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Long-term trends and variability of total and extreme precipitation in Thailand

Atsamon Limsakul [a,*], Patama Singhruck [b]

[a] Environmental Research and Training Center, Technopolis, Klong 5, Klong Luang, Pathumthani 12120, Thailand
[b] Department of Marine Science, Faculty of Science, Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok 10330, Thailand

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ABSTRACT

Based on quality-controlled daily station data, long-term trends and variability of total and extreme precipitation indices during 1955–2014 were examined for Thailand. An analysis showed that while precipitation events have been less frequent across most of Thailand, they have become more intense. Moreover, the indices measuring the magnitude of intense precipitation events indicate a trend toward wetter conditions, with heavy precipitation contributing a greater fraction to annual totals. One consequence of this change is the increased frequency and severity of flash floods as recently evidenced in many parts of Thailand. On interannual-to-interdecadal time scales, significant relationships between variability of precipitation indices and the indices for the state of El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) were found. These results provide additional evidence that large-scale climate phenomena in the Pacific Ocean are remote drivers of variability in Thailand's total and extreme precipitation. Thailand tended to have greater amounts of precipitation and more extreme events during La Niña years and the PDO cool phase, and vice versa during El Niño years and the PDO warm phase. Another noteworthy finding is that in 2011 Thailand experienced extensive flooding in a year characterized by exceptionally extreme precipitation events. Our results are consistent with the regional studies for the Asia-Pacific Network. However, this study provides a more detailed picture of coherent trends at a station scale and documents changes that have occurred in the twenty-first century, both of which help to inform decisions concerning effective management strategies.

1. Introduction

Precipitation is a key component of the hydrological cycle and a defining feature of Earth's changing climate. Of all meteorological variables, precipitation most likely affects life and civilization most directly and significantly because variations in precipitation often cause significant impacts on both human society and the natural environment (e.g., Barretta and Santos, 2014; Pielke and Downton, 2000; Guan et al., 2014; Trenberth et al., 2003). Over the last few decades, it has become increasingly evident that the frequency and intensity of extreme precipitation events have been changing especially under the anthropogenically induced climate warming (e.g., Allan and Soden, 2008; Coumou and Rahmstorf, 2012; Donat et al., 2013; Min et al., 2011). For the tropics and subtropics, the amount of research focused on extreme precipitation events has recently progressed enormously. Based on a daily rainfall dataset of 1803 stations, for example, Goswami et al. (2006) discovered significant trends for increases in the frequency and magnitude of extreme rain events occurring over central India during the monsoon seasons from 1951 to 2000. Endo et al. (2009) examined trends in precipitation extremes over Southeast Asia, and demonstrated that the average precipitation intensity of wet days exhibited an increasing trend at many stations. Analysis of daily data in the Philippines for the period of 1951–2010 showed significant increases in both frequency and intensity of extreme daily rainfall events at some stations (Cinco et al., 2014). In addition, the results based on a series of regional workshops have revealed that trends in precipitation extremes were less spatially consistent across the Indo-Pacific, Asia-Pacific and Arab regions (Caesar et al., 2011; Choi et al., 2009; Donat et al., 2014).

It is recognized that a key aspect of the analysis of precipitation extremes is to distinguish the difference between the detection of a change and the attribution of a change to some identifiable climate forcing factor (Griffiths and Bradley, 2007; Hoerling et al., 2010). Several studies have demonstrated that changes in extreme precipitation events are related to atmospheric circulation patterns (e.g., Kenyon and Hegerl, 2010; Caesar et al., 2011; Donat et al., 2014; McGree et al., 2014; Queralt et al., 2009; Zhang et al., 2010). Kenyon and Hegerl (2010) demonstrated that variations in global precipitation extremes are significantly affected by ENSO and that these effects are most evident around the Pacific Rim.

Given the potentially significant social, economic and ecological impacts of precipitation extremes, an up-to-date assessment at a local scale is required to support the decision-making processes associated

* Corresponding author. Tel.: +66 2 577 1136; fax: +66 2 577 1138.
E-mail address: atsamon@deqp.go.th (A. Limsakul).

