rainfall occurrence based on the BSISO index, P(BSISO_XZ) is the probability of phase X of BSISO occurring in month Z, and P(Ext | BSISO_XZ) is the conditional probability of extreme rainfall events given that the phase of BSISO is X in month Z. To focus on the effects of BSISO amplitude on occurrence of the extreme heavy rainfall, the BSISO index was categorized into four groups based on its

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amplitude, namely $(PC1^2+ PC1^2)^{1/2} >=1$, $(PC1^2+ PC1^2)^{1/2}<1$, $(PC2^2+ PC4^2)^{1/2} >=1$, $(PC3^2+ PC4^2)^{1/2} <1$

$$\mathrm{PA-dependent\ Pr\_O}(\%) = \mathrm{P}(\mathrm{Ext} / \mathrm{BSISO_{XYZ}}),$$

where P(BSISO_XYZ) is the propability that BSISO phase X which amplitude greater than Y, in month Z.

3. Results and discussions

3.1. Characteristics extreme rainfall in summer in Vietnam

Figure 1 illustrates the characteristics of the rainfall and extreme rainfall events in Vietnam during the rainy season. Rainfall primarily occurs in North and South Vietnam in summer while it starts to occur in Central Vietnam much latter, from September to October. While the monsoon westerlies bring a large amount of moisture to support for the development of deep convection, the Truong Son mountain runing along the country play a role as a nature barrier that prevents the low-level flow from developing to the east. Therefore, summer is dry season in Central Vietnam (Nguyen-Le et al. 2014). It is importat to note that, although the timing of rainy season onset is similar between the North and South Vietnam, the rainfall amount in the former is significantly higher than that in the later. This differrence in rainfall amount is primarily caused by the extratropical factors effecting the North Vietnam in summer (Tuan et al. 2019). Additionally, the highest amount of the summer rainfall is observed in the high and steep mountainous terrain in northwestern region, especially in Lai Chau and Bac Quang, implying the rainfall is significantly affected by topography. In the Central Highlands and South Vietnam, rainfall mostly concentrates in the western sides of the highlands, which may also result from the interaction of the southwest monsoon winds and terrain. In another hand, heavy rainfall only begins to appear in Central Vietnam in September which is related to the intensification of cold surge, activities of tropical disturbances and orographic effects (Yokoi and Matsumoto 2007).

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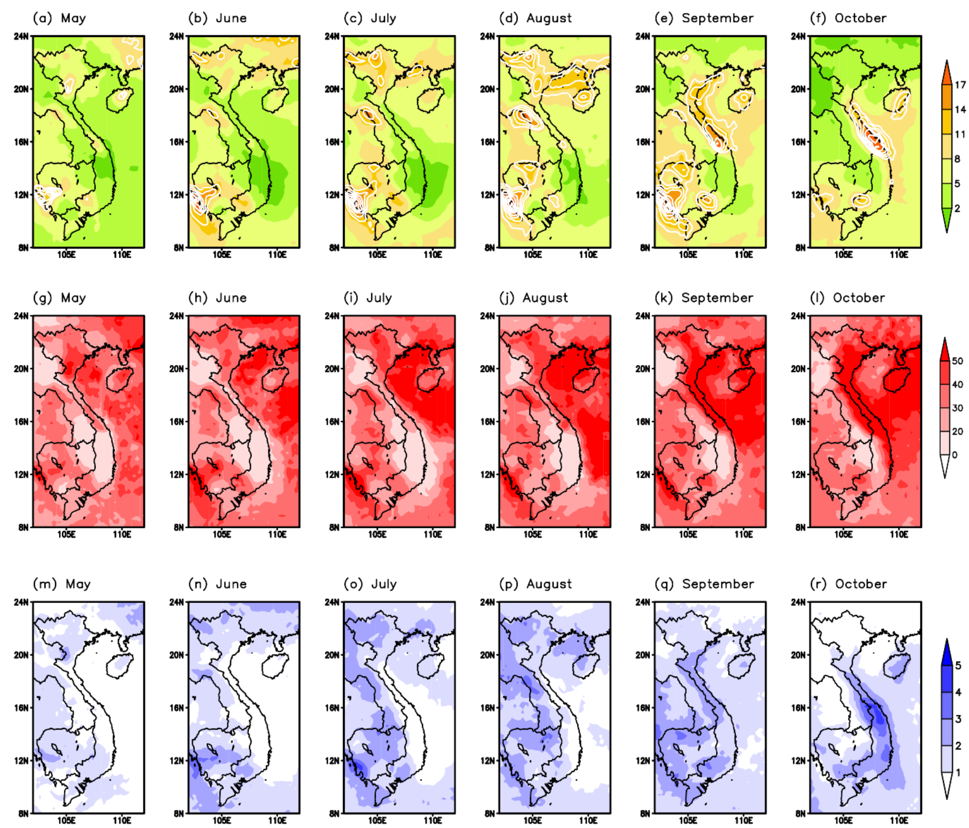

Figure 1: Top panel: climatological rainfall (color) and its standard deviation of daily rainfall (white lines) from May to October over 21 years (2000-2020); Middle panel: 90th percentile rainfall values for each month (mm/day); Bottom panel: Number of extreme rainfall days.

Similar to the distribution of climatological mean of the rainfall, the 90th percentile of rainfall also shows significant differences among the subregions. In the North Vietnam region, the 90 th percentile of rainfall ranges from 30–60 mm per day, with highest values in the Red River Delta. These rainfall values gradually increases as autumn approaches. Meanwhile, in South Vietnam, the 90th percentile of rainfall does not vary much throughout the year, which oscillates in a lower range, from 20–40 mm per day. The 90th percentile of rainfall in the Central Highlands displays the lowest values, only below 20 mm per day. Conversely, the 90th percentile of rainfall is also small over Central Vietnam in summer months, that is consistent with the fact that summer is dry season in the subregions. The rainfall abruptly increases in September, and then reaches over 60 mm per day in October.

