EnvironmentAsia
The international journal published by the Thai Society of Higher Education Institutes on Environment

Available online at www.tshe.org/ea/index.html
EnvironmentAsia 10(2) (2017) 162-176
DOI

Climatology and Spatio-Temporal Variability of Wintertime Total and Extreme Rainfall in Thailand during 1970-2012

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Abstract

This study aims at examining wintertime (December-January-February; DJF) climatology and spatio-temporal variability of Thailand's total and extreme rainfall during 1970-2012. Analysis showed that the area along the Gulf of Thailand's eastern coast not only received much amount of rainfall but also underwent great extremes and variances during the northeast monsoon (NEM) winters. Empirical Orthogonal Function (EOF) analysis similarly revealed that the leading mode of each DJF total or extreme rainfall index was marked by maximum loadings concentrated at the stations located at the exposed area of the NEM flow.

Correlation analysis indicated that the leading EOF mode of DJF total and extreme indices in Thailand tended to be higher (lower) than normal during strong (weak) East Asian Winter Monsoon (EAWM). On longer timescales, the recent decadal change observed in the leading EOF mode of all rainfall indices has been coincident with re-amplification of the EAWM taken place since the early/mid 2000. The leading EOF mode of DJF total and extreme rainfall indices in Thailand also exhibited strong correlations with the tropical-subtropical Pacific Ocean surface temperatures. It was characterized as the Pacific Decadal Oscillation (PDO)/El Niño Southern Oscillation (ENSO)-related boomerang-shaped spatial patterns, resembling the typical mature phases of the La Niña event and the PDO cool epoch. Based on our analysis, it is reasonable to believe that the anomalies of the NEM and other key EAWM-related circulations are likely to be the possible causes of DJF total and extreme rainfall variations in Thailand. In addition, the ENSO and PDO as the primary global atmospheric external forcing are likely to exert their influence on wintertime Thailand's climate via modulating the EAWM/NEM-related circulations anomalies.

Keywords: climatology; spatio-temporal variability; northeast monsoon; East Asian winter monsoon

1. Introduction

During boreal winter, the surface circulations over the Southeast Asia (SEA) are mainly governed by the NEM which is an integrated part of the planetary-scale EAWM system and interact actively with ocean and atmosphere in the tropical and extratropical regions (e.g., Juneng and Tangang, 2010; Wang *et al*., 2010; Huang *et al*., 2012; Siew *et al*., 2014; Sooktawee *et al*., 2014; Wang and Chen, 2014a). The northeasterly monsoon winds often transport abundant moisture from the South China Sea (SCS) which results in wetter condition over the maritime SEA during boreal winter and brings about 50% of annual total rainfall to some parts of the SEA (Cheang, 1987; Wong *et al*., 2009; Juneng and Tangang, 2010; Siew *et al*., 2014). A succession of cold surges originating from the cold and dry air outbreak of the Siberian High is an important synoptic feature associated with the intensified EAWM and NEM that always leads to a sharp temperature drop and severe weather extremes and climate disasters (Chen *et al*., 2004; Tangang *et al*., 2008; Hong and Li, 2009; Juneng and Tangang, 2010; Huang *et al*., 2012).

Accumulated evidence reveals that the active and inactive NEM causes substantial social and economic impacts (e.g., Tangang *et al*., 2008; Juneng and Tangang, 2010; Li and Yang, 2010; Wang *et al*., 2010; Siew *et al*., 2014). Anomalous fluctuations of the NEM can frequently bring not only hazardous weather but also heavy rainfall events and severe flooding to the SEA. For example, Wangwongchai *et al*. (2005) showed that the exceptionally heavy rainfall event occurred in Hat Yai municipality, southern Thailand in November 2000 was induced by the cold surge associated with the strong northeasterly winds. It has been further documented that the mid-December 2006 to late January 2007 severe flood happened in southern Peninsular Malaysia was caused by the stronger-than-usual NEM (Tangang *et al*., 2008). This destructive flood was the worst hydro-meteorological disasters in a century, causing the number of people evacuated in excess of 200,000 with 16 reported deaths and economic loss of about USD 500 million (Tangang *et al*., 2008). Record-breaking, long-persisting extreme cold and northerly anomalies over the SEA were observed during the winter season in 2008, resulting in numerous agriculture and fishery losses (Hong and Li, 2009). A series of flash floods hit different areas of southern Thailand was also recorded in the winter months of 2010 and 2016 (Floodlist, 2017; Wikipedia, 2017). Therefore, better understanding of variations associated with the EAWM and NEM is of particular significance for the SEA where is especially prone to climate-induced hydro-meteorological disasters and the inhabitants of the region depend strongly on the monsoonal rainfall for water resources, agriculture and other social-economic activities.

Despite its importance, the EAWM and NEM influence on wintertime climate over the SEA has been studied less extensively compared to their summer counterparts (e.g., Juneng and Tangang, 2005; 2010; Takahashi and Yasunari, 2006; 2008; Misra and DiNapoli, 2014; Siew *et al*., 2014; Loo *et al*., 2015). Thus, how this extratropical planetary-scale phenomenon affects local tropical weather poses a scientific challenge and public concern, especially because of the potential for the monsoonal changes under anthropogenically forced warmer climate. This study analyzed climatology and spatio-temporal variability of wintertime total and extreme rainfall in Thailand. Their possible relationships with the EAWM index (EAWMI) which represents primary large-scale climate phenomenon influencing Thailand's wintertime climate as well as spatial correlations with sea surface temperatures (SSTs) in the tropical-extratropical domain of the global ocean were further examined.

2. Data and Methods

2.1 Daily rainfall data

Daily rainfall data measured from the surface weather stations of Thailand Meteorological Department (TMD) covering the period from 1970 to 2012 provided the basis for this study. To analyze total and extreme rainfall indices, rather strict criteria were applied in selecting station data. The criteria include the following: (i) a month considered as having sufficiently complete data if there are less than or equal to 5 missing days; (ii) a year is considered complete if all months are complete according to item (i); (iii) a station is considered to have complete data if the entire record has less than or equal to 5 missing years according to (ii) (Moberg and Jones, 2005; Griffiths and Bradley, 2007; Chu *et al*., 2010). Based on these criteria, a total of 72 stations were selected for the subsequent quality control and homogeneity tests. Overall, the percentage of missing data ranges from 0% to 1%, with more than 50% of the total stations that do not have any missing values.

2.2 Quality control and homogeneity checks

All selected records were subjected to a further statistical quality control (QC) algorithm following the method outlined in Klein Tank *et al*. (2009). Outliers identified by the QC check were then evaluated by comparing their values to adjacent days and to the same day at nearby stations before being validated, edited or removed. As a second step, the quality-controlled records were assessed for homogeneity, based on the penalized *t*-test (Wang *et al*., 2007) and the penalized maximal *F*-test (Wang, 2008) using the RHtestsV4 software developed by the World Meteorological Organization-Commission for Climatology (WMO-CCI)/World Climate Research Program (WCRP)/Climate Variability and Predictability (CLIVAR) project's Expert Team on Climate Change Detection and Indices (ETCCDI). The method is capable of identifying multiple step changes in time series by comparing the goodness of fit of a two-phase regression model with that of a linear trend for the entire base series (Wang *et al*., 2007; Wang, 2008). In this study, homogeneity analyses were performed on monthly total rainfall series using a relative test in which the candidate series was examined in relation to a reference series (e.g., Aguilar *et al*., 2003; Cao and Yan, 2012). A set of homogeneous neighboring stations that well correlated with the candidate station was used as the reference series (Aguilar *et al*., 2003). Homogeneity testing identified no stations with significant step changes in their monthly total rainfall series. On the basis of the quality control and homogeneity tests, a set of 72 high-quality daily rainfall records (Fig. 1) were prepared for the calculation of total and extreme rainfall indices for winter seasons. Each winter season consists of 3-month period from the December of the current year to the January and February of the following year (DJF), which results in 42 winters (1970-2012). Here the winters of 1970 and 2011 refer to the 1970/1971 and 2011/2012, respectively.