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with the development of effective management strategies for agriculture, water resources and disasters. In this study, particular attention is paid to Thailand, a country for which the number of studies of changes in extreme precipitation events is still limited. To the best of our knowledge, only the works of Limjirakan et al. (2010) and Limsakul et al. (2010) who examined the changes in daily precipitation extreme events in the Bangkok Metropolitan area and along Thailand's coastal zones for the period of 1965–2006 are found in the literature. In this study, precipitation indices mostly focused on extreme events that are recommended 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) were calculated. The long-term trends for these indices in Thailand during the period from 1955 to 2014 were then examined, using quality-controlled daily station data. The relationships between the calculated precipitation indices and the indices for the state of ENSO and PDO on interannual-to-interdecadal time scales were further investigated.

2. Data and analytical methods

2.1. Daily precipitation data

Daily precipitation data from surface weather stations of the Thai Meteorological Department (TMD) covering the period from 1955 to 2014 provided the basis for this study. To analyze extreme climatic indices, rather strict criteria were applied in selecting station data. These criteria include the following: (i) a month is 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) (Griffiths and Bradley, 2007; Moberg and Jones, 2005; Chu et al., 2010). Based on these criteria, a total of 44 stations were selected for the subsequent quality control and homogeneity tests. Overall, the percentage of missing data ranged from 0% to 1.9%, with 15 stations that did 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) and using the ETCCDI RClimDex software. Outliers identified by the QC check were then evaluated by comparing their values to adjacent days, to the same day at nearby stations and to the expert knowledge of local climate conditions 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 ETCCDI RHtestsV4 software. This 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, 2008). In this study, homogeneity analyses were performed on the monthly total precipitation series using a relative test in which the candidate series was examined in relation to a reference series (e.g., Cao and Yan, 2012; Aguilar et al., 2003; Peterson et al., 1998). A set of homogeneous neighboring stations that were well correlated with the candidate station was used as the reference series (Aguilar et al., 2003). Most of the neighbors (90%) used to construct the reference series had high correlations (correlation coefficients > 0.7) with the candidate series.

Homogeneity testing identified 3 stations with significant step changes in their monthly total precipitation series. Based on information available from station history metadata, possible explanations for the causes of these step changes were unclear. No further attempt was made to adjust the data because the adjustment of inhomogeneous daily precipitation data is a complex problem with a number of uncertainties (Domonkos, 2011; Aguilar et al., 2003), and a conservative approach was taken to exclude inhomogeneous data. On the basis of the quality control and homogeneity tests, the daily precipitation data for a set of 41 high-quality records spanning from 1955 to 2014 were prepared for the calculation of precipitation indices (Fig. 1). Detailed information of the stations is provided in Table 1.

2.3. Precipitation indices

Eleven extreme precipitation indices, including precipitation totals (PRCPTOT) and the number of rainy days (RD; days with precipitation ≥ 1 mm), as 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 RClimDex software. For the percentile-based indices of very wet days (R95p) and extremely wet days (R99p), the methodology uses bootstrapping to calculate the values for the base period so that there is no discontinuity in the time series of the indices at the beginning or end of the base period (Klein Tank et al., 2009; Zhang et al., 2011). For comparative purpose with the previous studies, a base period of 1971–2000 was used when computing percentile-based indicators.

Table 2 provides a description of the eleven ETCCDI precipitation indices. The R95p, R99p and maximum 1-day and 5-day precipitation amount (RX1day and RX5day) indices characterize the magnitude of intense rainfall events, whereas, simple daily intensity index (SDII) is a measure of the mean total precipitation that falls on a wet day in a given year. R95pT represents the contribution from the very wet days to the annual precipitation totals. In this study, R20 (number of days with precipitation ≥ 20 mm) is applied to assess the frequency of heavy precipitation events because this threshold is more applicable to tropical climates, which obviously have greater daily precipitation totals than mid- and high-latitude regions. Finally, consecutive dry