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The number of extreme rainfall days also varies significantly among the climatic subregions. The number of extreme rainfall days in North Vietnam increases gradually from May, reaches a peak around July, then gradually decreases in September. Meanwhile, the number of extreme rainfall days in the Central Highlands and South Vietnam peaks later, around September. Lastly, the number of extreme rainfall days in Central Vietnam reaches its peak in October-November, corresponding to the increase of rainfall in the subregion in the period. This extreme rainfall patterns once again indicates the complex characteristics of extreme rainfall in Vietnam due to influences of multiple weather systems.

3.2. Evolution of the BSISO and the linkage with rainfall

Figure 2 illustrates the frequencies of the individual BSISO phases during the summer months. The anomalous rainfall associated with the highest frequency phase is also plotted. Although the difference in the frequencies among the phases is not too large, the highest frequency phase can be noted. In May, phase 1 of the BSISO-1 shows the highest frequency (approximately 120 days), followed by phases 2 and 3 (around 100 days). This phase is related to the decrease of rainfall in almost all Vietnam subregions, except for small areas in the North and Central Vietnam (Fig 2g). In June and July, phase 5 and phase 3 of the BSISO-2 exhibit the highest frequencies, respectively; however, the anomalous rainfall patterns is nearly uniform in entire Vietnam, indicating the insignificant contributions of these phases to the variation of the rainfall. The most important signals are only noticed in September and October. In September, phase 5 of the BSISO-1 shows the highest frequency, associated with a clear increase of rainfall in Central Vietnam and decrease of rainfall in North Vietnam. In contrast, in October, phase 3 displays the highest frequency, simultaneous with the outburst increase of rainfall in North Vietnam.

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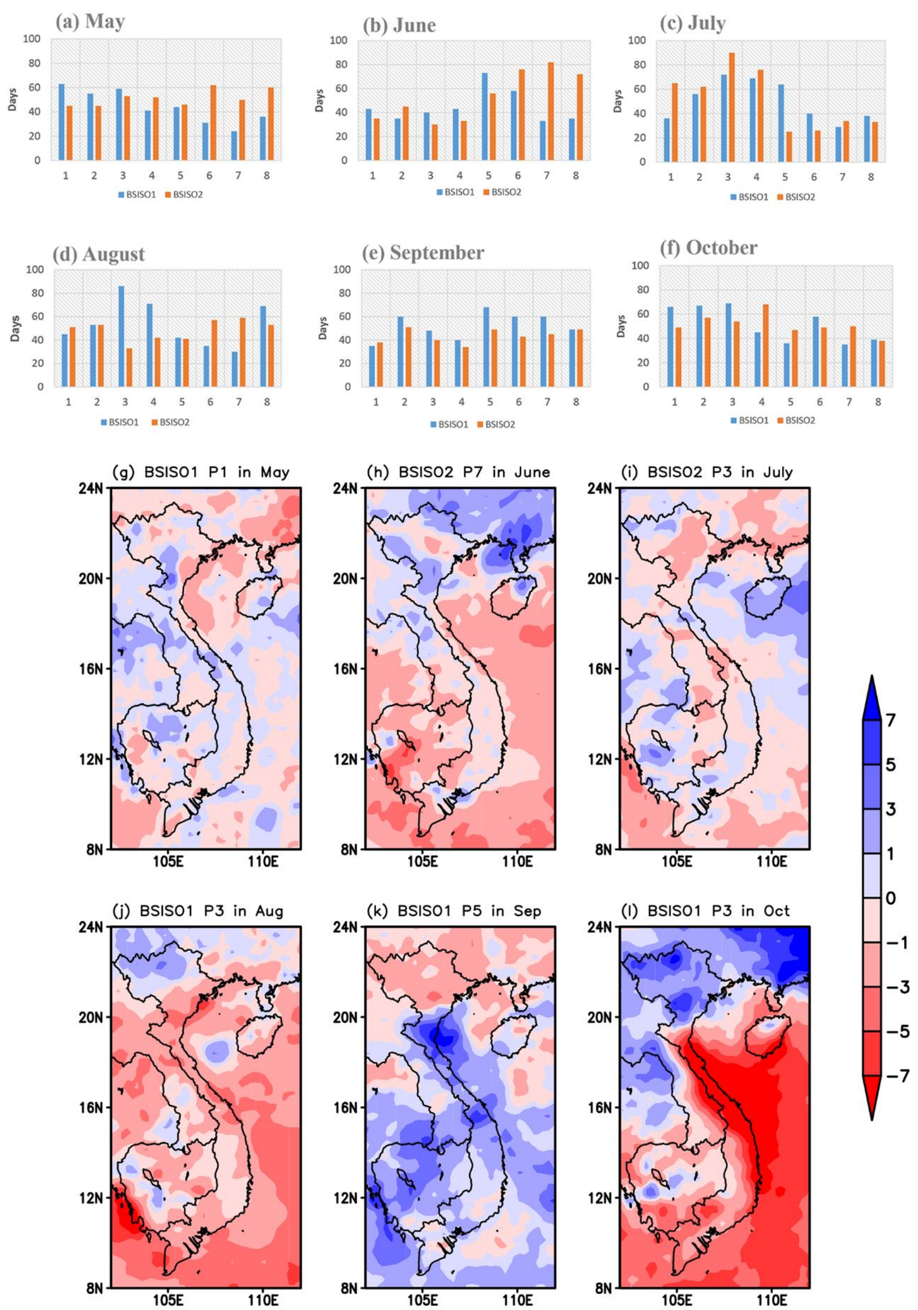

Figure 2. (a-f) Frequency of each BSISO1 and BSISO2 phase in May, June, July, August, September, October from 2000 to 2020. Figure (g-l) represents the corresponding anomalous rainfall associated with the phases of BSISO of highest frequency.

