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Asian Summer Monsoon and its Associated Rainfall Variability in Thailand

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Abstract

The Asian monsoon is an important component of the Earth's climate. Its associated rainfall variability is a crucial factor for Thailand's socio-economic development, water resources and agricultural management. An analysis shows that the Thailand rainfall annual cycle is in phase with the Indian summer monsoon (ISM) and the western North Pacific summer monsoon (WNPSM). On the basis of the Empirical Orthogonal Function (EOF) analysis, the dominant spatial-temporal interannual variability in summer monsoon rainfall (Jun.–Sep.) during 1975-2006 could be explained by the first two EOF modes, accounting for 34% of the total variance. The EOF1 was spatially dominated by strong positive signals in the central and east, whereas the EOF2 exhibited dipole variability. The coefficient time series of EOF1 significantly correlated positively with ISM index, but negatively with WNPSM index. The results suggest that summer monsoon rainfall in Thailand is higher (lower) than normal during the strengthening (weakening) of ISM. In contrast, rainfall in the north-east (central) is surplus (deficit) during the strengthening (weakening) of WNPSM. These findings imply that, on an interannual time scale, ISM and WNPSM exert their influence to a different extent on summer monsoon rainfall in Thailand. A clear picture of linking mechanisms and interactions with another climate mode in the Indo-Pacific sector needs to be understood. This knowledge is essential for effectively adapting to climate-related hazards and rainfall extremes and for better management of water resource and agriculture in Thailand, especially under current/future warming conditions.

Keywords: Indian summer monsoon; Western North Pacific summer monsoon; rainfall variability; Thailand

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1. Introduction

The Asian monsoon is one of dynamic components of the Earth's climate, broadly comprising of three interlinked subsystems, the Indian, the East Asian and the Southeast Asian monsoons (Ramage, 1971; Kripalani and Kulkarni, 2001; Goswami, 2005; Wang *et al.*, 2005a). It embraces an overturning circulation associated with seasonally reversing surface wind and precipitation between the tropics and subtropics (Trenberth *et al.*, 2000; Goswami, 2005; Wang *et al.*, 2005a; Wang and Ding, 2008). These three monsoon subsystems are linked to one another in varying degrees, and display great variability due to differing land-ocean configuration and topographic forcing (Wang *et al.*, 2005a). Variability within the Indian sector and East Asia-western North Pacific (EA-WNP) regions, interactions among them and the extent to which they interact with other natural climate phenomena and anthropogenic-induced climate change are one of current research tropics.

The Asian monsoon exhibits a wide spectrum of variability ranging from daily to tectonic timescales (Wang *et al.*, 2005b). Its variability depends on many factors from regional air-sea interaction and land processes to teleconnection influences of global climate modes. Interannual/interdecadal variations are mainly caused by physical processes internal to the Earth's climate system such as the El Niño-Southern Oscillation (ENSO) and local atmosphere-ocean-land interaction, whereas the tectonic forcing shapes the land-ocean distribution and controls the formation of the Asian monsoon on geologic timescales (*e.g.*, Torrence and Webster, 1999; Wu and Wang, 2002; Wang *et al.*, 2003; Wang *et al.*, 2005b; Wang *et al.*, 2008).

The Asian monsoon variability has considerable societal and economical impacts on the local inhabitants and global economy. Large amplitude and aperiodic fluctuations of the Asian monsoon affect over one-third of the world's population inhabiting in the Asian monsoon countries (Wang *et al.*, 2005a). Year-to-year variations in the long-term seasonal mean precipitation over the Indian region are strongly related to food production. Over the last four decades, a modest decrease in the monsoon rainfall (e.g. 10% of long-term mean) led to a significant decrease in rice production over India (Swaminathan, 1987; Parthasarathy *et al.*, 1988). Frequency of occurrence of active/break spells within the season and extreme daily rainfall has adverse effects either as major floods or as major droughts, and hence influences agricultural production. Moreover, extremes in monsoon rainfall result in enormous economic loss and human misery (Gadgil and Rao, 2000).

Thailand is strongly affected by the Asian monsoon, as it is situated near the key regions where either atmospheric circulation or precipitation exhibits pronounced annual cycles and displays maximum intensity (Wang *et al*., 2003). Most places in Thailand show strong monsoonal signals, characterized by seasonal reversal of wind regime and a contrast between a rainy summer and a dry winter (Khedari *et al*., 2002; Singhratina *et al*., 2005). Thus, monsoon-driven rainfall variability is a crucial factor for Thailand's socio-economic development, water resources and agricultural management. The primary objective of this paper is to make a comprehensive review on key aspects of the Asian summer monsoon. It is further elaborated by addressing its impact on rainfall variability in Thailand. What synthetically derived in this review is based primarily on a large body of literature in combination with additional analysis of rainfall data in Thailand.

