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Original Article

Multi-decadal trends and oscillations of Southeast Asian monsoon rainfall in northern Thailand

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Abstract

Understanding the rainfall patterns in northern Thailand is crucial for national water management since they affect several of Thailand's major rivers. This study aims to understand the trends of climatic variations in northern Thailand over the past 64 years (1951-2014). Pre- and post-monsoon rainfalls are considered to assess temporal Southeast Asian monsoon (SEAM) transition. Finally, multi-decadal oscillations of the rainfalls were evaluated using the Holt-Winters seasonal time-series analysis and their associations with the biennial oscillation, El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Madden-Julian Oscillation (MJO), and the Schwabe-Hale cycle were also discussed. The results showed a climatic trend toward earlier coming of the SEAM rainfall. The time-series and linear correlation analyses revealed that the ENSO, MJO, and solar irradiance influenced the rainfalls differently in the pre- or post-SEAM or both and they were also related to the periodicities of the extreme rainfall events. However, the IOD did not directly influence the local SEAM rainfall but it co-occurred with the ENSO.

Keywords: Southeast Asian monsoon, ENSO, Indian Ocean Dipole, Madden-Julian Oscillation, Schwabe-Hale cycle

1. Introduction

Asian monsoon systems consist of East, South, and Southeast Asian monsoons (Lau & Yang, 1997). The Southeast Asian monsoon (SEAM) starts, at the earliest, in early May over the Indochina Peninsular as a result of the convergence of southwesterly winds from the Bay of Bengal and easterly winds from the South China Sea (Lau & Yang, 1997; Zhang *et al.*, 2004). Increases in the sensible heat over the Indian subcontinent and the latent heat over the Indian Ocean during the local summer in April are the major factors driving the development of strong southwesterly winds associated with cyclonic vortices over the Bay of Bengal (Zhang *et al.*, 2004). However, SEAM does not start until the onset of cyclonic flow over the South China Sea which results in strong southeasterly winds (Zhang *et al.*, 2004). This SEAM influences the rainy season over the Southeast Asian (SEA) continent. The season begins as early as mid-May and continues until September with a 3- to 5-day cessation of rainfall between July and August, as a result of a low pressure trough moving northward from the Indian subcontinent (Krishnamurti & Bhalme, 1976).

The Asian monsoon including SEAM is currently weakening. Huijun (2001) found that after the end of the 1970's, westerly winds over the high latitude of Asia were enhancing but weakening over the mid-latitude. This indicated a weakening of the Asian monsoon circulation and decreasing rainfall over southern China and neighboring areas (Huijun, 2001). Ashfaq *et al.* (2009) also reported weaker south-westerly winds and cyclonic vertex strength over the Bay of Bengal that resulted in changes in the local Hadley circulation patterns. Furthermore, a delay in monsoon onset and an increase in monsoon break periods were also observed (Ashfaq *et al.*, 2009). Due to the results of the weakening

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Asian monsoons, the Indo-Chinese region is likely to experience droughts in the summers.

Natural forces could significantly induce inter-annual variations of the Asian monsoons with multiple time scales. Tropical biennial oscillation (~2.3 year mode) is caused by dynamic land-sea interaction and could be triggered by the El Niño Southern Oscillation (ENSO) (Meehl, 1997). This oscillation affects the Asian monsoons by providing conditions for a warm year (strong monsoon), followed by a cool year (weak monsoon) and vice versa (Meehl, 1997). ENSO cycles undoubtedly influence the temporal variability of the Asian monsoon system by changes in the Walker circulation associated with an anomalous sea surface temperature in the tropical Pacific Ocean (Barnett, 1991; Lau & Yang, 1997; Meehl, 1997; Wang *et al.,* 2005). Connections of ENSO with the Thai rainfall were reported in a previous study (Bridhikitti, 2013). Also, connections were reported with the central plain (Wikarmpapraharn & Kositsakulchai, 2010) and the northeast regions (Sriwicha *et al.,* 2016). Lau and Yang (1997) indicated that the delayed (advanced) onset of the SEAM could be related to warm (cool) events in the Pacific or the Indian Oceans or both. The short-term ENSO cycles are in a period of 3 to 8 years (Barnett, 1991; Meehl, 1997; Wang *et al.,* 2005). The anomalous changes in sea surface temperature in the Indian Ocean off Sumatra and the western Indian Ocean, the so-called Indian Ocean dipole (IOD), are also affecting SEA (Saji *et al.,* 1999), and they are generally co-incident with the development of ENSO (Izumo *et al.,* 2010). However, the IOD can be found without ENSO (Fischer *et al.,* 2005). Another major source of intraseasonal rainfall variability with a 40-50 day period in the tropical Indo-Pacific region is the Madden-Julian Oscillation (MJO) (Madden & Julian, 1972). Influence of the MJO on rainfall in SEA was observed by Xavier *et al.* (2014). Their work showed that convectively active phases of MJO (phases 2 to 4) can significantly increase the probability of extreme rain events on the SEA mainland (Xavier *et al.,* 2014). Furthermore, there are heliophysical factors that act on climatic variations with periodicities of every 11 years (Schwabe) and 22 years (Hale). These factors include variations of solar irradiance, galactic cosmic ray, and stardust flux in the solar system (Kasatkina *et al.,* 2007).