2.3 Total and extreme rainfall indices

Six total and extreme rainfall indices for DJF period including rainfall variance (R_variance) and the number of wet days (W_day; days with rainfall ≥1 mm) which most indices have been recommended by the WMO-CCI/WCRP/CLIVAR project's ETCCDI, were computed for each of the stations (Zhang *et al*., 2011). Data were processed using the ETCCDI's RClimDex software. For the percentile-based index of very wet day winter rainfall (R95p), the methodology uses bootstrapping to calculate the values for the base period so that there is no discontinuity in the time series of the index at the beginning or end of the base period (Klein Tank *et al*., 2009; Zhang *et al*., 2011). Table 1 provides a description of six total and extreme rainfall indices. The R95p and maximum 5-day winter rainfall amount (RX5day) indices characterize the magnitude of intense rainfall events, whereas, R10 is index of the frequency of heavy rainfall events for a given winter season.

2.4 Analytical methods

Anomaly series of each DJF total or extreme rainfall index was separately analyzed by the EOF method to objectively identify its most dominant spatio-temporal modes. The EOF is descriptive multivariate statistics among the most widely and extensively methods used in the climatological data analysis (e.g., Preisendorfer, 1988; von Storch and Zwiers, 1999; Hannachi *et al*., 2007). It is based on a linear transformation to decompose a space-time field into orthogonal basis functions (eigenvalue/eigenvector) of physically interpretable patterns of variability, while retaining as much as possible of the variance presented in the original data sets (Preisendorfer, 1988; von Storch and Zwiers, 1999; Hannachi *et al*., 2007). The primary goal of the EOF is to achieve a decomposition of a discrete and continuous space-time field X (t, s), where t and s denote respectively time and spatial position, as

$$X(t,s) = \sum_{k=1}^{M} c_k(t) u_k(s) \tag{1}$$

where M is the number of modes contained in the field, using an optimal set of basis functions of space $U_k(s)$ and expansion functions of time $c_k(t)$. In practice, the EOF technique generates three types of outputs: EOF coefficients (also called component scores), eigenvectors (also termed loading) and eigenvalues. In the climatological analysis, EOF coefficients give temporal variability of the isolated climate patterns or the EOF modes. The spatial patterns are illustrated by the loadings on the EOF modes. These loadings are usually presented either as correlation coefficient or variance between each raw data series and the associated EOF modes.

2.5 EAWM and SST relationship analysis

To examine the relationships between DJF total and extreme rainfall indices and large-scale wintertime climate variations, Spearman's rank-order correlation between the EOF1 coefficient time series of each rainfall index with the EAWMI time series was

Table 1. Definitions of the six ETCCDI-recommended indices for total and extreme rainfall during winter season (DJF months) examined in this study.

Index	Descriptive name	Definitions	Units
PRCPTOT	winter total rainfall amount	total rainfall amount of wet days during DJF period	mm
R_variance	winter rainfall variance	variance of daily rainfall during DJF period	mm^2
W_day	number of winter wet days	counts of days during DJF period when RR ≥ 1 mm	days
R10	number of winter heavy rainfall days	counts of days during DJF period when rainfall ≥ 10 mm	days
R95p	very wet day winter rainfall	total rainfall of RR > 95^{th} percentile during DJF period	mm
RX5day	winter maximum 5-day rainfall amount	monthly maximum 5-day rainfall during DJF period	mm

A wet day is defined as a day when RR ≥ 1 mm.

calculated. The EAWMI based on the normalized area-averaged winter mean sea level pressure (SLP) over Siberia (40°-60° N, 70°-120° E), the North Pacific (30°-50° N, 140° E-170° W), and the Maritime Continent (20° S -10° N, 110°-160° E) was used to depict the intensity of the EAWM (Wang and Chen, 2014a). This SLP-based EAWMI was developed by explicitly taking into account both the east-west and the north-south pressure gradients around the East Asia (Wang and Chen, 2014a). The EAWMI can therefore delineate the EAWM-related circulation anomalies well, and is strongly correlated with several atmospheric teleconnections such as the Arctic Oscillation, the North Pacific Oscillation and ENSO (Wang and Chen, 2014a). More details on how EAWMI has been formulated can be found in Wang and Chen (2014a).