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Further investigation on the linkages between the BSISO variations of rainfall in Vietnam is displayed in Figure 3. The anomalous rainfall values in each BSISO-1 phase (Fig 3a-h) and probability of extreme rainfall occurrence in the phases which their amplitude greater than 1 (Fig 3i-p) are plotted. It can be seen that, although the anomalous rainfall are nearly uniform in many BSISO-1 phases, the increase rainfall is clearly observed in North Vietnam in the phases 2, 4 and 8. This result indicates the insignificant influences of the BSISO-1 activities on rainfall in Vietnam. Similarly, in the phase 2, 4 and 8, the anomalous and extreme rainfall are also enhanced over the North Vietnam and the southern of Central Highland. Therefore, the BSISO might also contribute to the occurrence of extreme rainfall in the country in some specific months. Note that, the anomalous rainfall and probability of extreme rainfall is calculated in all day that the phase occurs, the signal of rainfall variations might not be clear.

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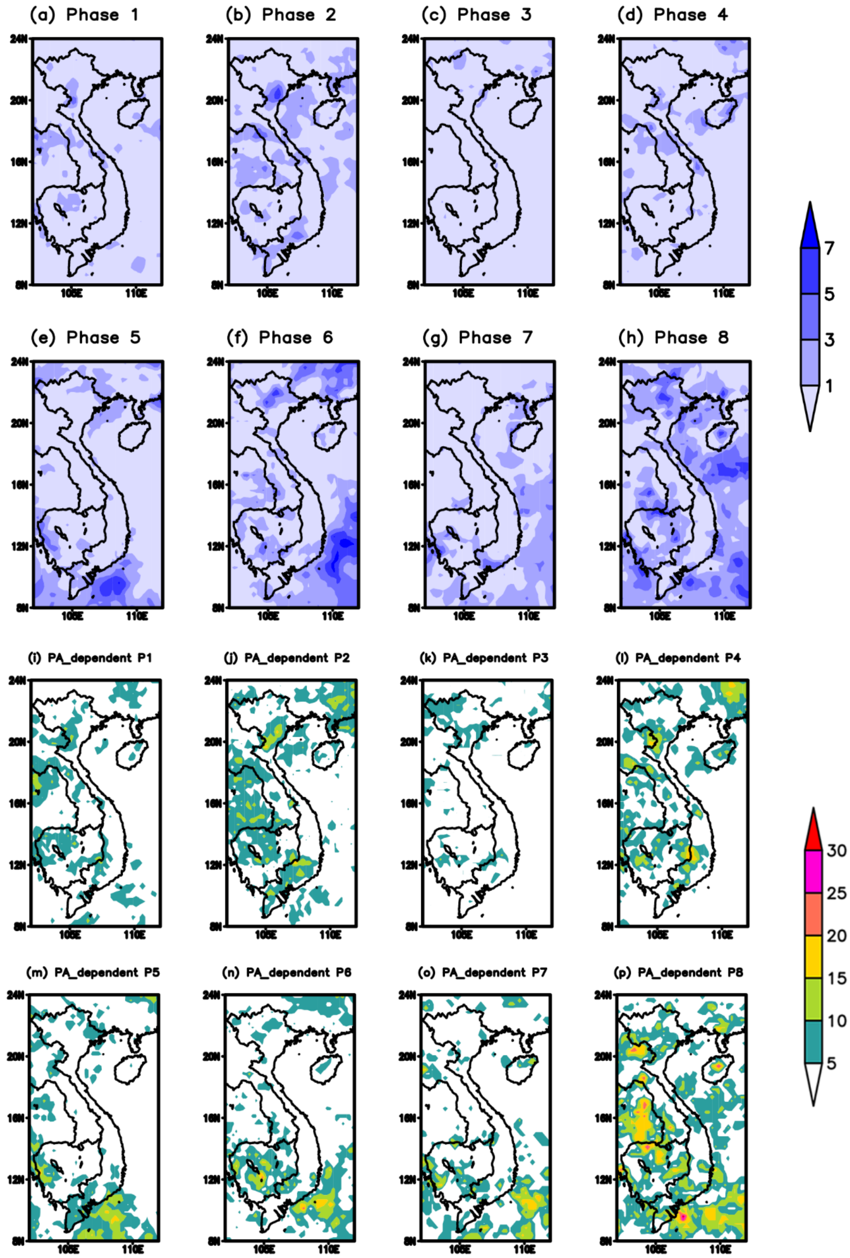

Figure 3. Anomalous rainfall and probability of extreme rainfall occurrence in BSISO-1 phases.

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Since the extreme rainfall has significant seasonal variability, the probability of extreme rainfall in each BSISO-1 phases in specific month are plotted (Fig. 4). To highlight the effect of of the BSISO-1 intensity on rainfall, only the phases which the BSISO-1 amplitude greater than 1 are plotted. This approach might help to better recognize the linkage between the BSISO-1 and the extreme rainfall in Vietnam. In June, the phase 6 and phase 7 of the BISOS-1 play the most important role in modulating the extreme rainfall, with the high probability of extreme rainfall observed in North and Southern Vietnam (Fig. 4a-b). From July to August, these two phases still the controlling factors of the extreme rainfall. The high probability of extreme rainfall values are not only observed over the North and South Vietnam, it also expanses to Central Highlands. From September to October, there are additional contributions of phase 5 and phase 8 on the frequency of extreme rainfall. While the probability of extreme rainfall tends to decrease over the North Vietnam, it is rapidly intensified significantly in the North Central and South Vietnam, consistent with the development of cold surge and activities of tropical disturbances during this period.