2. Overview of the Asian Monsoon Processes, Mechanisms and Interactions

A classical view of monsoon contemplates the land-sea thermal contrast and annual cycle of solar radiation as fundamental factors that establish monsoon. It is generally referred to as tropical and subtropical seasonal reversals in the surface winds, precipitation-evaporation and the associated transport of the latent energy, characterized by a deep baroclinic vertical structure with low-level convergence and upper-level divergence (Trenberth *et al*., 2000; Goswami, 2005). The monsoon in the Asian region can be interpreted as a result of northward seasonal migration of the east-west oriented precipitation belt from southern hemisphere in winter to northern hemisphere in summer. Rainfall is an essential meteorological parameter describing monsoon climate, rainfall distribution indicates the location of the atmospheric heat source that drives tropical circulation; thus, its variation reflects the variability of the entire monsoon circulation system (Wang *et al*., 2005a). From the monsoon climate perspective, the line of 105°E longitude, which runs along the eastern flank of the Tibetan Plateau and through Indo-China, provides a natural division between the Indian and EA-WNP monsoon climate (Wang *et al*., 2003).

While the EA-WNP monsoon and the Indian monsoon are intimately linked, there are many distinctive features between them. The Indian monsoon system is dominant by a distinct clockwise monsoon gyre centered in the equatorial Indian Ocean, which ties the Indian monsoon trough, Somalia jet and southeast winds associated with Mascarene High (Goswami, 2005; Wang *et al*., 2005a). In contrast, the EA-WNP monsoon is driven by a coupled tropical monsoon system consisting of the WNP monsoon trough or Inter-Tropical Convergence Zone (ITCZ), WNP Subtropical ridge and the East Asian Subtropical Front (Wang *et al*., 2003). The difference between the Indian and EA-WNP monsoons can be distinguished in terms of temporal evolution. The Indian rainy season reaches peaks in early June to mid-July, while maximum rainfall intensity over the EA-WNP sector is found in August. This phase difference in the annual rainfall cycle implies an eastward shift of convection centers from India to WNP during boreal summer (Wang *et al*., 2005a). Wang *et al*. (2003) pointed out that the differences in the annual cycle within these two subsystems result primarily from the effect of different land-ocean configuration and topography on the atmospheric response to annually varying solar forcing. Strong north-south thermal contrast between the heated Asian and cold southern Indian arises from the meridionally differential solar radiative heating over the India sector during boreal summer. Thermal effects of the elevated Tibetan Plateau heat source additionally strengthen this north-south temperature gradient. On the other hand, summer monsoon over the EA-WNP is driven by both the north-south thermal contrast between cold Australian land and warmer WNP and the east-west thermal contrast between heated East Asian landmass and relatively cold North Pacific Ocean (Wang *et al*., 2005a; Huang *et al*., 2004).

3. Indices for the Asian summer monsoons

All Indian Summer Rainfall Index (AIRI) defined by the seasonally averaged precipitation over the Indian subdivision during June to September has long been used as a measure of the Indian summer monsoon (Parthasarathy *et al*., 1992). AIRI is a good indicator of the strength of the monsoon rainfall only over India. To reflect the variability of the broad-scale Asian summer monsoon, Webster and Yang (1992) used a circulation index which is defined by the vertical wind shear between 850 and 200 hPa averaged over the south Asian

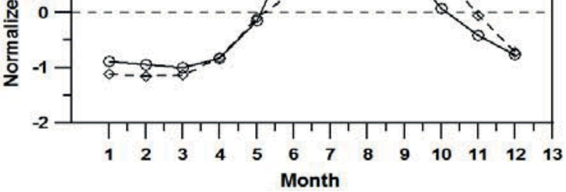

Figure 1. Annual cycles of the climatological mean ISM index (circles) and WNPSM index (squares). Monthly ISM/WNPSM values during 1975-2006 obtained from http://iprc.soest.hawaii.edu/~ykaji/monsoon/definition.html are used.

region (5°-20° N, 40°-110° E). Goswami *et al*. (1999) showed that the seasonal mean Webster-Yang index has a low correlation with AIRI. To measure variability of ISM and WNPSM separately, Wang and Fan (1999) and Wang *et al*. (2001) proposed useful dynamic convective indices based on theoretical considerations and empirical relationships between the lower-tropospheric winds (850 hPa) and two major convective heat sources over the Bay of Bengal and the Philippine Sea that drive the Asian summer monsoon. The dynamic indices are defined using the differences of 850-hPa zonal winds (between a southern region of 5°-15° N, 40°-80° E and a northern region of 20°-30° N, 70°-90° E for ISM, and between a southern region of 5°-15° N, 100° -130° E and a northern region of 20°-30° N, 110° -140° E for WNPSM). These defined indices reflect both the intensity of the tropical westerly monsoon and the lower-level vorticity anomalies associated with ISM and WNP monsoon troughs (Wang and Fan, 1999; Wang *et al*., 2001). Two convective indices are statistically insignificant at the 95% confidence level, but are highly correlated with the leading EOF modes of the low-level monsoon winds in the Indian and EA-WNP sectors. It is suggested that convection in the summer monsoon regions vary more or less independently (Wang and Fan, 1999; Wang *et al*., 2001). They, therefore, recommend two indices to be used to measure variations of ISM and WNPSM, respectively.