Northern Thailand is mainly a mountainous region and it contains the origins of many of the country's major rivers, including the Ping, the Wang, the Yom, the Nan, and the Chao Phraya Rivers. The watershed area of these rivers covers approximately 30% of the total area of the country (Komori *et al.,* 2012). Many great dams, including the Bhumibol (capacity of 13.5 billion m^3) and Sirikit Dams (9.5 billion m^3), are in this region. These two dams function significantly for irrigation, public water consumption, natural area conservation, and power generation (Komori *et al.,* 2012). Presently, the northern region is highly susceptible to landslides and flooding (Komori *et al.,* 2012). Furthermore, droughts during the dry season also happen in many parts of the country and some areas have both flooding and drought in the same years (Chitradon *et al.,* 2009; Pavelic *et al.,* 2012). An understanding of rainfall variability during the SEAM season is crucial for natural disaster mitigation and water security management in Thailand. This issue is challenging nowadays when both anthropogenic and natural factors are interacting.

This study aimed to investigate trends of climatic variations from long-term meteorological records in northern Thailand. Pre-and post-monsoon rainfalls are used to assess the temporal SEAM transition. Finally, the variability of the pre- and post-monsoon rainfalls is evaluated using the Holt-Winters seasonal time-series analysis and their associations with biennial, ENSO, IOD, MJO, and variations of solar irradiance are discussed.

2. Methodology

2.1. Studied area

Northern Thailand is located between 15.3° to 20°N latitude and 97.8° to 102°E longitude. It is characterized as a mountainous area oriented north-south in the upper part, covered with grass, croplands, forests, and a savanna low land in the lower part. It has a tropical climate that is influenced by the SEAM system. A typical rainy season is from mid-May to October, winter is from November to mid-February, and summer is from mid-February to mid-May. The average seasonal temperature ranges from 23.4 °C in winter to 28.1 °C in summer, and rainfall varies from 100.4 mm in winter to 943 mm in the rainy season.

2.2. Data description

Monthly rainfall data at 22 monitoring stations in northern Thailand were used in this study. The details of the stations and data requisition period are shown in Table 1. The data for years 1951–2014 were acquired from the Thai Meteorological Department. Spatial distribution of the stations could minimize uncertainty due to topographic variability since the reference stations are densely distributed in mountainous area in the northern part; whereas in the southern plain area they are few and far between (Figure 3).

The Southern Oscillation Index (SOI) is the anomalous spatial sea surface temperature gradient in the Pacific Ocean that departs from the 1981-2010 base period. The spatial sea surface temperature is the difference in standardized sea surface temperature at Tahiti and at Darwin. The SOI is used to indicate the ENSO signal. A positive SOI indicates La Niña and negative values indicate El Niño. In this study, the monthly SOI values used for the analysis were acquired online from the NOAA Center for Weather and Climate Prediction for the years 1951–2014.

The Dipole Mode Index (DMI) is the anomalous sea surface temperature gradient in the Indian Ocean that departs from the long-term mean. The gradient is between the western equatorial Indian Ocean and the southeastern equatorial Indian Ocean. The DMI is used to represent the IOD. A positive DMI is associated with a warmer Indian continent and a negative DMI is associated with a warmer SEA. The monthly DMI values used in this study were acquired interactively from the Japan Agency for Marine-Earth Science and Technology website for the years 1951-2007.

The tropical MJO in this study is defined from two real-time multivariate MJO indices, i.e. RMM1 and RMM2, available online from the Australian Weather and Climate

Table 1. Twenty-two meteorological stations used in this study.