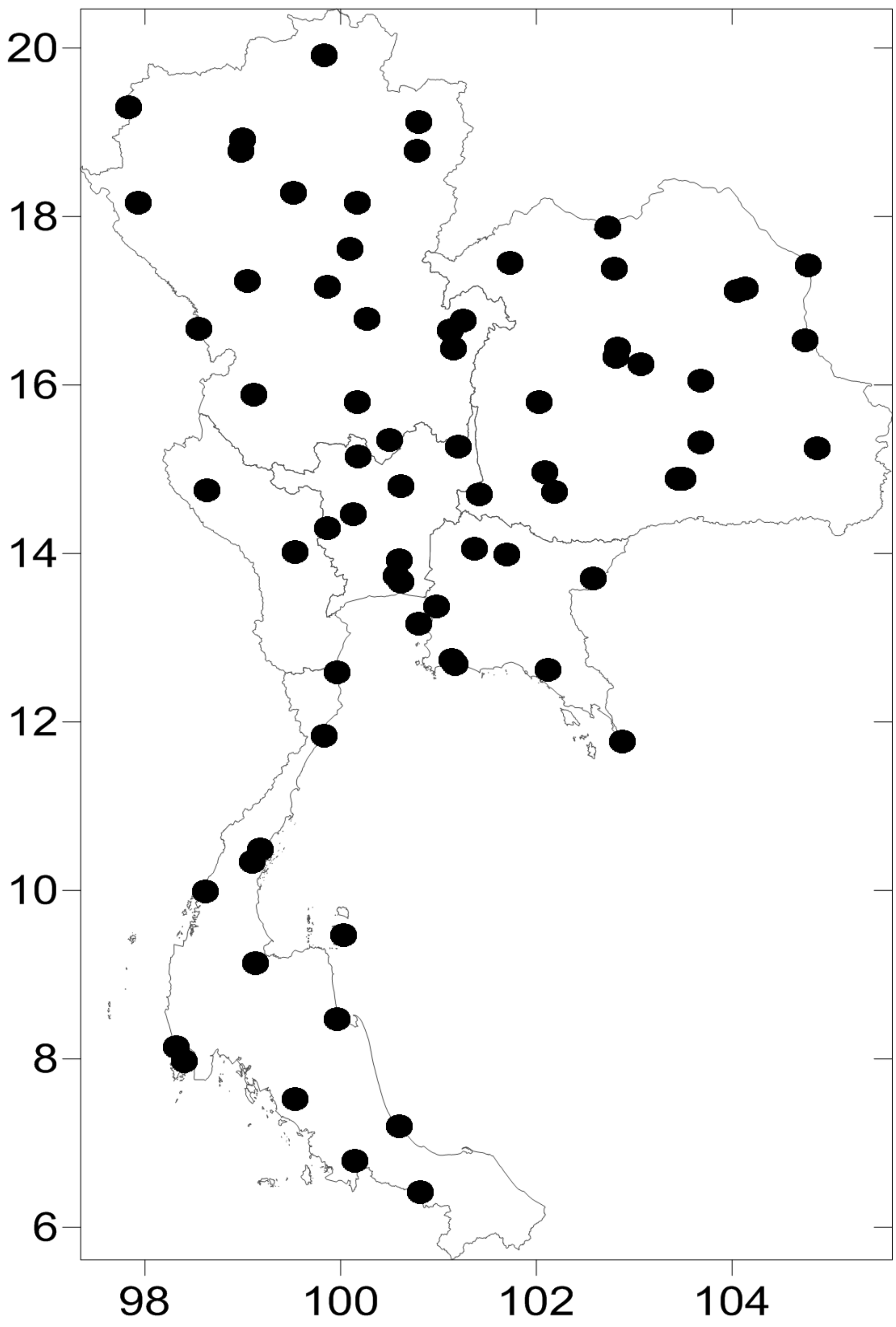

Figure 1. Geographic distribution of Thailand Meteorological Department's surface weather stations with quality controlled daily rainfall records for the period 1970 to 2012.

To further investigate the spatial relationships with the atmospheric external forcing patterns, the EOF1 coefficient time series of three rainfall indices (PRCPTOT, R95p and RX5day) were correlated with sea surface temperature (SST) time series at each grid box in the global ocean of latitudinal domain of 60° N and 30° S. The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) version4 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website (http://www.esrl.noaa.gov/psd/) was used. The ERSST is a global monthly SST analysis derived from the International Comprehensive Ocean-Atmosphere (ICOADS) dataset with missing data filled in by statistical methods (Smith *et al*., 2008). This global monthly SST analysis covers the period from 1985 to the present with a 2.0° latitude-longitude grid.

3. Results and Discussion

3.1 Climatology of wintertime total and extreme rainfall indices in Thailand

Rainfall in Thailand varies greatly over time and space, due to the combined effects resulting from the monsoonal influence, remote forcing arising from the interactions among climate modes associated with the Pacific and Indian Oceans and orographic effects (e.g., Juneng and Tangang, 2005; Takahashi and Yasunari, 2006; Tangang *et al*., 2012; Misra and DiNapoli, 2014; Limsakul and Singhruck, 2015; Loo *et al*., 2015). Most parts of Thailand show strong monsoonal signals, typically producing a marked summer and winter maximum in total rainfall amount and the likelihood of associated extreme events (Limsakul *et al*., 2010). From the climatological analysis for 42 winter seasons during 1970-2012, Thailand's total rainfall amount during DJF period when the NEM prevailed exhibited a relatively wide range of variations with less than 70 mm to more than 500 mm (Fig. 2(a)). Spatial coherence with total rainfall amount could also be seen in the climatology of the number of DJF wet days which large values were confined in the particular sub-region (Fig. 2(b)). The NEM usually brings cold and dry air from the anticyclone Siberian High over major parts of Thailand. However, there is a particular exception for the eastern coast of the southern Thailand where DJF period corresponds to a rainy season. From our analysis, total rainfall amount at the stations along the eastern coast of the Gulf of Thailand underwent exceptionally large magnitudes during DJF period (Fig. 2(a)). This sub-region is usually wetter condition during the intensified NEM, as the northeasterly monsoon wind and strong pulses of cold surge enhance moisture transport from the SCS and the Gulf of Thailand to the lower part of the Indochina Peninsula together with the Inter-tropical Convergence Zone (ITCZ) is located close to the equator (Suhaila *et al*., 2010; Tangang *et al*., 2012; Limsakul and Singhruck, 2015; Loo *et al*., 2015).

During the last 42 years from 1970 to 2012, the contribution of DJF rainfall amount to annual total rainfall in the lower part of the southern Thailand was in the range of 12-29% with the number of averaged rainy days of 21 days. However, it was less than 8% for the remaining parts of Thailand. Suhaila *et al*. (2010) found that Malaysia's total rainfall amount tended to be higher on the east coast that was exposed to the NEM flow. The Borneo Vortex which interacts closely with the NEM has been previously documented as the other complementary synoptic circulation that modulates the convective activities over the western Maritime Continent and the lower part of the Indochina Peninsula (Chang *et al*., 2005; Juneng and Tangang, 2010; Tangang *et al*., 2012). Chang *et al.* (2005) showed that, without the presence of the Borneo Vortex, strong convective activities largely occurred over Peninsular Malaysia and adjacent areas. When the Borneo vortex is active, on the other hand, excess moisture is channeled to the western Borneo causing strong convective activities over the western region of Borneo (Chang *et al*., 2005; Tangang *et al*., 2012).

Our analysis also showed that the indices looking at the amount of rainfall coming from intense and extreme events (R95p and RX5day) at the stations located along the Gulf of Thailand's eastern coast exhibited large magnitudes during DJF period as well (Fig. 3). The spatial coherence of both total and extreme rainfall indices indicated that the exposed area on the eastern coast of the Gulf of Thailand not only received much amount of rainfall but also underwent great extremes and variance during the NEM winters.

3.2 Dominant spatio-temporal modes of wintertime total and extreme rainfall indices in Thailand

The EOF analysis disclosed that the leading mode of each DJF total or extreme rainfall index explained greater than 40% of the total fractional variance (Table 2). PRCPTOT demonstrated the greatest variance contribution in the first EOF mode (Table 2), implying that the leading mode of this index varied with greatest space-time covariations as compared with other rainfall indices. According to the rule given