Annual cycles of the climatological mean ISM and WNPSM indices based on monthly data during 1975-2006 are shown in the Fig. 1. The climatological mean annual cycles of ISM and WNPSM indices are characterized by sharp transition at the beginning of the summer monsoon season (May) known as the *'onset'* of the Asian monsoon, followed by exceptionally heavy rain. There is a phase shift in the annual cycles of ISM and WNPSM indices, implying that the peak rainy season and fall transition in the EA-WNP sector are about one-two months later than their counterpart in the Indian sector. Hence, the Indian rainy season ends in late-September, while the EA-WNP rainy season retreats in late October. Interannual variability of the seasonal mean ISM and WNPSM indices averaged during June-September is indicated in Fig. 2. As shown in Fig. 2, amplitude of ISM index on an interannual timescale is, on average, about one half of that of WNPSM index, indicating that WNPSM is much more variable than ISM. Another prominent feature as previously documented by Wang *et al*. (2001) and Wang *et al*. (2003) is that amplitude of WNPSM index has increased significantly since 1980, while ISM index has displayed a decreased variability in the recent decades. Since the late 1970s when the North Pacific climatic regime shift and changes in El Niño properties have occurred (Trenberth and Hurrell, 1994; Zhang *et al*., 1997), however, ISM index exhibited large variability while WNPSM variability was moderate. This implies an out-of-phase change in interdecadal modulations of interannual variability of ISM and WNPSM. Based on power spectrum analysis, Wang *et al*. (2001) found different dominant periodicities of ISM and WNPSM. The spectrum of ISM has a leading energy peak at a period of 30 months representing a quasi-biennial rhythm in the Indian monsoon, whereas WNPSM shows two preferred timescales: one at the low-frequency ENSO timescale (about 50 months), and the other around 16 months (Wang *et al*., 2001).

4. ISM & WNPSM indices and Thailand rainfall variability relationships

In this section, ISM and WNPSM indices and high-quality monthly rainfall data from 107 meteorological stations distributed over Thailand were used to examine and address empirical association on an annual

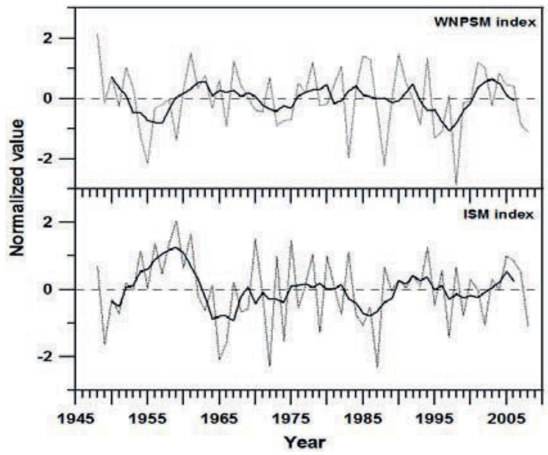

Figure 2. The normalized seasonal means (June-September) of ISM and WNPSM indices during 1948-2008. Seasonal means during 1948-2008 obtained from http://iprc.soest.hawaii.edu/~ykaji/monsoon/definition.html are used. The solid lines represent 5-yr running means.

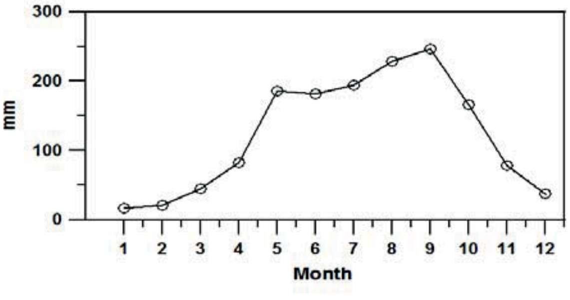

Figure 3. An annual cycle of climatological mean rainfall in Thailand. Monthly rainfall data from 107 stations during 1975-2006 are used to construct climatological means.

timescale and interannual spatio-temporal variability. Monthly rainfall data during 1975-2006 (31 years) were chosen to optimize data availability and spatial coverage. All data series were passed a multi-stage of objective quality control and homogeneity tests. More details of methodologies and procedures of quality control and homogeneity tests can be found in Limsakul and Goes (2008) and Limsakul *et al*. (2009).

To objectively extract the most important modes of interannual rainfall variability, EOF technique was employed. EOF has a long history of use in climatology, so the methodology will not be extensively reviewed here as numerous books and articles have provided a thorough review of the formation and properties of EOF (*e.g*., Preisendorfer, 1988; Emery and Thomson, 1997; Von Storch and Zwiers, 1999). The goal of EOF analysis is to consolidate most of the variance associated with a large dataset into a small number of physically interpretable patterns of variability. EOF technique generates three types of outputs: EOF components (also called component scores), eigenvectors (also termed loading) and eigenvalues. In climatological analysis, EOF components give the temporal variability of the isolated climate patterns or EOF modes. The patterns are illustrated by the loadings on EOF modes. These loading are usually presented either as correlation coefficient or variance between each time series and the associated EOF modes, and may be considered as a measure of the relative importance of each time series in the extracted EOF.