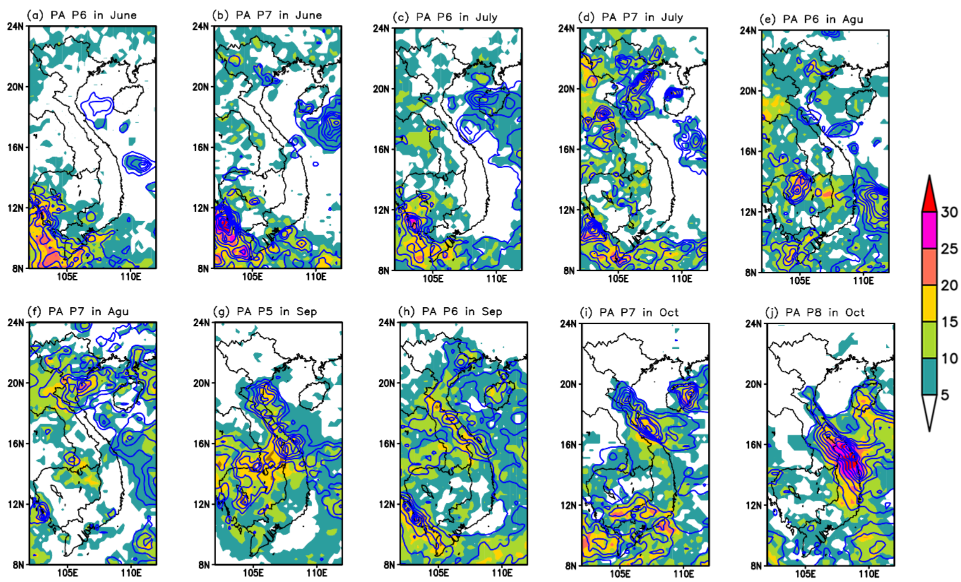

Figure 4. Probability of extreme rainfall occurrence in the BSISO-1 phases in specific month

Similar to Figure 4, Figure 5 illustrates the probability of extreme rainfall caused by each the BSISO-2 phases in specific months. From May to July, the phase 1, 3, 6 and 8 display the closest linkage with the extreme rainfall, with the highest probability of extreme rainfall is

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observed in North Vietnam (Fig. 5a, e, f, g) and Central Highlands (Fig. 5b, g). However, from August the phase 3, 1, 4 and 6 play the most important role in modulating the occurrence of extreme rainfall. The high propabilities of extreme rainfall tend to occurs in North Vietnam in September and then propagate southward to Central Highland and Southern Vietnam in October. Therefore, although the BSISO-2 has different period compared to the BSISO-1, it also related to the southward propagation of extreme rainfall in Vietnam from summer to autumn.

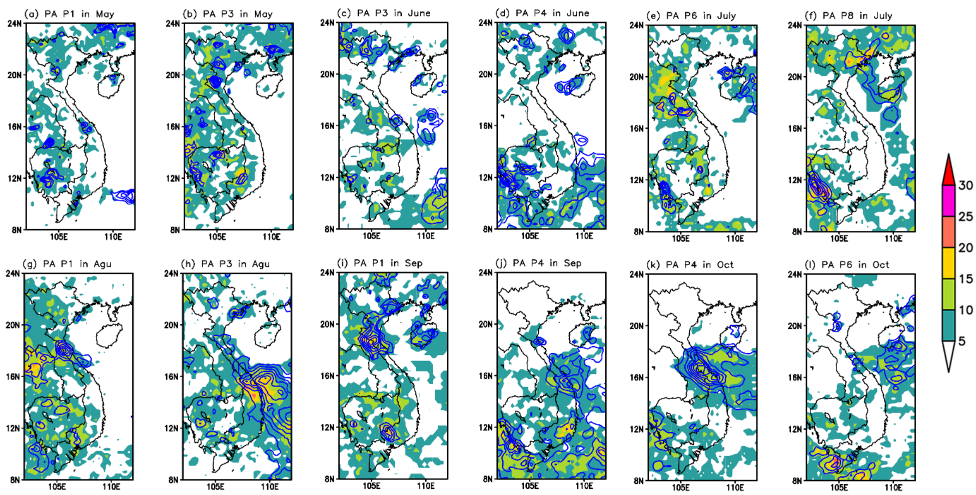

Figure 5. Same as Fig. 4, except for the BSISO-2 phases

3.3. Linkages of MJO and the occurrence of extreme rainfall

Figures 6 and 7 depict the frequency of occurrence of MJO phases and the corresponding anomalous rainfall associated with the most frequent MJO phase. It can be seen that in certain months, some MJO phases tend to occur more frequently than others, although the difference in frequency between phases is not significant. In January, phases 6 and 7 exhibit higher frequencies (112 and 103 days, respectively) compared to other phases. Moving to February, phase 7 has the highest occurrence frequency (112 days) while from March to April, it is replaced by phase 3. From May to July, phases 1 has the highest occurrence frequencies, followed by Phase 2 in August. From September to October, phase 5 occurs the most frequently, that then replaced by phase 4 in November. Finally, in December, phase 5 once again is the most frequent phase among these others. While anomalous rainfall displays negative values in almost phase in summer months, it is significantly increased in Central and North Vietnam in phase 5, from September to October. This result indicates that, the activities

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of MJO primarily inhibit the rainfall in Vietnam in summer while they intensify the rainfall from late summer to early autumn.