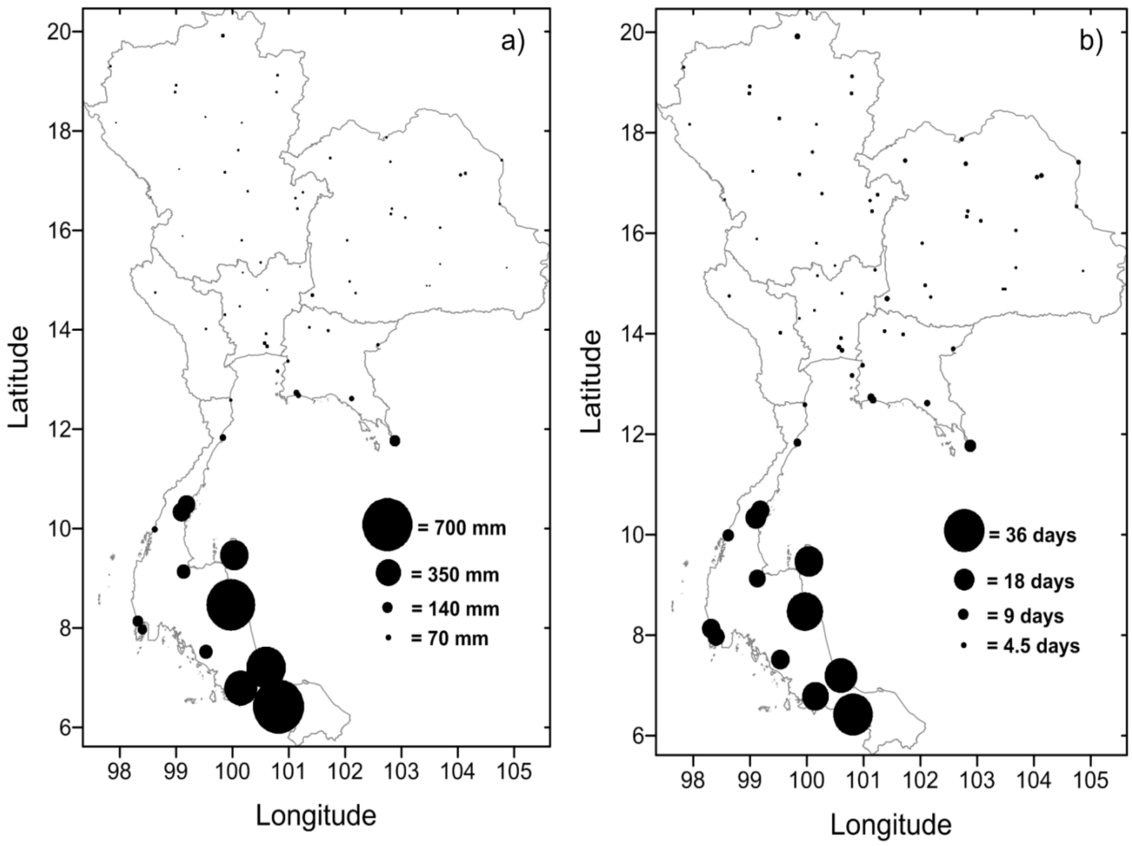

Figure 2. Station-by-station climatology of PRCPTOT (a) and W_day (b) averaged over 42 winter seasons (DJF) during 1970-2012.

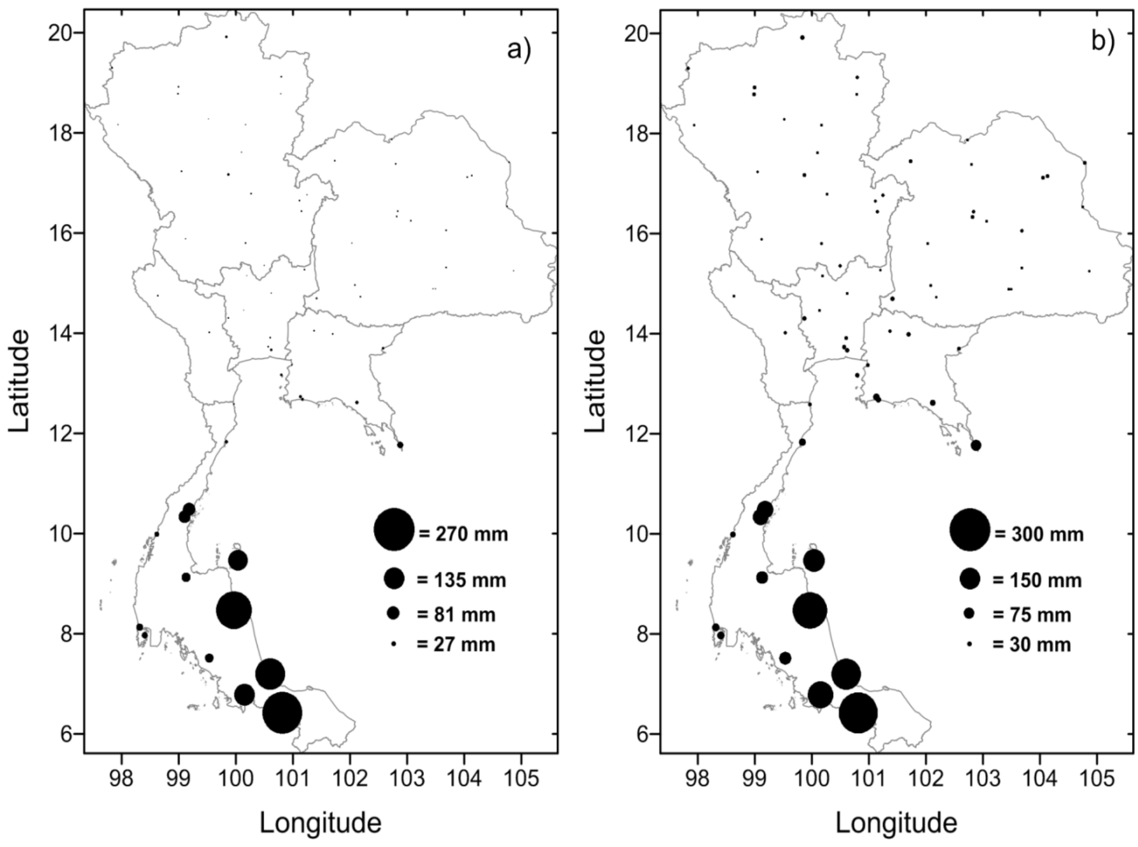

Figure 3. Same as Fig. 2 but for R95p (a) and RX5day (b).

Table 2. Percentage proportion of the total variance explained by the first and second EOF modes for each of six rainfall indices.

Index	Variance explained (%)	
	EOF1	EOF2
PRCPTOT	61.6	17.0
R_variance	58.4	21.1
W_day	44.8	12.2
R10	49.3	14.9
R95p	47.6	21.9
RX5day	41.3	20.8

by North *et al*. (1982), the leading mode was statistically distinguished from the rest of the eigenvectors in terms of the sampling error bars. The second EOF mode, which accounted on an average for 18% of the total variance, was not separable from the higher modes. It should be noted that the first two EOF modes together explained significant fractions of the variance ranging from 62.1% to 79.5% of the total variance. This character of variance decomposition suggests that only the first EOF mode is physically meaningful in determining the dominant mode of variability and the higher EOF modes are potentially mixed and physically non-interpretable.

As illustrated by the loadings displayed graphically in Figs. 4 and 5, the leading EOF mode for each of six rainfall indices was similarly characterized by a positive mono-sign pattern with the maximum loadings concentrated at the stations located in the South, and amplitudes obviously decreasing in the other parts of Thailand. Analysis showed that the loadings of all indices highly correlated each other (Table 3), suggesting a great spatial coherence of the leading EOF mode of total and extreme rainfall indices in Thailand. The spatial patterns revealed that the stations located at the exposed area of the NEM flow where rainfall exhibited large variations and great extremes during DJF period as identified in the climatological figures contributed most of the variance carried by the first EOF mode. The dominant spatial distributions of DJF total and extreme rainfall indices in Thailand, therefore, reflected the coherent variations that appeared to be related to the NEM, the EAWM and other large-scale climate phenomena which prevailed during boreal winter. Based on the similar analysis that was used to determine the dominant modes of rainfall variability over the whole of the Indo-Pacific region, Nguyen *et al*. (2014) found that the spatial structure of the leading EOF mode for DJF mean displayed quite strong ENSO-related variability. With our initial hypothesis above, the first EOF mode for each of six rainfall indices was then retained to further examine in more details of the physical meaning and possible links to the EAWMI and SST.