Fig. 3 shows seasonal variations of the climatologically monthly mean rainfall amounts averaged all stations in Thailand. Based on Fig. 3, it is suggested that the annual cycle of rainfall in Thailand is far from a smoothed seasonal variation. This climatologically annual cycle is in phase with ISM and WNPSM indices, and can be viewed as a mixed pattern of ISM and WNPSM signals characterized by two rainfall peaks and prominent intra-seasonal oscillations (ISOs) in between. A dry phase of monsoon rainfall in Thailand that occurs after the onset peak around June-July is a manifestation of *'grand'* monsoon break that has previously been identified to exist over ISM and WNPSM (Wang and Xu, 1997; Kang *et al*., 1999). Monsoon ISOs composed mainly of 10-20 and 30-60 oscillations are considered as a fast annual component superposed on a slow annual cycle (Goswami, 2005). Major ISO cycles in the Asian monsoon regions have been discussed in details in Wang and Xu (1997). It should be noted that climatological rainfall maximum in Thailand roughly corresponds to that of WNPSM index (Figs. 1 and 3).

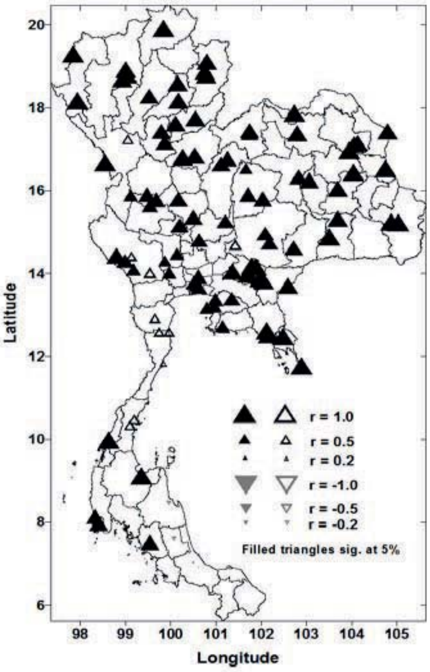

Figure 4. Correlation coefficients of climatologically annual cycles between rainfall and ISM index. Analysis is based on monthly data during 1975-2006.

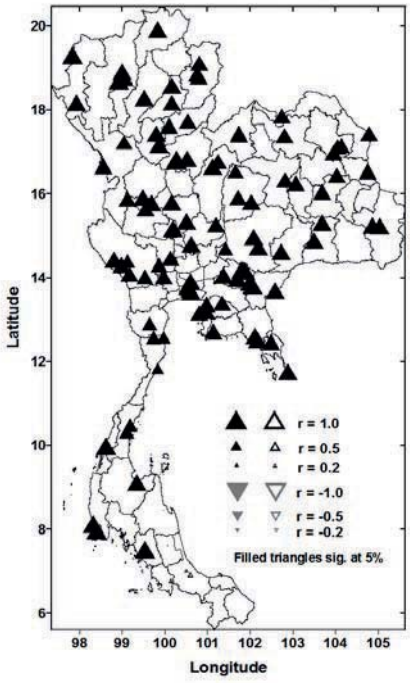

Figure 5. Correlation coefficients of climatological annual cycles between rainfall and WNPSM index. Analysis is based on monthly data during 1975-2006.

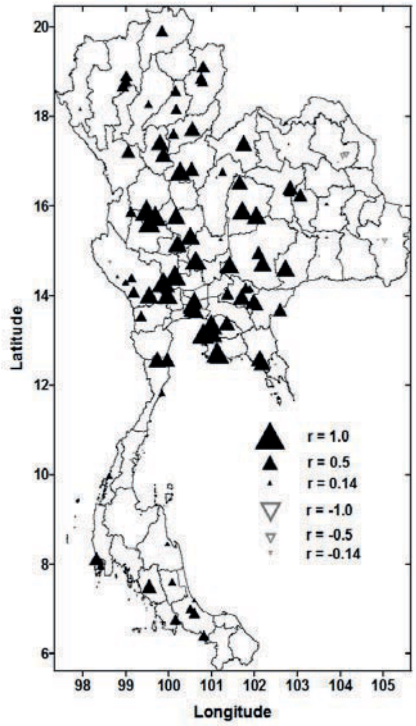

Figure 6. Loadings on the first EOF mode of summer monsoon rainfall (June-September) during 1975-2006. The loadings are correlation coefficients between each time series and the first EOF mode. The sizes of cycles are proportional to correlation coefficients.

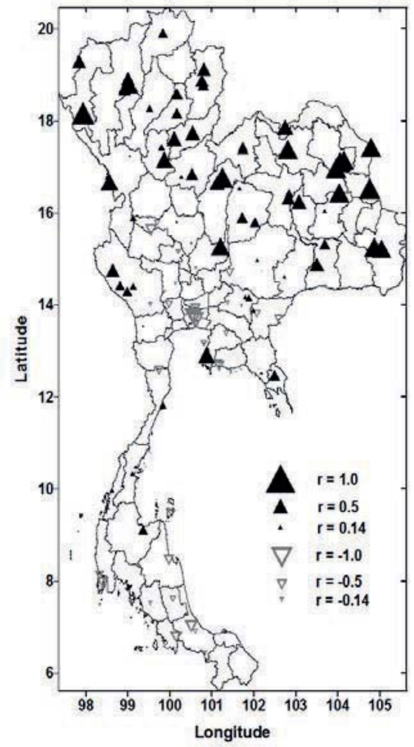

Figure 7. Loadings on the second EOF mode of summer monsoon rainfall (June-September) during 1975-2006. The loadings are correlation coefficients between each time series and the second EOF mode. The sizes of cycles are proportional to correlation coefficients.