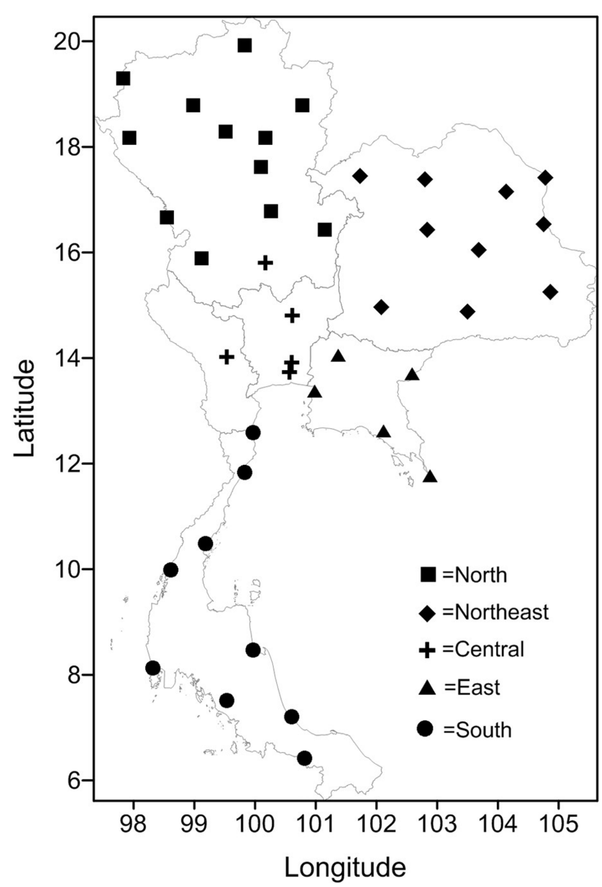

Fig. 1. Geographical distribution of the TMD's surface weather stations with long-running quality controlled daily precipitation records for the period from 1955 to 2014. Locations of the stations are basically divided into five topographic regions: 1) North, 2) Northeast, 3) Central, 4) East and 5) South, respectively.

Table 1
Details of the TMD's surface weather stations used in this study.

WMO	Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Completeness (%)
48400	Nakhon Sawan	15.80	100.17	34.0	99.97
48426	Lop Buri	14.80	100.62	10.0	100
48450	Kanchanaburi	14.02	99.53	28.0	100
48455	Bangkok Metropolis	13.73	100.57	3.0	99.85
48456	Donmuang	13.92	100.60	4.0	99.99
48430	Prachin Buri	14.05	101.37	4.0	100
48462	Aranyaprathet	13.70	102.58	47.0	99.87
48459	Chon Buri	13.37	100.98	1.0	99.99
48480	Chanthaburi	12.62	102.12	3.0	100
48501	Klong Yai	11.77	102.88	2.0	99.21
48353	Loei	17.45	101.73	253.0	99.95
48354	Udon Thani	17.38	102.80	177.0	100
48356	Sakon Nakhon	17.15	104.13	171.0	100
48357	Nakhon Phanom	17.42	104.78	146.0	99.94
48381	Khon Kaen	16.43	102.83	165.0	99.98
48383	Mukdahan	16.53	104.75	138.0	99.87
48405	Roi Et	16.05	103.68	140.0	100
48407	Ubon Ratchathani	15.25	104.87	123.0	99.99
48431	Nakhon Ratchasima	14.97	102.08	187.0	99.94
48432	Surin	14.88	103.50	146.0	100
48300	Mae Hong Son	19.30	97.83	268.0	99.22
48325	Mae Sariang	18.17	97.93	211.0	99.82
48303	Chiang Rai	19.92	99.83	394.0	99.73
48327	Chiang Mai	18.78	98.98	312.0	100
48328	Lampang	18.28	99.52	242.0	100
48330	Phrae	18.17	100.17	161.0	99.87
48331	Nan	18.78	100.78	200.0	99.87
48351	Uttaradit	17.62	100.10	63.0	99.87
48376	Tak	15.88	99.12	124.0	99.85
48375	Mae Sot	16.67	98.55	196.0	99.86
48378	Phitsanulok	16.78	100.27	44.0	99.85
48379	Phetchabun	16.43	101.15	114.0	99.87
48500	Prachuap Khiri Khan	11.83	99.83	4.0	99.88
48475	Hua Hin	12.58	99.97	5.0	99.88
48517	Chumphon	10.48	99.18	3.0	99.84
48532	Ranong	9.98	98.62	7.0	100
48552	Nakhon Sri Thammarat	8.47	99.97	4.0	100
48565	Phuket Airport	8.13	98.32	6.0	100
48567	Trang Airport	7.52	99.53	14.0	100
48568	Songkhla	7.20	100.60	4.0	100
48583	Narathiwat	6.42	100.82	2.0	98.10