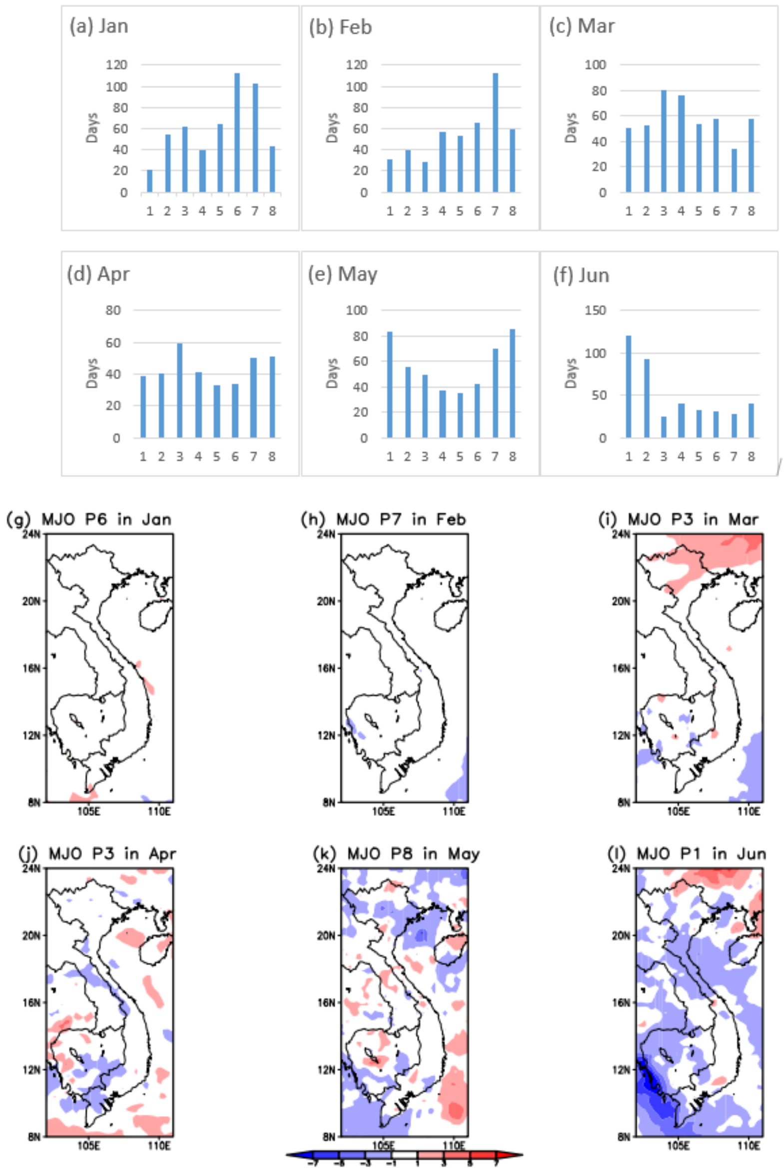

Figure 6. Same as Fig. 2, except for the MJO

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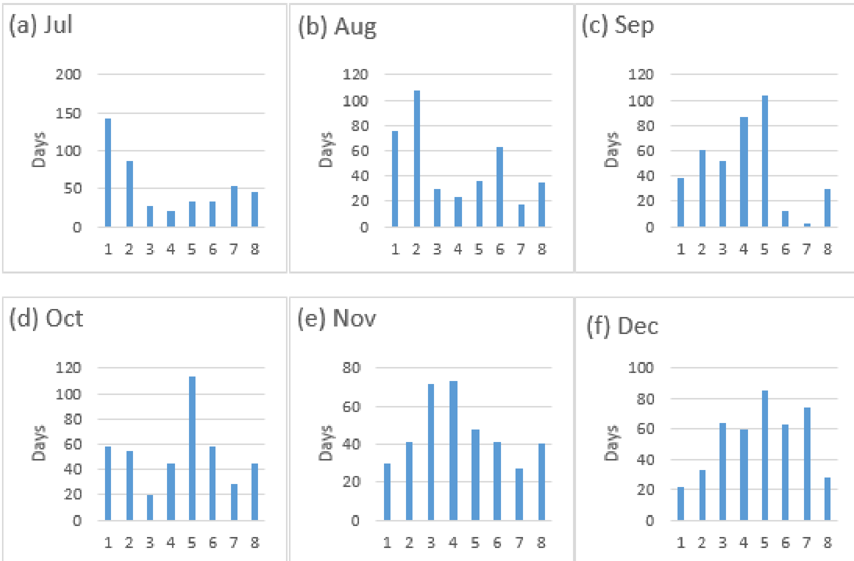