Correlation maps based on analysis of climatologically annual cycles between each rainfall series in Thailand and ISM & WNPSM indices reveal a close association between annual rainfall variability and ISM & WNPSM (Figs. 4-5). 82% and 93% of all climatologically annual rainfall series have significantly positive correlations with ISM and WNPSM indices, respectively. This indicates that annual rainfall variability generally exhibits stronger correlations with WNPSM index than ISM index. Based on correlation analysis, it is reasonable to suggest that ISM and WNPSM are an important climate mode that exerts substantial influence on annual rainfall variability over Thailand.

EOF-based results of summer monsoon rainfall (June-September) in Thailand during 1975-2006 showed that first and second EOF modes accounted for 20% and 14% of the total variance, respectively. The remaining EOF modes explain considerable less with each EOF capturing less than 10%. Spatial structures as presented by the loadings on the first two EOFs modes are graphically illustrated in Figs. 6-7. To delineate more a clear picture of local characteristics, the first two EOFs modes are rotated using VARIMAX (Aldrian and Susanto, 2003). Spatial pattern of the leading EOF mode is characterized by strong positive signals in the central, east and lower part of the north, with weak negative association in the region along the Mekong River (Fig. 6). Whereas the second EOF mode displays a somewhat distinct pattern which exhibits dipole variability. There are noticeably positive associations located in the north-east and upper part of the north. In contrast, negative signals are mostly confined in the central and southern peninsular. The coefficient time series of the leading EOF mode significantly positively correlated with ISM index but significantly negatively correlates with WNPSM index, with correlation coefficients of 0.42 and -0.53, respectively for the 32-yr period from 1975 to 2006 (Figs. 8-11). Positive correlations with comparable coefficients between summer rainfall variations over north-west Thailand and the Indian rainfall was also mentioned by Kripalani and Kulkarni (1997). Such correlations indicate that summer monsoon rainfall amounts in the central, east and lower part of the north tend to be higher than normal during stronger ISM years, but are lower than usual during the years when ISM is weakening. However, changes in summer monsoon rainfall amounts in those regions appear to have opposite polarities during strengthening and weakening of WNPSM. The time-dependent amplitude series of the second EOF mode showed only a significant relation to WNPSM index (Figs. 9-11). A significantly negative correlation between the coefficient time series of the second EOF mode and WNPSM index implies that, during stronger WNPSM years, summer monsoon rainfall amounts enhance in the central and south but deficit in the north-east and upper part of the north. However, the opposite change in summer monsoon rainfall amounts in those regions takes place during the other phase of WNPSM. On the basis of EOF analysis, it is worth noting that both ISM and WNPSM exert influence to a different extent on interannual variability of summer monsoon rainfall in Thailand. Evidence of significant correlations between the coefficient time series of both first and second EOF modes and WNPSM index also provides another vital clue that WNPSM has greater impacts on interannual summer rainfall in Thailand than ISM.

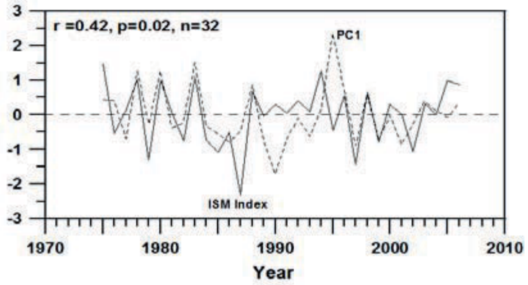

Figure 8. Correlation between the coefficient time series of the first EOF mode and ISM index

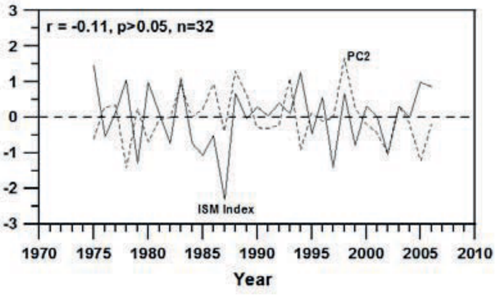

Figure 9. Correlation between the coefficient time series of the second EOF mode and ISM index

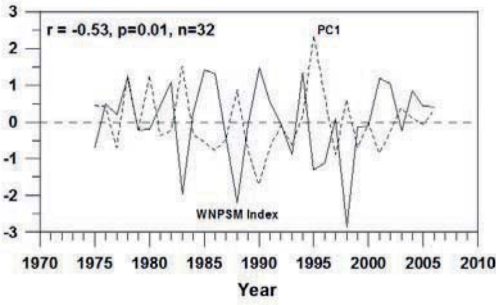

Figure 10. Correlation between the coefficient time series of the first EOF mode and WNPSM index