days (CDD) and consecutive wet days (CWD) are indices that quantify the lengths of the wettest and driest parts of the year. PRCPTOT and RD indices were also calculated for the rainy and dry seasons. Taking the annual cycle of precipitation over most of Thailand into account, the rainy season is defined as the period from May to October, while the dry season runs from November through April of the next year (Takahashi and Yasunari, 2006). However, the May–September rainy season classification does not hold for the eastern part of southern Thailand, where the wettest months are from November to February of the next year.

2.4. Trend calculations and regional average series

Linear trends were calculated from the annual and seasonal series of precipitation indices using a non-parametric Kendall's tau-based slope estimator (Aguilar et al., 2005; Zhang et al., 2005). This method is more suitable for addressing non-normal distributions of data and robust to the effect of outliers in a series. A station-by-station analysis was performed and mapped to explore spatial patterns. Regional time series for the years 1955–2014 were also created for every index by averaging the anomalies of each station to the base period from 1971 to 2000. Further examination showed that the magnitude of changes in each precipitation index was insignificantly different, when regional time series were calculated from the base periods between 1971–2000 and 1981–2100. In the averaging procedure, the anomaly series of each station was weighted with the inverse of the number of stations within its spatial de-correlation length using the method described in Maraun et al. (2008). This procedure avoids any bias toward regions with clusters of closely spaced stations.

2.5. ENSO and PDO relationship analysis

To examine the relationships of the precipitation indices with interannual-to-interdecadal variability in large-scale atmospheric circulations, correlations with the ENSO and PDO indices were calculated. The Multivariate ENSO Index (MEI), calculated as the first unrotated principal component of six observed atmospheric and oceanic variables in the tropical Pacific (Wolter and Timlin, 1998), was used to represent the state of ENSO. The MEI more fully reflects the nature of the coupled ocean–atmosphere system because the MEI integrates more information than other indices and, therefore, is more suitable for monitoring the ENSO phenomenon than SOI or sea surface temperature (SST)-based indices (Wolter and Timlin, 1998). The PDO index (PDOI) is derived as the leading principal component of the mean monthly SST in the Pacific Ocean north of 20°N (Mantua et al., 1997). The PDO is a pattern of Pacific climate variability similar to ENSO in character, but which varies over a much longer time scale (Mantua et al., 1997). During the past century, there have been only two complete cycles of the PDO (Mantua et al., 1997). Cool phases of the PDO have persisted from 1890 to 1924 and from 1947 to 1976, while warm phases persisted from 1925 to 1946 and from 1977 through at least the late 1990s. Spearman's rank-order correlations between MEI and PDOI and precipitation indices were calculated for individual stations and area averages. The annual series of MEI and PDOI and precipitation indices were detrended before the correlations were calculated.

3. Results

3.1. Trends in annual/seasonal PRCPTOT

Precipitation varies greatly by season and region across Thailand, as a result of complex interactions among the climate modes in the Indo-

Table 2
Definitions of the eleven ETCCDI precipitation extreme indices examined in this study.

Index	Descriptive name	Definitions	Units
PRCPTOT	Annual precipitation total	Annual precipitation total of rainy days (RR ≥ 1 mm)	mm
RD	Number of annual rainy days	Annual counts of days when RR ≥ 1.0 mm	Days
SDII	Simple daily intensity index	Annual precipitation total divided by the number of annual rainy days (RR ≥ 1 mm)	mm day^{-1}
RX1day	Maximum 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation amount	Monthly maximum 5-day precipitation	mm
R20	Number of heavy precipitation days	Annual counts of days when PRCP ≥ 20 mm	Days
R95p	Very wet day precipitation	Annual precipitation total of RR > 95th percentile	mm
R99p	Extremely wet day precipitation	Annual precipitation total of RR > 99th percentile	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Days
R95pT	Contribution from very wet days	100 * R95p/PRCPTOT	%

A rainy day is defined as a day when RR ≥ 1 mm, whereas a dry day is defined as one when RR < 1 mm.