Time evolution associated with the first EOF mode for each of six rainfall indices is shown in the corresponding coefficient time series (Fig. 6). As can be seen, all EOF1 coefficient time series exhibited considerable year-to-year fluctuations superimposed upon longer-term variations especially a decadal time scale (Fig. 6). No decreasing or increasing linear trends were however observed in each of the EOF1 coefficient time series (Fig. 6). Similar to the loadings, high correlations among the EOF1 coefficient time series were emerged (Table 4). Such high correlations indicate that the leading mode of DJF total and extreme indices in Thailand has strong associations and great interdependence each other over time and space scales. PRCPTOT showed strong correlations with all rainfall indices (Table 4). For R10, R95p and RX5day which are the indices measuring the frequency and magnitude of heavy rainfall events, the correlations with PRCPTOT were greater than 0.9 (Table 4).

3.3 Relationship between the EOF1 time coefficients of rainfall indices and EAWMI

The EAWMI as shown in Fig. 7 can delineate circulation anomalies related to the EAWM including the NEM, and captures both the interannual and the interdecadal variations of the EAWM reported in previous studies well (Wang and Chen, 2014a). The positive (negative) values of the EAWMI generally represent strong (weak) EAWM winters which are characterized by the deepened (shallow) mid-tropospheric East Asian trough, sharpened and accelerated (widened and decelerated) upper-tropospheric East Asian jet stream, and enhanced (weakened) NEM (Wang and Chen, 2014a). Spearman's rank-order correlation coefficients calculated from the EAWMI series and the EOF1 coefficient series revealed significant relationships for all rainfall indices (Table 5). Analysis showed that stronger relationships were observed for the indices representing the number of wet days and the frequency of heavy rainfall events (Table 5). The relationships observed from analysis together with visual comparison with the states of the

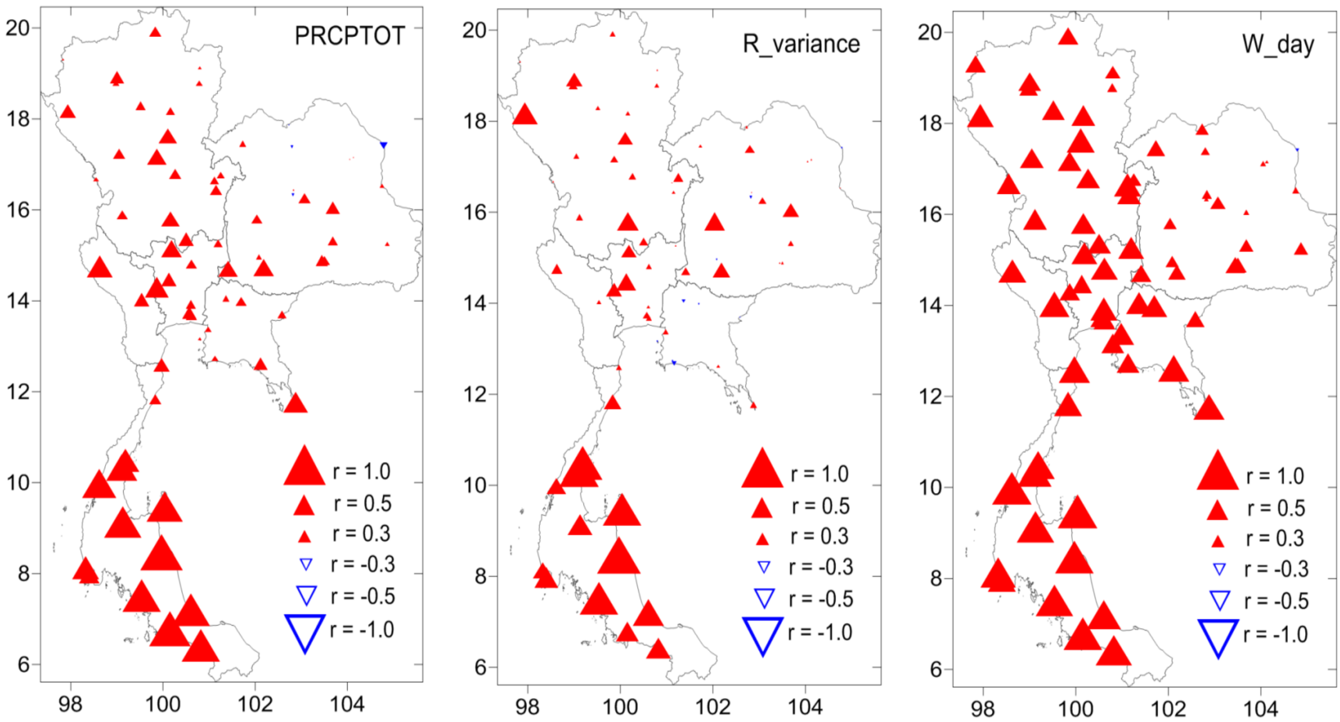

Figure 4. Spatial patterns as presented by the loadings of the first EOF mode of PRCPTOT, R_variance and W_day during DJF period. The loadings are correlation coefficients between each time series and the EOF1 coefficient series. The sizes of triangles are proportional to correlation coefficients.

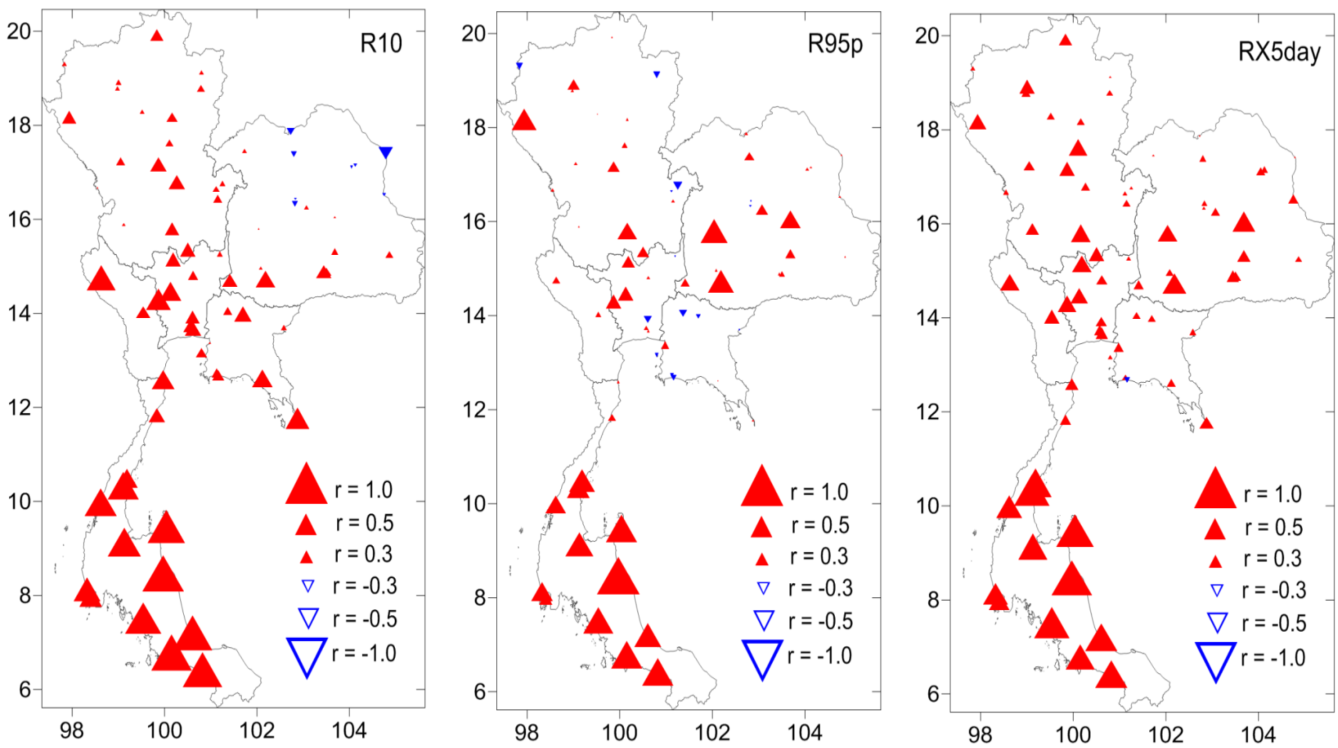

Figure 5. Same as Fig. 4 but for R10, R95p and RX5day.