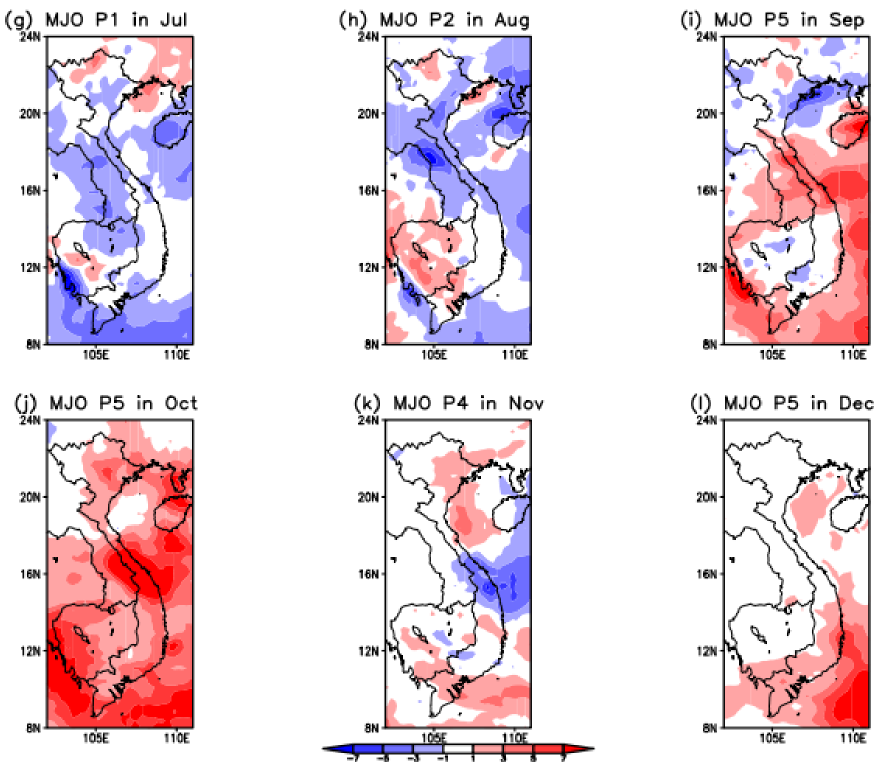

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Figure 7 Same as Fig. 2, except for the MJO

From January to April, while the MJO displays high frequency, the anomalous rainfall is very small in Vietnam, indicating the insignificant relationship of the MJO with rainfall in the country (Fig. 6g–k). These patterns are consistent with the fact that this period is dry season in Vietnam. The domination of cold surge setups a stable condition that prevent the formation of deep convection. In summer months, from May to August, the phase 1, 2 and 8 display highest relationship with the anomalous rainfall, which is characterized by decrease of rainfall in North Central. In contrast, from September to October, the phase 5 is the most important phase modulating anomalous rainfall in Vietnam, with an high positive anomalous rainfall values in North Central. In the following months, there is additional contribution of phase 4 on the variation of rainfall; however, positive anomalous rainfall tend to diminish and propagate southward as winter approaches.

Figure 8 depicts the anomalous rainfall and the probability of extreme rainfall occur in each MJO phase in October. It can be seen that, while the singal of rainfall is insignificant in phase 1, 2, 7 and 8, consistent with the fact that deep convection in the Western North Pacific is surrpessed in these MJO phases. In contrrast, the anomalous rainfall and extreme rainfall display great values in the phases from 3 to 6, especially over North Central since these phase favor for the development of deep convection. Note that, the highest anomalous values are observed in phase 5, indicating the closest relationship of this MJO phase and rainfall in Central Vietnam.

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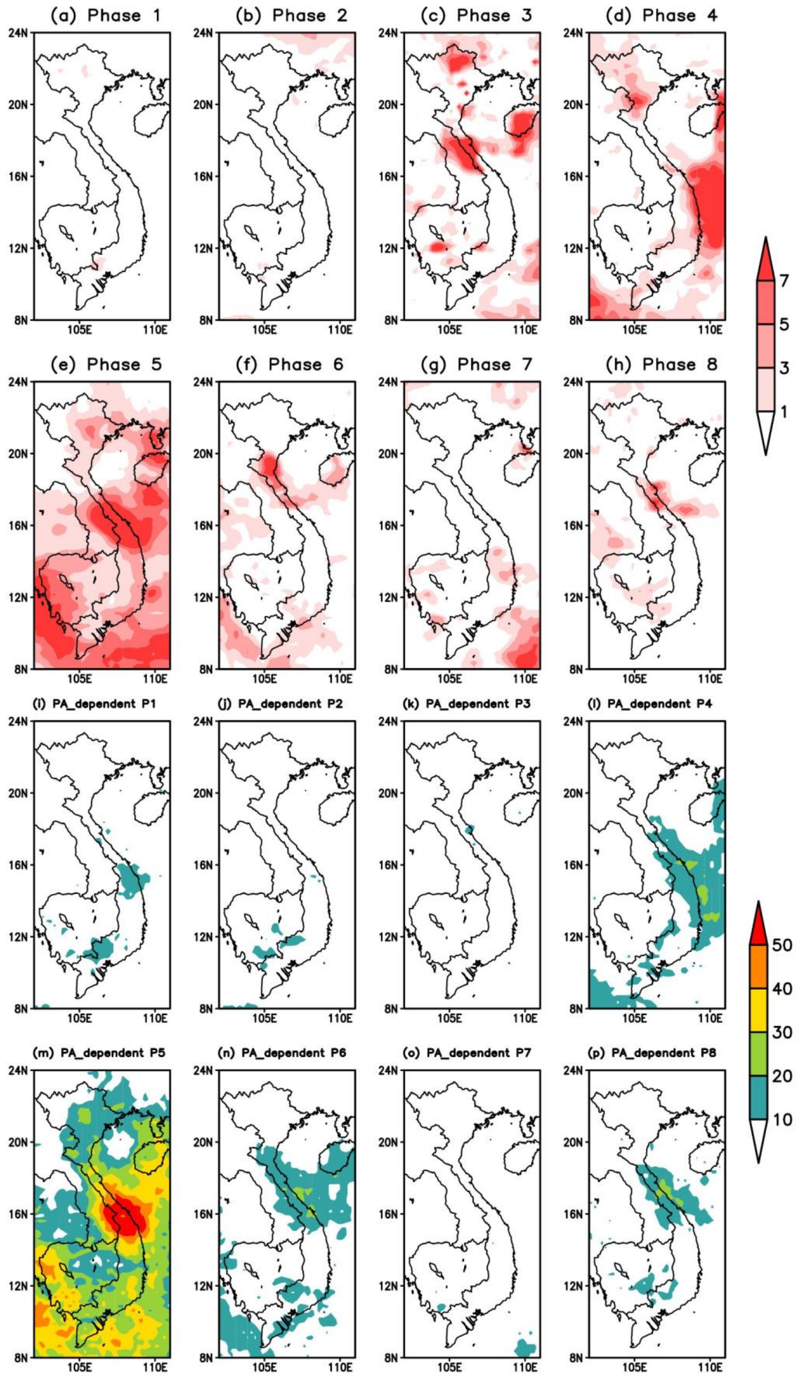