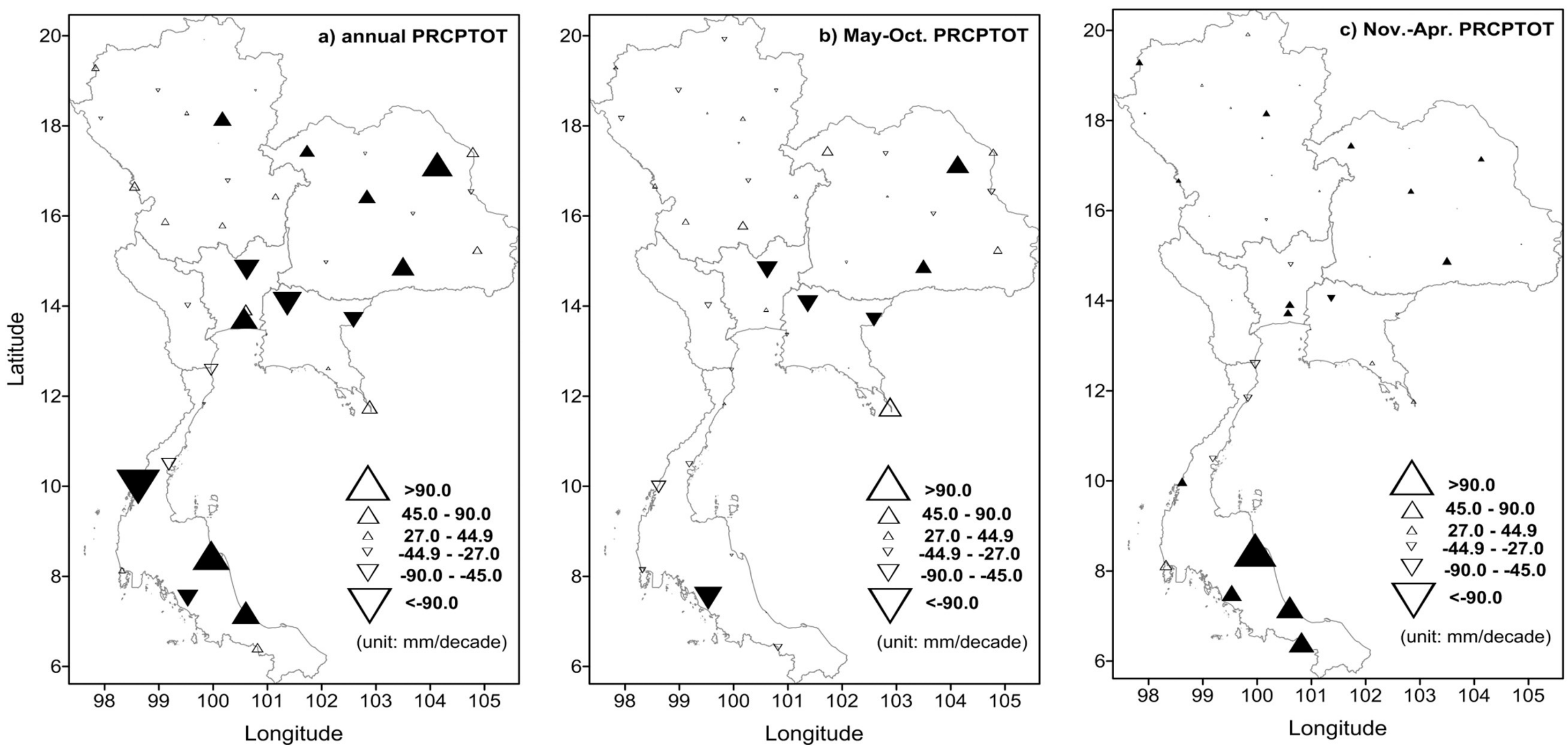

Fig. 2. Spatial distribution maps of trends for (a) annual PRCPTOT, (b) May–Oct. PRCPTOT and (c) Nov.–Apr. PRCPTOT. The upward-pointing triangles show increasing trends, while the downward-pointing triangles indicate decreasing trends. Significant changes at the 5% level are indicated by filled black triangles.