Station code	Station Number	Station Name	Latitude, degree N	Longitude, degree E	Elevation, m MSL	Period of Record
303201	1	Chiang Rai	19.917	99.833	394	1951–2014
303301	2	Chiang RaiAgromet	19.871	99.783	416	1979–2014
300201	3	Mae Hong Son	19.300	97.833	268	1951–2014
300202	4	Mae Sariang	18.167	97.933	211	1951–2014
327501	5	Chiang Rai	18.783	98.983	305	1951–2014
327301	6	Mae Jo Agromet	18.917	99.000	316	1969–2014
331201	7	Nan	18.783	100.783	200	1951–2014
331301	8	Nan Agromet	18.867	100.75	264	1969–2014
331401	9	Tha Wang Pha	19.117	100.800	235	1970–2014
329201	10	Lamphun	18.567	99.033	296	1981–2014
328201	11	Lampang	18.283	99.517	243	1951–2014
330201	12	Phrae	18.167	100.167	162	1953–2014
351201	13	Uttaradit	17.617	100.100	63	1951–2014
373301	14	Si SampongAgromet	17.167	99.867	53	1969–2014
376201	15	Tak	15.883	99.117	124	1955–2014
376202	16	Mae Sot	16.667	98.550	196	1951–2014
376203	17	Bhumibol Dam	17.233	99.050	143	1969–2014
376401	18	Umphang	16.017	98.883	454	1977–2014
378201	19	Phitsanulok	16.783	100.267	45	1951–2014
379201	20	Phetchabun	16.433	101.150	114	1951–2014
379401	21	LomSak	16.767	101.250	142	1970–2014
379402	22	WichianBuri	15.650	101.117	68	1970–2014

Research Website at www cawcr.gov.au. The RMM1 and RMM2 are the first two Empirical Orthogonal Functions of the combined fields of near-equatorially-averaged zonal wind at 850 hPa, zonal wind at 200 hPa, and satellite-observed outgoing longwave radiation data. A time-series plot of RMM1 against RMM2 indicates eight MJO phases centered near the western Indian Ocean. More details on MJO can be seen in the work of Wheeler et al. (2004). Xavier et al. (2014) showed high forecast skills of extreme rainfall in the SEA mainland associated with MJO phases 2 to 4. Therefore, the monthly MJO in this study is the averaged daily MJO observed in phases 2 to 4.

A variation of solar irradiance in this study is implied from the time-series sunspot number. The sunspot number data for the years 1951-2014 was downloaded from the World Data Center-Sunspot Index and Long-term Solar Observations (WDC-SILSO), Royal Observatory of Belgium, Brussels.

2.3. Data analysis

Long-term annual changes in rainfall acquired at the 22 stations were estimated by subtracting the monthly values of the years 1952-2014 from the preceding year. A positive value suggests potential increasing trends and a negative value means the reverse.

Multi-decadal oscillations of pre- and post-SEAM rainfalls were indicated from differences between the actual rainfall and the estimated rainfall using the Holt-Winters seasonal algorithm. The Holt-Winters seasonal algorithm was applied to extract noise, trend, and seasonality contained in the time-series rainfall data. The trend is estimated using the exponential smoothing method (Brockwell & Davis, 2002). The algorithm requires estimations of the coefficients describing trend level, trend slope, and a seasonal component for any time periods. In this study, they were estimated to minimize the sum of the squared one-step errors (Brockwell & David, 2002). The rainfall data used for the time-series model simulation were acquired in May and October, apart from eight extreme weather years, which were 1997 (drought year with maximum monthly rainfall of 348 mm), 1998 (drought, 302 mm), 2004 (flood, 412 mm), 2005 (flood, 416 mm), 2006 (flood, 454 mm, 2007 (drought, 317 mm), 2011 (flood, 438 mm), and 2012 (drought, 381 mm). The model was later used to predict the rainfalls in the extreme weather years. Temporal periodicities considered in this study were from 2 to 25 years. The analysis used the ITSM2000 software provided by Brockwell and Davis (2002).

Correlations between the pre- and post-SEAM rainfalls and natural influencing factors, that included ENSO, IOD, MJO, and solar irradiance, were analyzed using linear correlation analysis and the results were spatially interpolated using the Kridging geostatistical technique with the Gaussian semi-variogram model through EasyKrig 3.0 software developed by Dezhang Chu (downloadable from the U.S. GLOBEC Georges Bank Project's Program Service and Data Management Office, the National Science Foundation). Furthermore, associations among the natural factors were analyzed using principal component analysis on a correlation matrix.