Figure 8: Anomalous rainfall and the probability of extreme rainfall occur in each MJO phase in October

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The probability of extreme rainfall events in individual MJO phase in certain months are plotted in Fig. 9. It can be seen that, from January to April, signal of extreme rainfall is insignificant, consistent with the dry season in the country. The probability of extreme rainfall events starts increasing in May, with the most pronounced values are observed in North and South Vietnam. These values range from 4–20 percentage, occurring in the phase 1 and 7 in May and phase 4 and 5 in June. This incement of the probability of extreme rainfall is due to the fact that, summer is rainy season in Vietnam. Similar to Figure 9, Figure 10 illustrates the probability of extreme rainfall caused by each phase in specific months. In July, the probability of extreme rainfall is nearly negligible; however, it increases significantly in phase 6 in August. Moving to September, the probability of extreme rainfall is continuously intensified in the Central and Southern regions during phases 3 and 4. In October, the highest frequency of extreme rainfall is found in the midle of Central Vietnam during phase 5 while it shows small values in the Northern Central during phase 6. In the following months, the probability of extreme rainfall diminishes rapidly, that is consistent with the withdrawal of rainy season in Vietnam. The probability of extreme rainfall is nearly zero in December, and the signal of the high probability is only observed in the oceanic regions to the south of the Bien Dong.

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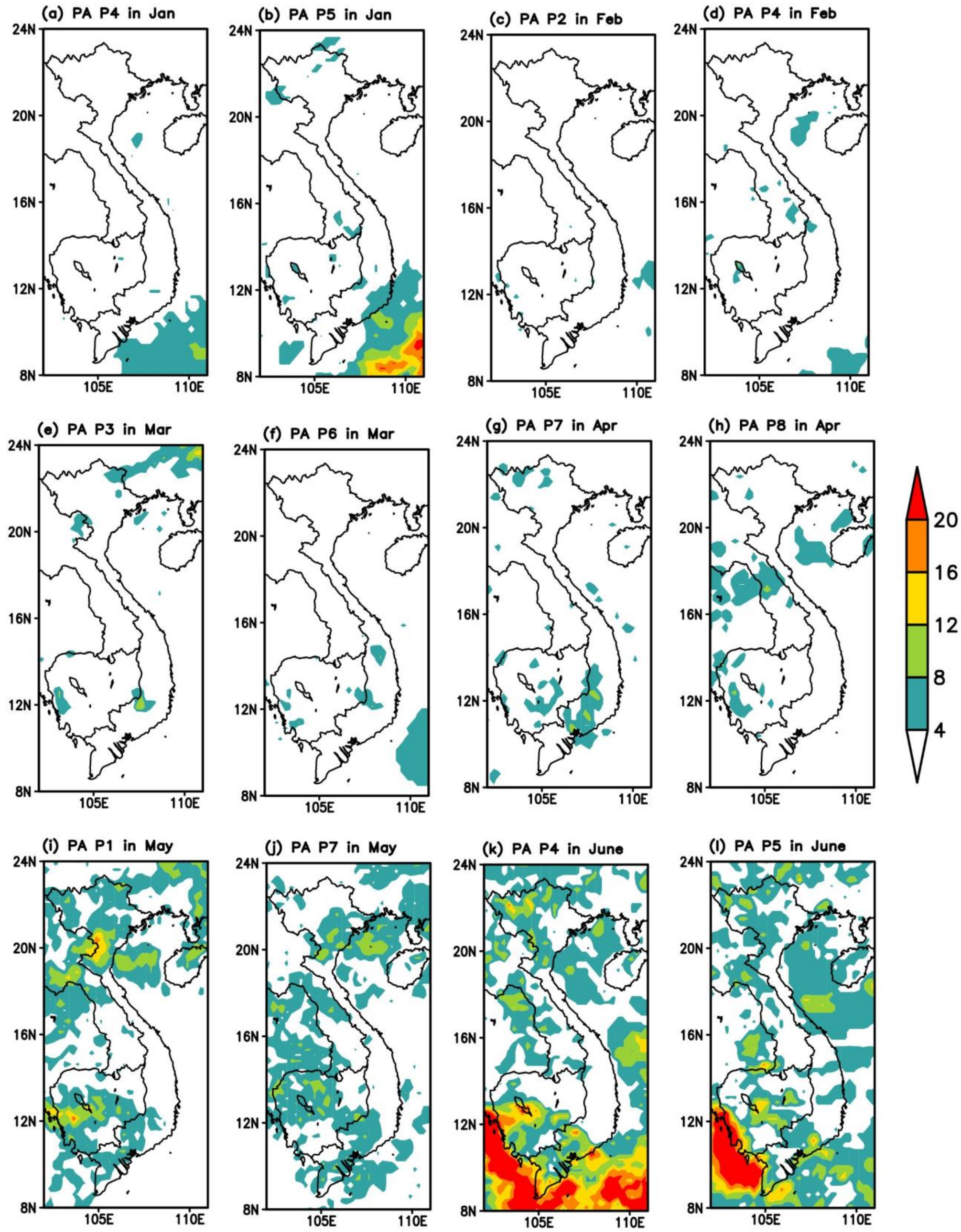

Figure 9 illustrates some conditional probabilities (PA) of extreme rainfall events occurring with various phases in months 1-6 of the MJO