Pacific sector in combination with orographic effects (Juneng and Tangang, 2005; Misra and DiNapoli, 2014; Takahashi and Yasunari, 2006). In the long-term context, our results revealed that there was a mixture of drying and wetting trends in the annual PRCPTOT in Thailand (Fig. 2a), consistent with what has been previously documented in other Asia-Pacific Network countries (Caesar et al., 2011; Choi et al., 2009; Endo et al., 2009). Compared with these regional studies, however, our analysis based on a greater number of stations could bring some interesting changes in PRCPTOT at a smaller spatial scale in Thailand. About one-third of the total stations recorded significant changes in annual PRCPTOT from 1955 to 2014, with 12.2% and 19.5% exhibiting significant negative and positive trends, respectively. The stations with significant decreasing trends were generally located in Central and East Thailand as well as along the Andaman Sea, whereas significant increasing trends were observed at the stations situated in the Northeast, the Gulf of Thailand's coast and Bangkok Metropolis (Fig. 2a). Similar changes in the annual PRCPTOT along Thailand's coasts and in Bangkok Metropolis were previously documented by Limjirakan et al. (2010) and Limsakul et al. (2010).

The weighted regional-average anomalies of the annual PRCPTOT series did not display any significant trends (Fig. 3a), owing to large year-to-year fluctuations superimposed on prominent interdecadal variations. For example, the years 1977, 1979, 1992 and 1993 were very dry, while the years 1966, 1970, 1999 and 2011 were extremely wet (Fig. 3a). The period from the late 1950s to the mid-1970s was mostly wet, but the period between the late 1970s and mid-1990s was obviously dry (Fig. 3a). From the early 2000s onward, the annual PRCPTOT in Thailand as a whole returned to be higher than the long-term average (Fig. 3a). Limsakul et al. (2007) showed that an unusual decade-long deficit in annual PRCPTOT accompanied by a concomitant reduction of rainy days from the late 1970s to the mid 1990 has occurred coincidently with the tendency for the occurrence of more El Niño and fewer La Niña events starting in the late 1970s and the warm phase of the PDO (Mantua et al., 1997; Zhang et al., 1997). Singhrattna et al. (2005) showed that the Walker circulation underwent a persistent southeastward shift over the Thailand–Indonesia region in the post-1980 period, leading to significantly reducing convection and summer monsoon rainfall over Thailand. Takahashi and Yasunari (2008) found that the significant decrease in September rainfall over Thailand from 1951 to 2000 was related to a weakening trend of westward-propagating tropical cyclones over the Indochina Peninsula. Based on our result and previous evidence, it may suggest that, in addition to the dominant year-to-year timescale, PRCPTOT in Thailand exhibits decadal/interdecadal variations in response to changes in oceanic and atmospheric circulations in the Pacific Ocean.

When linear trends for four sub-regions were further considered, noticeable decreasing/increasing changes in annual PRCPTOT were apparent (Fig. 3c–f). Opposite trends (significant at the 95% level of confidence) were found between the western part and the eastern part of southern Thailand (Fig. 3e and f). Moreover, averaged trends for Northeast and East can be characterized by discernible increase and decrease, respectively (Fig. 3c and d).