3. Results and Discussion

3.1. Multi-decadal trends of monthly rainfalls over northern Thailand

Figure 1 shows temporal patterns of monthly rainfall trends observed at ground stations in northern Thailand. The ground observations during the pre-SEAM period of May exhibited increasing rainfall (~+2.1 mm year^{-1} at 50th percentile), whereas those in the post-SEAM of October were decreasing at a median rate of ~-2.7 mm year^{-1}. The median rates for June to October were also negative with a maximum rate that appeared in August (-3.5 mm year^{-1}) (Figure 1). Even though the trends showed changes associated with large variations, these median rates could suggest the signs of an early initiating SEAM and then a weakening towards the end. This temporal rainfall variation pattern could be attributed to a reduction in land-sea thermal contrast due to the sea surface warming and Chinese mainland cooling, which would then promote weaker trade winds over the Eastern Pacific and consequently weaken the Asian monsoon circulation. A weakened Asian monsoon has been observed since the end of the 1970’s and was found to connect with the suppression of precipitation in South and East Asia, especially in boreal summers during the period of June to August (Huijun, 2001; Kwon *et al.,* 2007; Ashfaq *et al.,* 2009).

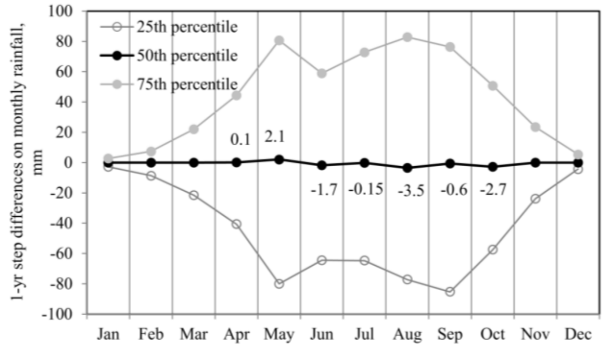

Figure 1. Spatial average 1-year step differences (the latter minus the former) of monthly rainfalls in northern Thailand.

3.2. Multi-decadal oscillations of pre- and post-SEAM rainfalls

The results obtained from Holt-Winters seasonal time-series analysis show that the pre-SEAM rainfall in May in the extreme weather years exhibited periodicities of 9, 12, and 14 years (Figure 2). However, the post-SEAM rainfalls in October had periodicities of 9, 12, 13, 16, 18, and 24 years. Meehl (1997) hypothesized that the tropical biennial oscillation (~2.3 year mode) affected the Asian monsoons by providing conditions of a warm year (strong monsoon), followed by a cool year (weak monsoon) and vice versa. Nevertheless, the results of this study, showed a weak association between the estimated and actual rainfalls for seasonal mode of every 2 years (Figure 2). This finding suggests that the biennial cycle did not substantially affect rainfall variability in the extreme weather years in this region.

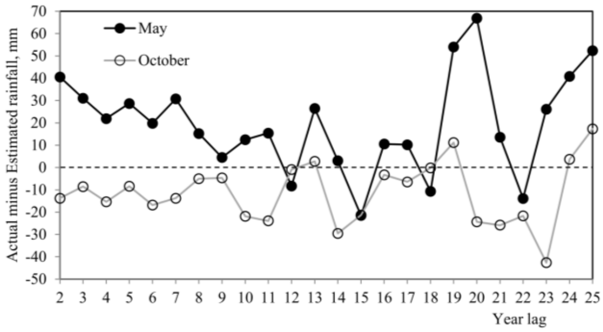

Figure 2. Spatial average differences of actual rainfall and the estimated rainfall using the Holt-Winters seasonal algorithm using various year lags from 2 to 25 years for monthly rainfalls in May (solid circle) and October (open circle) in the extreme weather years.