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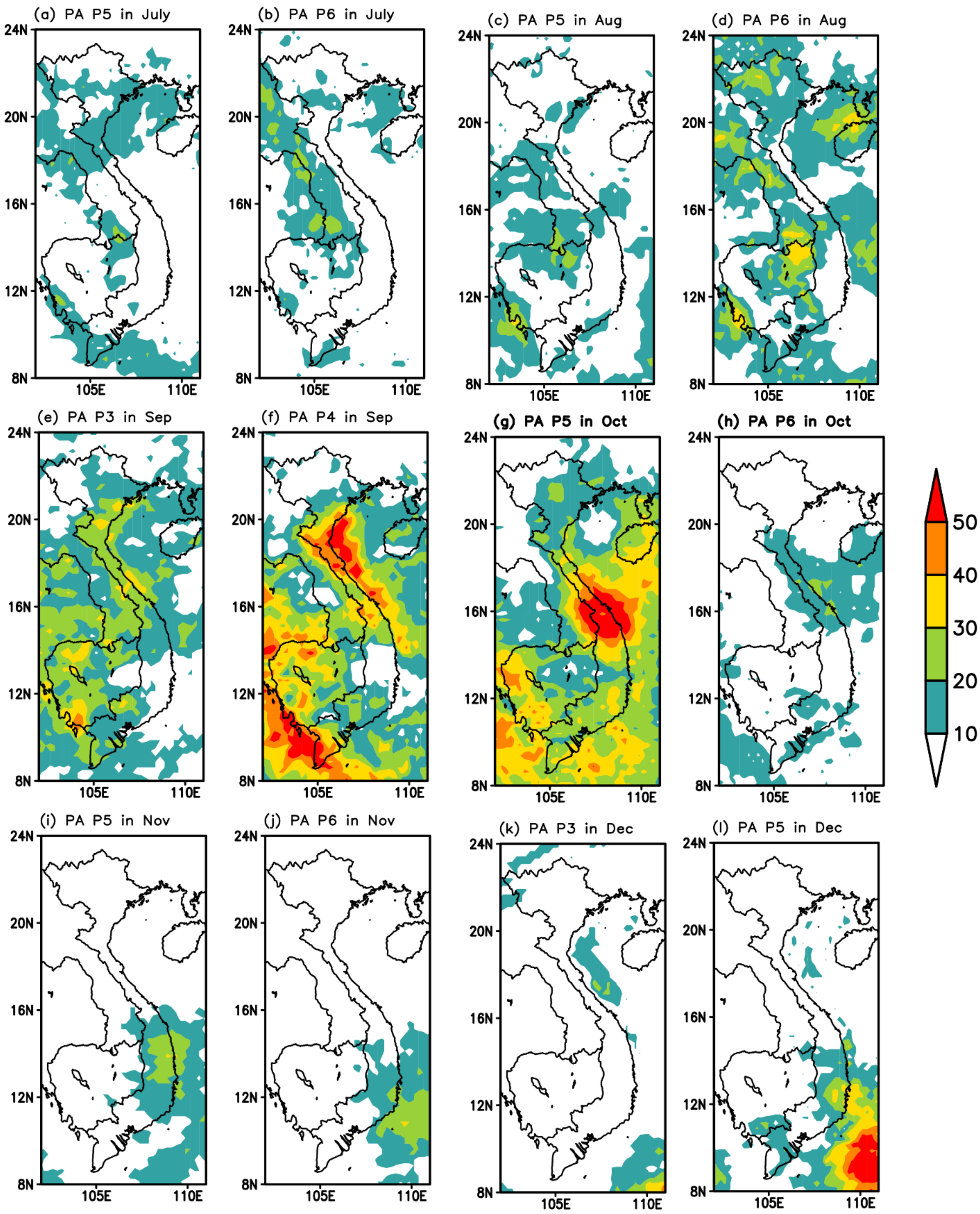

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328 *Figure 10. Same as Fig. 9, except for other months*

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4. Conclusion

In this study, the linkage between the activities of the BSISO and MJO and extreme rainfall events in Vietnam were explored using high-resolution satellite rainfall data (CMORPH) and BSISO and MJO indexes. The results can be summarized as below:

The BSISO is most active in summer, that primarily influence the variation of rainfall in North and South Vietnam. The phase 6 and phase 7 of BSISO-1 appear to be the two most important phases contributing to the increase of the probability of extreme rainfall in North and South Vietnam in summer. As autumn approaches, there are additional contributions of phase 5 and phase 8 on the occurrence of the extreme rainfall. Note that, the extreme rainfall display a southward propagation, from North to Central Vietnam in autumn. On the other hand, the phase 3, 6 and 8 of BSISO-2 has most important influence on the probability of extreme rainfall in summer and the phase 1, 3 and 4 play the most important role in modulating extreme rainfall in autumn.

In a different manner, the MJO is most active in autumn, that primarily influences the rainfall variations in Central Vietnam. In summer, the relationship of MJO and rainfall in Vietnam is not as clear, although decrease of rainfall is observed over North Central in some phase. The relationship become more dominant as autumn approaches. While the phase 1, 2, 7 and 8 are associated with dry condition in Vietnam, the propability of the extreme rainfall tends to increase in phase 3 to 6. Especially in phase 5, the propability display the highest values, indicating the close relationship between the MJO and extreme rainfall in Vietnam.

Competing interests

The authors declare that they have no conflict of interest

Acknowledgment

This research is funded by the Ministry of Natural Resources and Environment in project code 2022.06.07 entitled “Research and develop technology for intraseasonal forecasting (10 to 45 days) to predict severe rainfall and prevent natural disasters”

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Preprint. Discussion started: 13 August 2024

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