Table 3. Spearman's rank correlation coefficients among the EOF's loadings of six rainfall indices.

PRCPTOT	R_variance	W_day	R10	R95p	RX5day
PRCPTOT	0.76**	0.82**	0.93**	0.82**	0.89**
R_variance		0.74**	0.73**	0.88**	0.90**
W_day			0.86**	0.71**	0.75**
R10				0.77**	0.78**
R95p					0.89**

The sample size for each series used for correlation analysis = 72.
**Significant at the 1% level (*p*-value=*0.01*).

EAWM categorized by Wang and Chen (2010; 2014a; 2014b) indicated that positive/negative EOF1 coefficient anomalies of each rainfall index appeared to be in phase with strong/weak EAWM (positive/negative EAWMI) (Fig. 6 and Table 5). There was an indication that the leading mode of DJF total and extreme indices in Thailand tended to be higher (lower) than normal during strong (weak) EAWM. During the strong EAWM occurred in the winters of 1974/1975, 2005/2006, 2009/2010, 2010/2011 and 2011/2012, for example, the EOF1 coefficient values of all indices were prominently higher than normal (Fig. 6). While, they were obviously lower than average during the weak EAWM in the winters of 1978/1979, 1988/1989, 1989/1990, 2001/2002 and 2006/2007 (Fig. 6). Our results are in agreement with the previous studies showing that strong EAWM facilitates enhanced rainfall in low latitudes (e.g., Sun and Li, 1997; Wang and Chen, 2010; 2014a; Wang and Feng, 2011). For example, the similar significant correlation between interannual variations of the EAWM and January-February-March (JFM) rainfall was evidenced over southeastern China (Zhou, 2011). The deepened mid-tropospheric East Asian trough, sharpened and accelerated upper-tropospheric East Asian jet stream, and enhanced NEM in the strong EAWM winters have been suggested to be the plausible mechanisms for enhanced rainfall over the Maritime SEA (Wang and Chen, 2014a). Whereas, suppressed rainfall over the Maritime SEA has been observed to occur correspondingly in the weak EAWM winters when changes in these key elements of the EAWM system have been opposite (Wang and Chen, 2014a). Based on our results in combination with the recent evidence, it is reasonably believed that the anomalies of the NEM and other key EAWM-related circulations are likely to be the possible causes of DJF total and extreme rainfall variations in Thailand.

On longer timescales, noticeable decadal variations were also observed in all EOF1 coefficient series (Fig. 6). The EOF1 coefficient series of all rainfall indices showed negative values from the mid 1970s and to the mid 1990s. Following this period, they returned to positive values (Fig. 6). The recent decadal change observed in the EOF1 coefficient series of all rainfall indices has been coincident with re-amplification of the EAWM with the increased frequency of the strong EAWM taken place since the early/mid 2000 as shown in Fig. 7 and thoroughly discussed in the study of Wang and Chen (2014b). It was evidenced that East Asia experienced more cold winters and significant negative surface air temperature anomalies during the recent strong EAWM epoch spanning the period 2004-2012 (Wang and Chen, 2014b). Enhanced wintertime blocking activity around the Ural mountain region in combination with diminished Arctic sea ice concentration in the previous September have been suggested to be the responsible internal atmospheric process and external driver for the recent re-amplification of the EAWM (Wang and Chen, 2014b).

Table 4. Same as Table 3 but for EOF1 coefficient series.

PRCPTOT	R_variance	W_day	R10	R95p	RX5day
PRCPTOT	0.82**	0.82**	0.96**	0.94**	0.91**
R_variance		0.75**	0.73**	0.91**	0.91**
W_day			0.87**	0.72**	0.72**
R10				0.84**	0.81**
R95p					0.96**

The sample size for each series used for correlation analysis = 42.
**Significant at the 1% level (*p*-value=*0.01*).