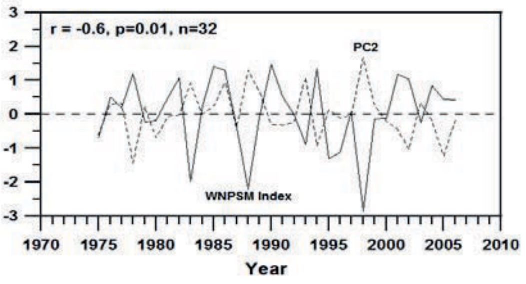

Figure 11. Correlation between the coefficient time series of the second EOF mode and WNPSM index

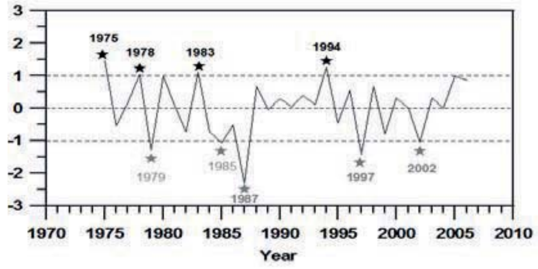

Figure 12. Strong and weak monsoon years which are defined as ISM index greater (less) than one standard deviation

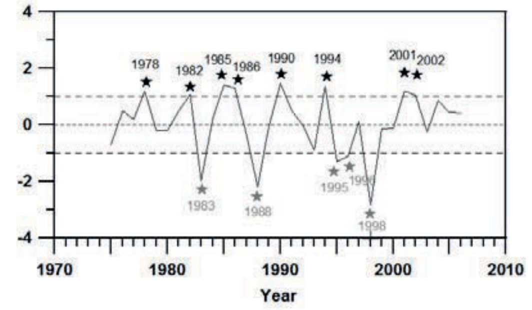

Figure 13. Strong and weak monsoon years which are defined as WNPSM index greater (less) than one standard deviation.

5. Thailand rainfall variability during monsoon extremes

To further illustrate spatial rainfall variability during monsoon extremes, composite analysis of rainfall in Thailand for strong and weak monsoon years was employed. The strong and weak monsoon years were selected based on ISM and WNPSM indices. The criterion used by Wang *et al*. (2001) was applied to define strong (weak) monsoon years, which ISM and WNPSM indices are greater (less) than one standard deviation.

On the basis of this criterion, there were 4 strong and 5 weak ISM during 1975-2006, while 8 strong and 5 weak WNPSM occurred during the same period (Figs. 12-13). In general, the anomalies associated with the strong and weak ISM tend to have opposite polarities, characterized by widespread enhanced rainfall in Thailand during strong ISM but an overall decrease during the other extreme phase of ISM (Figs. 14-15). However, the anomalies associated with the strong and weak WNPSM showed different spatial patterns, which are out-of-phase changes between the central and north-east (Figs. 16-17). This feature is consistent well with the EOF-based results. During strong WNPSM, the rainfall noticeably decreased in the central but tended to increase in the north-east (Fig. 16). However, rainfall remarkably increased in the central and south, but generally declined in the upper part of the north-east during the weak WNPSM (Fig. 17). Changes in low-level circulation and associated rainfall in the Asian monsoon region were also documented by Wang *et al*. (2001). They showed that anomalous circulation pattern during a strong ISM including increased rainfall over India and the Bay of Bengal, an enhanced low-level cross-equatorial gyre over the tropical Indian Ocean and enhanced upper-level Tibetan Plateau and Mascarene highs all contributed to a strengthening of the entire ISM circulation system. In sharp contrast, changes during a strong WNPSM which are increased rainfall over the South China Sea and WNP, a low-level elongated cyclonic circulation anomaly in the subtropical WNP and enhanced upper-level divergence over the Philippine Sea indicate a strong coupling between WNPSM and EASM circulations, and consequently a strengthening of the entire WNP-EASM system (Wang *et al*., 2001).

6. ENSO-Asian summer monsoon interactions and Thailand rainfall variability

One notable connection with interannual variability of the Asian summer monsoon is that with ENSO. Wang *et al*. (2005a) pointed out that large changes in tropical Pacific thermal configurations and conditions could significantly alter intensity of WNPSM but not ISM. It has also been documented that a strong (weak) ISM tends to occur in developing phases of El Niño (La Niña) episodes, whereas, a strengthening (weakening) of WNPSM takes place in the decaying year of the cold (warm) ENSO events (Wang *et al*., 2001). Since the late 1970s when the North Pacific climatic regime shift and changes in El Niño properties have occurred (Trenberth and Hurrell, 1994; Zhang *et al*., 1997), WNPSM has become more variable, but its relationship with El Niño remained steady (Wang *et al*., 2001; Wang *et al*., 2008).

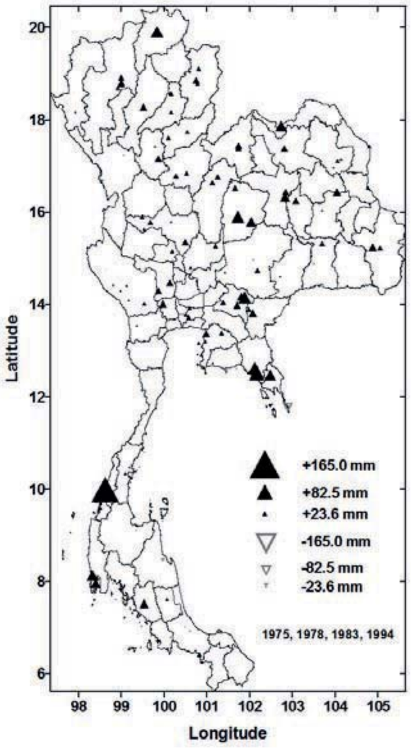

Figure 14. Composite rainfall map for strong ISM years.