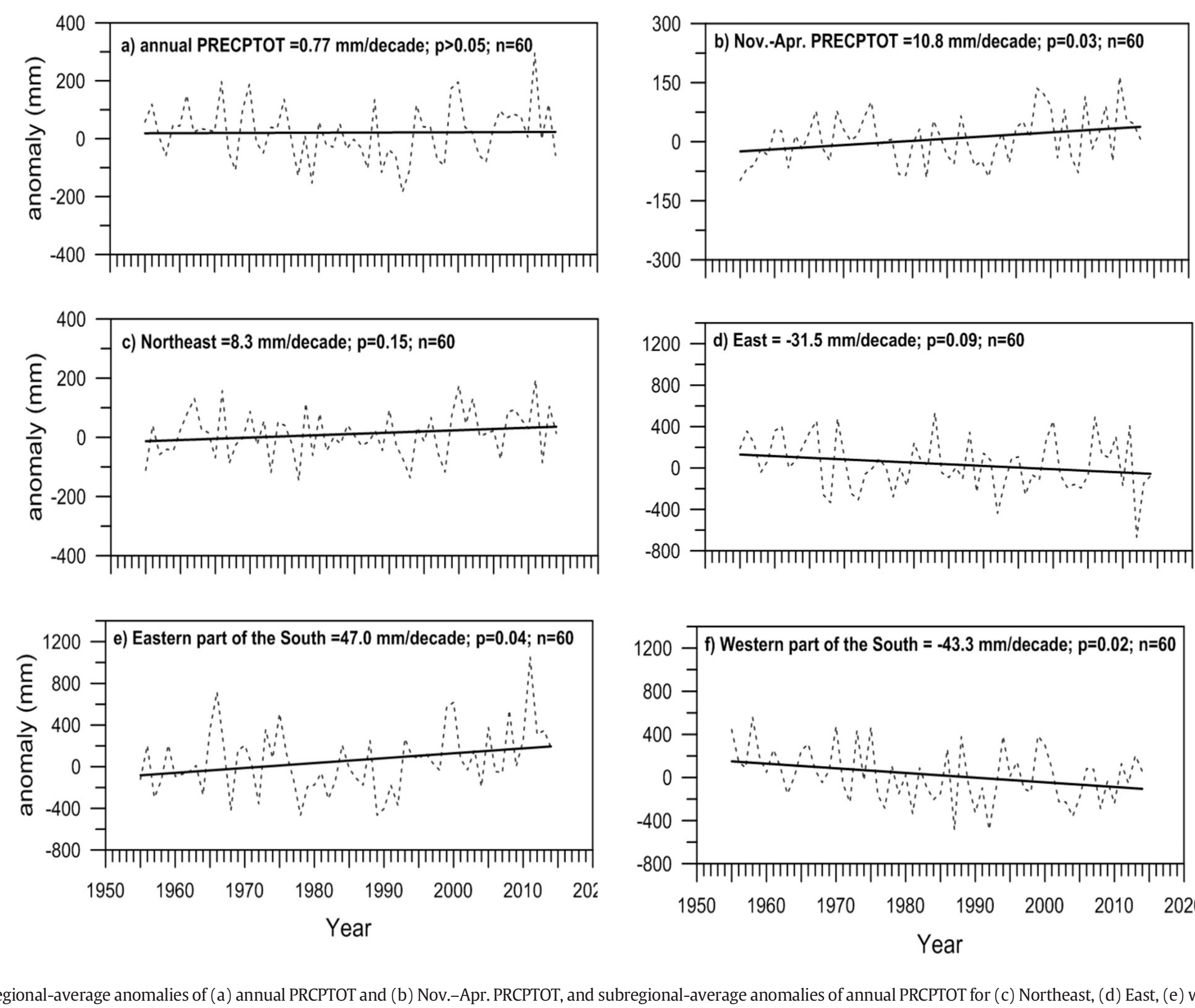

Fig. 3. Regional-average anomalies of (a) annual PRCPTOT and (b) Nov.–Apr. PRCPTOT, and subregional-average anomalies of annual PRCPTOT for (c) Northeast, (d) East, (e) western part of the South and (f) eastern part of the South. The solid lines represent linear trends, and the significance of the trends was assessed by Kendall's tau test. The 1971–2000 means at the individual stations for PRCPTOT which the anomalies are departure from are in range of 981–4718 mm.