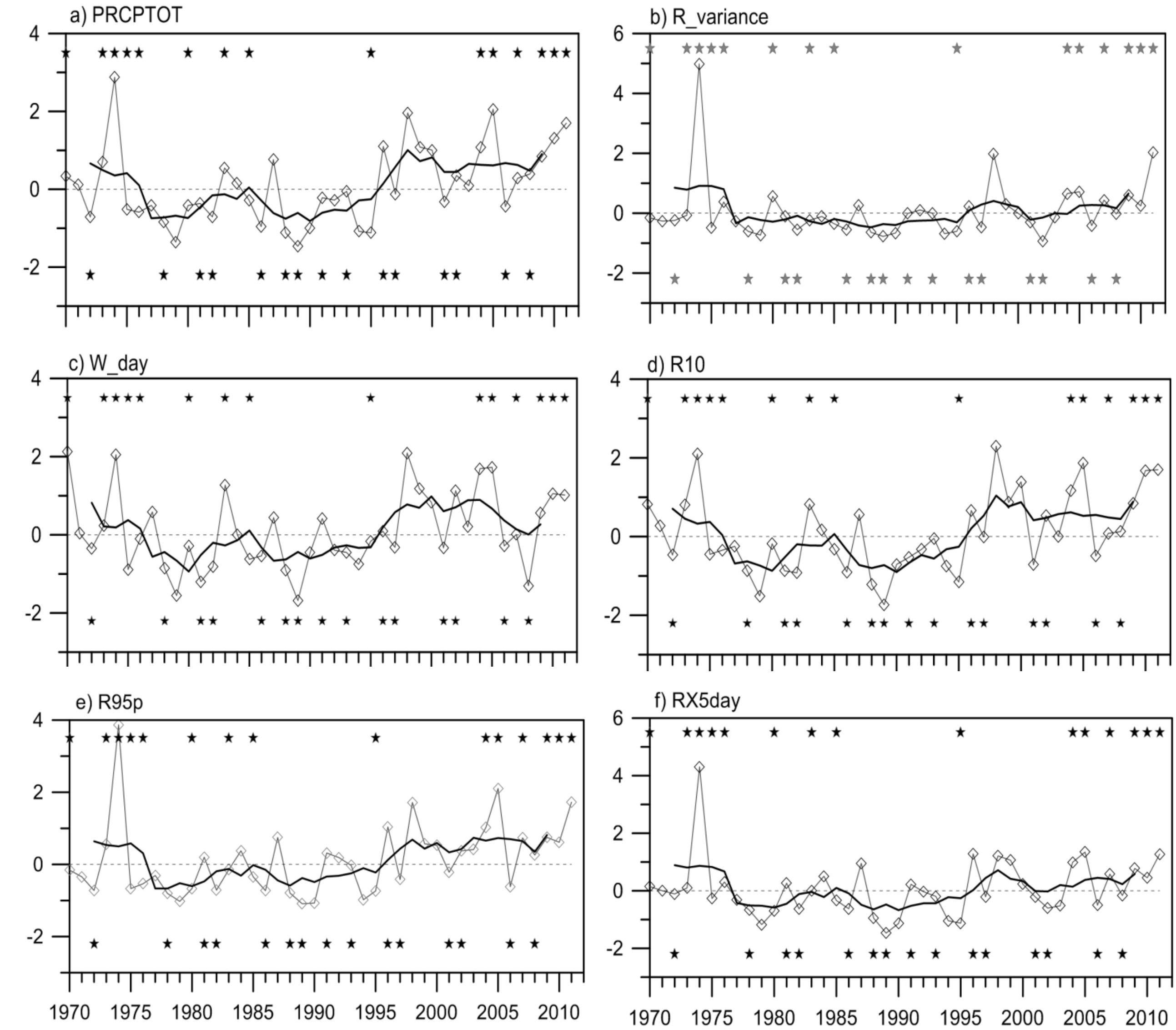

Figure 6. Normalized EOF1 coefficient time series of PRCPTOT, R_variance, W_day, R10, R95p and RX5day during DJF period. Thick lines denote 5-year running means of the EOF1 coefficient time series. The ★'s represent the strong and weak EAWMs as categorized by Wang and Chen (2010; 2014a; 2014b).

3.4 Relations with SST

As the ocean is an important driving force of the NEM and EAWM variability (e.g., Li and Yang, 2010; Huang *et al*., 2012; Wang and Chen, 2014a), so we further investigated possible relationships between the dominant mode of total and extreme rainfall indices in Thailand and SST in the tropical-extratropical domain of the global ocean. Fig. 8 shows correlation maps of the EOF1 time coefficients of PRCPTOT, R95p and RX5day with anomalies of SST for DJF period. What clearly stands out emerged from Fig. 8 is that the dominant mode of DJF total and extreme rainfall indices in Thailand exhibited strong correlations with the tropical-subtropical Pacific Ocean surface temperatures. It was characterized as the Pacific Decadal Oscillation (PDO)/ENSO-related boomerang-shaped spatial patterns. Significant correlations with the tropical-subtropical Pacific Ocean temperatures reached maximum spatial extent with the PRCPTOT index (Fig. 8). This spatial correlation pattern well resembles the typical mature phases of the La Niña event and the PDO cool epoch (e.g., Philander, 1990; Mantua *et al*., 1997; Zhang *et al*., 1997; Deser *et al*., 2010; Trenberth, 2013). By analyzing the covariability between the NEM rainfall in Malaysia and the large-scale SST in the Indian-Pacific sector, Juneng and Tangang (2006) showed that the first coupled mode highlighted the covariability between anomalous NEM rainfall in the East Malaysia and anomalous SST associated with the ENSO. Caesar *et al*. (2011) found that the correlation

Table 5. The Spearman's rank correlation coefficients between the EOF1 coefficient series of six rainfall indices and the EAWMI series.

Index	EAWMI
PRCPTOT	0.41*
R_variance	0.48*
W_day	0.51*
R10	0.51*
R95p	0.48*
RX5day	0.39*

The sample size for each series used for correlation analysis = 42.
*Significant at the 5% level (p-value=0.05).

patterns between global SST and some extreme rainfall indices related to heavy rainfall in the Indo-Pacific had an ENSO-like pattern, highlighting that increased heavy rainfall days were related to negative SST anomalies in the equatorial Pacific (i.e. La Niña conditions). Based on investigating the changes in annual and seasonal maximum daily rainfall in the SEA using the generalized extreme value (GEV) distribution, Villafuerte II and Matsumoto (2015) further found negative covariations between the location parameter of the GEV and the ENSO index over the Maritime Continent, implying a higher (lower) likelihood of extreme rainfall during the La Niña (El Niño). In line with those studies, Fig. 8 indicates that negative and positive SST anomalies in the central-eastern equatorial Pacific and central subtropical-western equatorial Pacific respectively, which typically correspond to the mature phases of the La Niña event and the PDO cool epoch, are correlated with increased DJF total and extreme rainfall in Thailand. However, the correlations between them reverse during the El Niño event and the PDO warm epoch when positive and negative SST anomalies occur the central-eastern equatorial Pacific and central subtropical-western equatorial Pacific respectively (Fig. 8).

As pointed out from previous studies, the El Niño is usually accompanied by a weaker EAWM system, and vice versa for La Niña (Li and Yang, 2010; Huang *et al*., 2012; Wang and Chen, 2014a). The impact of the ENSO cycle on the EAWM system variability is also modulated by the PDO (e.g., Chen *et al*., 2013; He and Wang, 2013; Kim *et al*., 2014). The ENSO cycle has strong impact on the EAWM system when the PDO is in its cool phase, causing significantly anomalous temperatures and rainfall over the East Asia and SEA (e.g., Chen *et al*., 2013; He and Wang, 2013; Kim *et al*., 2014). Our analysis agrees with the above-mentioned notation highlighting that the ENSO and PDO as the primary global atmospheric external forcing are likely to exert their influence on wintertime climate over the SEA including Thailand via modulating the EAWM/NEM-related circulations anomalies.

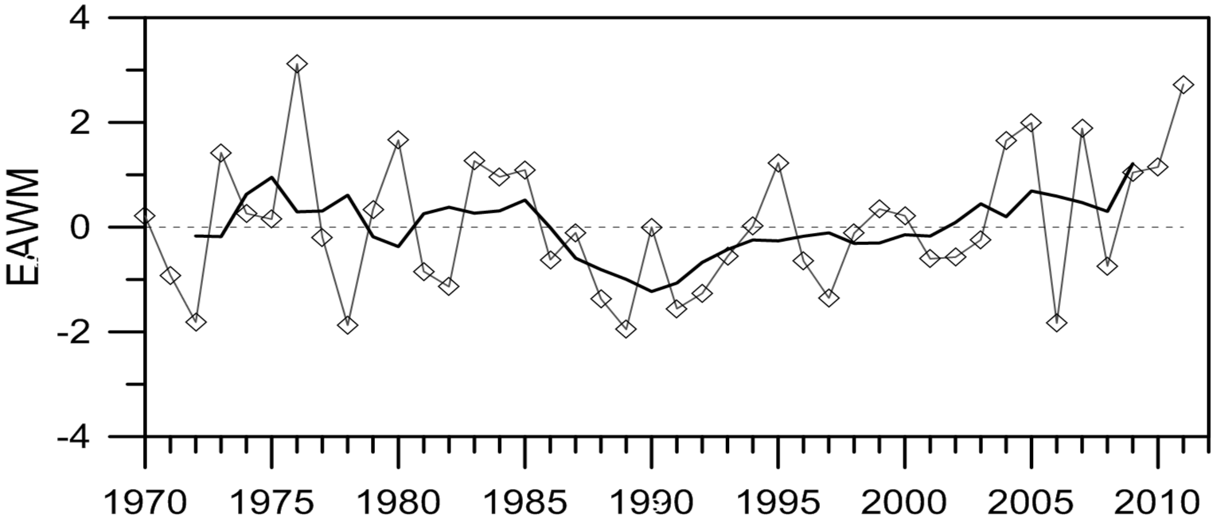

Figure 7. Time series of the EAWM index during DJF period.