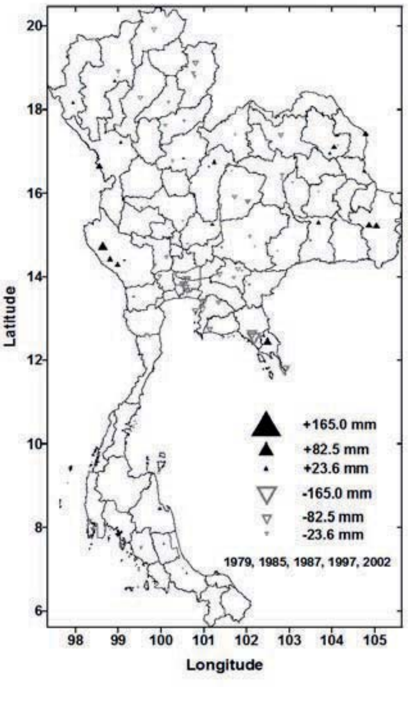

Figure 15. Composite rainfall map for weak ISM years

On the other hand, ISM has become less variable and its linkage with El Niño dramatically weakened (Kumar *et al*., 1999; Chang *et al*., 2000; Wang *et al*., 2008). At the same time, a notable change between the East Asian monsoon and ENSO in the northern China and Japan has emerged (Wu and Wang, 2002; Wang *et al*., 2008), and the negative correlation between Indonesian monsoon rainfall and ENSO has become enhanced since the late 1970s (Chang *et al*., 2004; Wang *et al*., 2008). It is generally accepted that the ENSO-Asian summer monsoon interactions are primarily via the change in the equatorial Walker circulation influencing the regional Hadley circulation associated with convective heat sources of the Asian summer monsoon (Goswami, 1998; Lau and Nath, 2000). Juneng and Tangang (2005) showed that the Southeast Asia (SEA) rainfall anomalies depend strongly on phases of El Niño (La Niña). Previous studies have also demonstrated that ENSO-monsoon rainfall connectivity in the SEA exhibits considerable spatial and strong seasonal variations (*e.g*., Hastenrath, 1987; Ropelewski and Halpert, 1996; Haylock and McBride, 2001; Hendon, 2003; Aldrian and Susanto, 2003; Chang *et al*., 2003; Tangang and Juneng, 2004). In general, a prolonged drought condition in SEA region is associated with El Niño while severe floods tend to be associated with La Niña. Singhrattna *et al*. (2005) found that spectrum of summer monsoon rainfall in the central and northern regions of Thailand shows a significant band of interannual/interdecadal timescales, and its variability is linked to ENSO especially in the recent decades when strong relationship has been evident. They hypothesized that ENSO teleconnections depend on the sea surface temperature configuration in the tropical Pacific Ocean, that is, an eastern Pacific-based El Niño pattern tends to place the descending limb of the Walker circulation over the Thailand–Indonesian region, thereby significantly reducing convection and consequently, rainfall over Thailand. These finds are in line with the study of Limsakul *et al*. (2007), illustrating that interannual rainfall amounts in Thailand tend to be greater (lower) than normal during the La Niña (El Niño) phase of ENSO while the unusual and persistent deficit in rainfall amounts over the last three decades has been observed. They suggested that the recent drought-like condition in Thailand has been closely associated with the shift in ENSO towards more El Niño events since the late 1970s, and coincided with a warming condition.

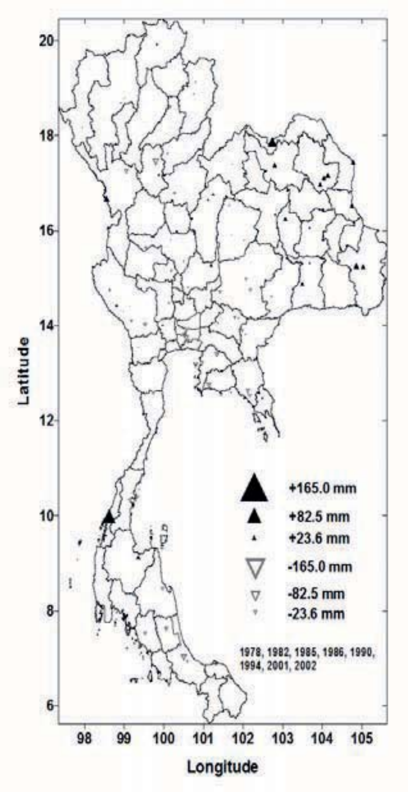

Figure 16. Composite rainfall map for strong WNPSM years.