The short-term ENSO cycles have periodicities of 3 to 8 years and the long-term ENSO cycles have periodicities of 15 to 18 years. These cycles evidently interact with the tropical climate and Asian monsoons (Barnett, 1991; Mann & Park, 1994; Meehl, 1997; Wang *et al.,* 2005). Similarly, Buckley, and colleagues (2007) revealed that the ENSO modes of 2.2 to 4 years were contributing to drought in northwestern Thailand. In this study of northern Thailand, the long-term ENSO epochs corresponded well with the observed rainfall periodicities of 16 and 18 years for the post-SEAM in extreme weather years, but not for the pre-SEAM. However, the short-term ENSO modes were not found in the association. La Niña (El Niño)-associated high (low) rainfall in northern Thailand was clearly illustrated not only in the extreme years but also in any year (Figure 3). The average linear correlation coefficient between the rainfalls and SOI signal was high, r up to 0.48, in both pre-SEAM (May) and post-SEAM (October) periods. This finding suggested that the ENSO signal could be linked to trends of early SEAM formation and its suppression toward the ends in this region. Singhrattna *et al.* (2005) analyzed a 21-year moving correlation and they also found a strong relationship between summer rainfall monsoons (August to October) in Thailand and an ENSO signal during the post-1980 period.

The IOD did not show a significant correlation with the rainfall in northern Thailand (Figure 3). However, the IOD likely co-occurred with ENSO. The first principal components that explained the greatest variation among the observations suggested a positive correlation between the SOI and DMI in the pre-SEAM (May) but a negative correlation in the post-SEAM (October) (Table 2). The results for the post-SEAM, when the IOD usually peaks (Izumo *et al.,* 2010), is consistent

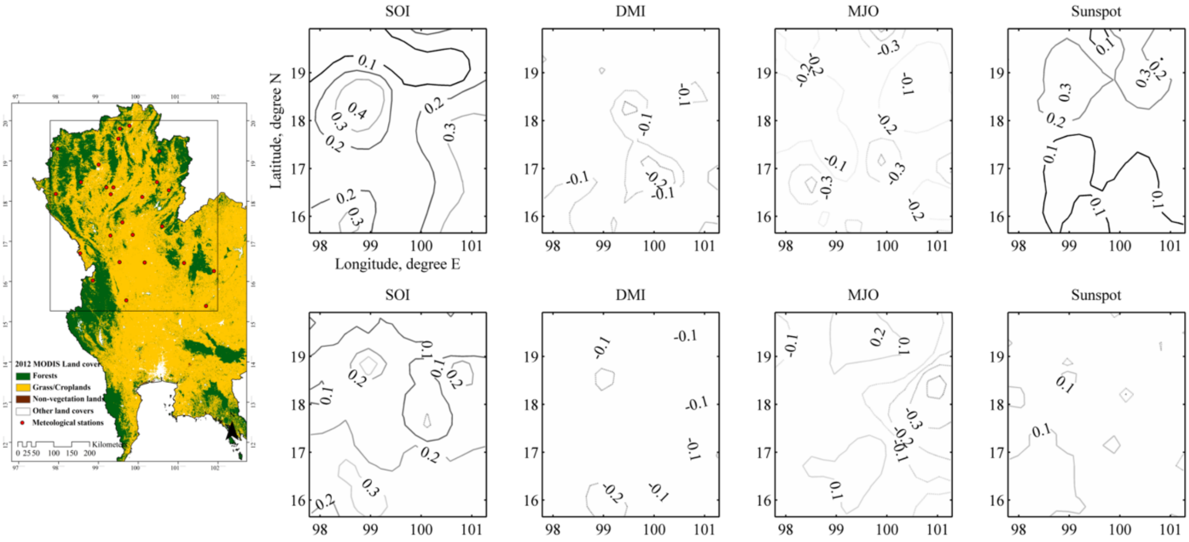

Figure 3. Linear correlation coefficients between monthly rainfall (May in the first row and October in the second row) with various influencing factors. Red dots in the map represent locations of the 22 meteorological stations.

Table 2. Eigenvectors of the principal components on each factor.

Components	May				October			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
SOI	0.679	0.038	0.153	0.717	–0.704	0.066	–0.124	0.696
DMI	0.565	–0.459	0.355	–0.586	0.707	–0.022	–0.098	0.700
MJO	–0.336	0.124	0.922	0.113	0.057	0.706	–0.693	–0.132
Sunspot	0.326	0.874	0.017	–0.360	0.031	0.704	0.704	0.090
Eigenvalue	1.62	1.00	0.93	0.45	1.65	1.26	0.745	0.35

with those reported in the work of Izumo *et al.* (2010) that showed a coincidence between positive phases of the IOD and El Niño (negative SOI) and between negative phases and La Niña (positive SOI). Furthermore, Izumo *et al.* (2010) found that the IOD not only co-occurred with ENSO but also led them. A negative (positive) phase of the IOD is a resourceful predictor of El Niño (La Niña) ~14 months before its peak. Similar to this study, a positive association between the SOI (eigenvector = 0.679) and IOD (eigenvector = 0.565) in the early SEAM (5 months ahead of October) was also observed (Table 2).