4. Conclusions

Analysis of total and extreme rainfall indices for the period from 1970 to 2012 in the context of wintertime climatology and spatio-temporal variability in Thailand can highlight some interesting findings as flows:

1. The area along the Gulf of Thailand's eastern coast not only received much amount of rainfall but also underwent great extremes and variances during the NEM winters, due to enhanced moisture transport caused by strengthening of the northeasterly monsoon wind and strong pulses of cold surge.

2. The leading EOF mode of each DJF total or extreme rainfall index explained significant fractions of the total variance. Spatial structures of the leading EOF mode for each of six rainfall indices were similarly marked by maximum loadings concentrated at the stations located at the exposed area of the NEM flow where rainfall showed large variations and great extremes. Time evolution associated with the leading EOF mode of all six rainfall indices exhibited considerable year-to-year fluctuations superimposed on longer-term variations.

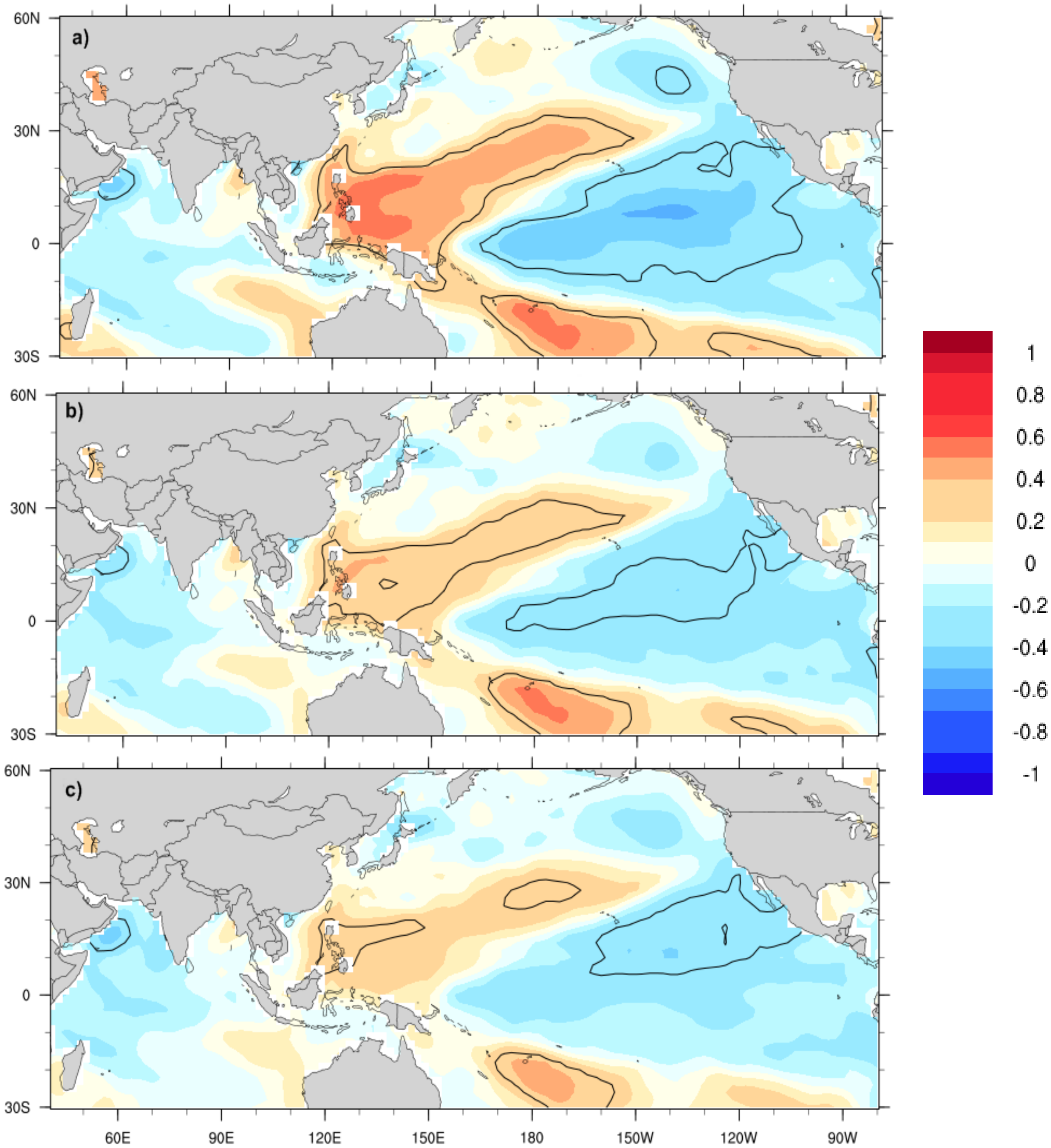

Figure 8. Grid-by-grid correlations of 1970-2012 DJF series between ERSST anomalies and the normalized EOF1 time coefficients of PRCPTOT (a), R95p (b) and RX5day (c). Contour lines indicate the correlation coefficients which are the 95% confidence levels based on a two-sided Student's t test.

3. Correlation analysis revealed that the leading EOF mode of all DJF total and extreme indices in Thailand tended to be higher (lower) than normal during strong (weak) EAWM. Based on these results in combination with the evidence from previous studies, it is reasonably believed that the anomalies of the NEM and other key EAWM-related circulations are likely to be possible causes of DJF total and extreme rainfall variations in Thailand.

4. On longer timescales, the recent decadal change observed in the leading EOF mode of all rainfall indices has been coincident with re-amplification of the EAWM with the increased frequency of the strong EAWM taken place since the early/mid 2000.

5. The leading EOF mode of DJF total and extreme rainfall indices in Thailand also exhibited strong correlations with the subtropical-tropical Pacific Ocean surface temperatures. It was characterized as the PDO/ENSO-related boomerang-shaped spatial patterns, resembling the typical mature phases of the La Niña event and the PDO cool epoch. This analysis is in line with the previous studies highlighting that the ENSO and PDO as the primary global atmospheric external forcing are likely to exert their influence on wintertime climate in Thailand via modulating the EAWM/NEM-related circulations anomalies.

Given the significant social, economic and ecological impacts of the EAWM/NEM and their potential changes under warmer climate conditions, study of predictability may further shed more light on better understanding the predictable dynamics of local climate variability related to those phenomena.

Acknowledgements

We would like to thank the Thai Meteorological Department for kindly providing valuable daily rainfall data. This study is part of the Thailand-China collaborative project entitled ‘Decadal Climate Variations and the Near-Term Climate Projection over the Southeast Asian Monsoon Region’ funded by the Thailand Research Fund (TRF; TRF Project Number RDG6030002) and The National Natural Science Foundation of China (NSFC; NSFC Project Number 4166114406).

We also extend our thanks to the editor and anonymous reviewers for their insightful critiques and constructive comments to substantially improve the quality of the earlier version of the manuscript.

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Received 6 May 2017
Accepted 12 June 2017

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