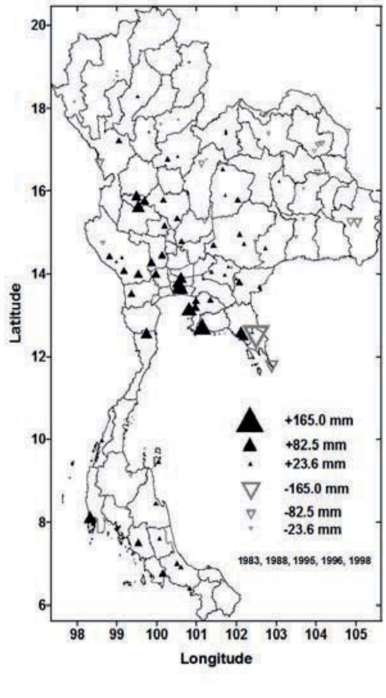

Figure 17. Composite rainfall map for weak WNPSM years.

7. Concluding remarks

In this report, we make a comprehensive review on key aspects of the Asian monsoon with special attention paying to describe ISM and WNPSM, and relate these two monsoon subsystems using the useful dynamic convective indices to Thailand rainfall variability on annual and interannual timescales. Based on empirical evidence, associations and possible links are then highlighted. As yet, advances have been made to substantially understand the Asian summer monsoon processes and mechanisms, variability over time and space and interactions among them and the extent to which they interact with other regional and global climate modes. An array of scientific papers related to this matter has been constantly published. Special volume of the global monsoon system : research and forecast has been compiled from the Third World Meteorological Organization (WHO) International Workshop on

Monsoon, and recently made available to scientific communities by Change et al. (2005) and Secretariat of the WMO.

From a circulation perspective, the Asian summer monsoon is dominated by the lowest baroclinic mode, which is stimulated by the latent heat released in the middle troposphere. In the south Asian region, two of major areas of intensive convective activity associated with ISM and WNPSM are located near the Bay of Bengal and in the vicinity of the Philippines. The enhanced convection over the Bay of Bengal and Indian continents is coupled with reinforced monsoon circulation west of 80°E, In contrast, the enhanced convection in the vicinity of the Philippines is consistent with intensified monsoon circulation primarily east of 80°E over southeast Asian including Indochina peninsula and maritime continent. It has documented that change in the Bay of Bengal convection associated with ISM has planetary-scale implication, whereas change in Philippine convection has primarily a regional impact (Wang and Fan, 1999). Available evidence indicates that these two monsoon subsystems display great variability over time and space, due to different land-ocean configurations and topographic forcing (Wang *et al*., 2001; Wang *et al*., 2003). They also interact to different extent with other climate phenomena especially ENSO.

Empirical results suggest that ISM and WNPSM are an important climate mode that exerts substantial influence on annual rainfall variability over Thailand. The climatologically annual cycle of rainfall in Thailand can be viewed as a mixed pattern of the ISM and WNPSM signals. Correlation analysis further indicates that annual rainfall variability generally exhibits stronger association with WNPSM than ISM. On the basis of EOF analysis on summer monsoon rainfall in Thailand during 1975-2006, it is worth noting that both ISM and WNPSM induce to a different extent on interannual variability of summer monsoon rainfall in Thailand. In the leading EOF mode, it is found that summer monsoon rainfall amounts in the central, east and lower part of the north tend to be higher than normal during stronger ISM years, but are lower than usual during the weakening ISM years. However, changes in summer monsoon rainfall amounts in those regions appear to have opposite polarities during strengthening and weakening of WNPSM. Dipole variability as captured by the second EOF and significantly correlated with WNPSM implies that summer monsoon rainfall amounts enhance in the central and south but deficit in the north-east and upper part of the north during stronger WNPSM years. Evidence of significant correlations between the coefficient time series of both first and second EOF modes and WNPSM index provides another vital clue that WNPSM has greater impacts on interannual summer rainfall in Thailand than the ISM. Composite analysis of Thailand rainfall for strong and weak monsoon years reveals consistent feature with the EOF-based results. In general, the anomalies associated with the strong and weak ISM tend to have opposite polarities, characterized by widespread enhanced rainfall in Thailand during strong ISM but an overall decrease during the other extreme phase of ISM. However, the anomalies associated with the strong and weak WNPSM show different spatial patterns, which are out-of-phase changes between the central and north-east. During strong WNPSM, the rainfall noticeably decreases in the central but tends to increase in the north-east. However, rainfall remarkably increases in the central and south, but generally declines in the upper part of the north-east during the weak WNPSM.

These findings imply that the two inter-linked Asian monsoon subsystems act in complex manners to modulate and enhance summer monsoon rainfall in Thailand. A clear picture of linking mechanisms and interactions with the natural/anthropogenic-induced climatic changes needs to be further studied. In addition, changes in winter monsoon especially along the Gulf of Thailand where monsoon variables have been observed to become stronger in the recent years deserve to be better understood. Research areas should be given special attention including changes in onset/withdrawn and their interannual variability, intraseasonal variation, changes in extreme events associated with summer and winter monsoon variations and interactions with ENSO and Indian Ocean Dipole (IOD). This knowledge is essential for instituting effective adapting strategies against rainfall extremes and better management of water resource and agriculture in Thailand, especially under current and future regimes of a warming condition and a changing climate.

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