The MJO is one of the dominant modes of tropical intraseasonal variability, which has a time scale ranging from 20 to 90 days (Madden & Julian, 1974). A linear correlation between the active MJO signals in phase 2 to 4 and rainfall was significantly high in the pre-SEAM. The negative correlation coefficient (r up to -0.54,) suggested that the strong (weak) MJO phases were associated with low (high) rainfall in the pre-SEAM period in northern Thailand (Figure 3). Nevertheless, Xavier *et al.* (2014) showed that the active MJO phases could increase the probability of extreme rain events over the SEA mainland in the dry period from November to March.

Periodicities of 12 or 24 years were observed in the pre-and post-SEAM rainfalls in the extreme weather years (Figure 2). These frequency bands matched well with Schwabe-Hale periodicity that resulted from variations of solar irradiance (Kasatkina *et al.,* 2007). Haigh (1996) and Lohmann *et al.* (2004) showed evidential effects of solar irradiance variations in multi-decadal climate. The evidence included the discerned associations between the Schwabe cycle mode (11 years) related to solar irradiance fluctuations and atmospheric temperature variations, as well as the Atlantic multi-decadal mode related to ocean circulation. The 12- and 24-year modes are within the solar cycle variability, which are 10- to 12-year mode oscillations for the Schwabe mode (Shindell *et al.,* 1999), responsible for the 20-24 years of the Hale mode. Furthermore for any pre-SEAM events, the rainfall was highly correlated with the number of sunspots (r up to 0.44 in May) mainly in the upper part the northern Thailand, whereas the correlation in the post-SEAM was poor (Figure 3).

Additionally, a 9-year rainfall cycle was clearly identified in both the pre- and the post-SEAM (Figure 2). As previously mentioned, this time scale came later than the typical short-term ENSO epochs and also sooner than the typical Schwabe cycle. This rainfall periodicity needs further study in order to better understand rainfall variability in this region.

4. Conclusions

This study attempted to investigate the trends of climatic variations in northern Thailand over the past 64 years (1951-2014) from long-term meteorological records acquired from the Thai Meteorology Department. Pre- (May) and post- (October) monsoon rainfalls were used to assess the temporal SEAM transition. Finally, periodicities of the pre- and post-monsoon rainfalls were evaluated using Holt-Winters seasonal time-series analysis. Their associations with the biennial ENSO, IOD, MJO, and the Schwabe-Hale cycle related to solar irradiance variation were discussed.

The climatic trends in the pre-SEAM were toward higher rainfall (+2.1 mm year^{-1}). During the SEAM between June and October, rainfalls often decreased (-2.7 mm year^{-1} in October). Less rainfall in the post-SEAM was caused by a reduction in the land-sea thermal contrast which weakened the Asian monsoon circulation. This suggested the possibility of an early SEAM onset and a weakening SEAM towards the end of the season in northern Thailand.

A time-series analysis of the historical monthly rainfall using the Holt-Winters seasonal model showed multi-decadal oscillations of pre- and post-SEAM rainfalls in northern Thailand. Post-SEAM rainfall variations in the extreme weather years corresponded with the long-term ENSO cycles (15-18 years) and Schwabe-Hale mode (10-12 years and 20-24 years) as a result of the solar irradiance variations. The biennial cycle did not substantially affect rainfall variability in the extreme weather years in this region. In this post-SEAM, at which the IOD usually peaks, the El Niño events co-occurred with the positive phases of IOD and the La Niña co-occurred with the negative phases. In addition, a 9-year rainfall cycle was also clearly identified in this work but its explanation requires further studies.

The linear correlation analyses for any pre- and post-SEAM events showed that correlations between the rainfalls and the ENSO signal were high and the pre-SEAM rainfall correlated well with the number of sunspots mainly in the upper part of northern Thailand. However, the IOD did not show significant correlations with rainfalls in the same months, but correlated with the ENSO signal. Furthermore, tropical intraseasonal variability influenced by the active MJO phases had a role to play in the rainfall magnitude in the pre-SEAM. The strong (weak) MJO phases were associated with low (high) rainfall.

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