On a seasonal basis, the distinctive features of the trends in PRCPTOT differed between the wet season and the dry season (Fig. 2b and c). There was an approximately equal number of stations with increasing and decreasing trends in PRCPTOT from the May to Oct. period (Fig. 2b). In contrast, the PRCPTOT trends from the Nov. to Apr. period exhibited different spatial patterns, with comparatively larger magnitudes of changes observed in the lower part of the South (Fig. 2c) because this period corresponds to the rainy season in the eastern part of southern Thailand. The majority of stations recorded increasing trends in the Nov.–Apr. PRCPTOTs, with 34.1% of the stations revealing a significant increase. The weighted regional-average anomalies of the Nov.–Apr. PRCPTOT series displayed an upward trend of 10.8 mm per decade with significance at the 95% level of confidence (Fig. 3b). The recent increase in the Nov.–Apr. PRCPTOT in southern Thailand appears to have coincided with the changes in the decade-long variations in the East Asian winter monsoon, especially the northward–southward shift in its trough axis and the active outbreaks of cold surges (Wang et al., 2009a). Climate variations associated with the East Asian winter monsoon often bring not only heavy precipitation events but also hydrometeorological disasters to Southeast Asia (Hong and Li, 2009; Tangang et al., 2008). The severe floods that occurred in southern Thailand and southern Peninsular Malaysia in November 2000, December 2006–January 2007 and March 2011 are the most recent devastating consequences of heavy precipitation events induced by the active cold surge outbursts that are associated with strong East Asian winter monsoons (Peterson et al., 2012; Tangang et al., 2008; Wangwongchai et al., 2005).

3.2. Trends in annual/seasonal RD and SDII

The annual RD and May–Oct. RD (Fig. 4a and b) were dominated by negative trends across most of Thailand. This result indicates that precipitation events, especially during the summer monsoon season when the precipitation amounts account for 60%–90% of the annual totals in most parts of the country, have been generally becoming less frequent. The significant decreasing trends in annual RD and May–Oct. RD, which ranged from -5.9 to -1.3 days per decade, were observed at 15 (36.6%) stations and 17 stations (41.5%), respectively, and were geographically concentrated in the Central, East and South (Fig. 4a and b). When considering Thailand as a whole, the annual RD and May–Oct. RD significantly decreased at the rates of 0.99 and 0.97 days per decade, respectively (Fig. 5a and b).

Fig. 6a illustrates the spatial distribution maps of the trends in annual SDII. A noteworthy pattern evident in Fig. 6a is the dominance of increasing trends in annual SDII (39 stations (95.1%)) across Thailand, with statistically significant increases observed at 22 stations (53.7%). The magnitudes of the significant positive trends in annual SDII ranged between 0.24 and 0.73 mm day^{-1} per decade. An analysis also revealed that there are a number of stations recording significant trends in SDII in the wet season, with the majority of stations having a 0.33–0.56 mm day^{-1} per decade. Our result reasonably suggests that the widespread increase in SDII throughout most of Thailand reflects a reduction in the number of rainy days rather than an increase in the precipitation totals. When considering the entire country, the weighted regional-average anomaly time series of annual SDII for the period from 1955 to 2014 exhibited significant positive trends at the rate of 0.17 mm day^{-1} per decade (Fig. 5c).

A consideration of the observed trends in PRCPTOT, RD and SDII together suggests that while precipitation has become less frequent in most parts of Thailand, precipitation events have become more intense. These findings agree with a number of previous studies illustrating increases in precipitation intensity in many parts of the world (e.g., Alexander et al., 2006; Caesar et al., 2011; Endo et al., 2009; Moberg et al., 2006) and also provide further insight into how precipitation characteristics have changed at a smaller spatial scale.

3.3. Trends in the magnitude and frequency of extreme precipitation events

A notable response was also evident for the index measuring the magnitude of intense precipitation on very wet day events (R95p). Similar to SDII, the R95p result revealed that the majority of stations had an increasing trend toward wetter conditions (Fig. 6b). Statistically significant upward trends, which ranged from 21.0 to 86.8 mm per decade, occurred at 36.6% of the stations (Fig. 6b). To further investigate the contributions from very wet days to the annual precipitation totals, the R95pT index, defined as the ratio of R95p/total precipitation was calculated, and a spatial map of the estimated trends is displayed in Fig. 6c. Comparatively, the station-by-station trends in R95pT displayed similar spatial distributions to those of R95p, and a large percentage (75.6%) of stations recorded positive trends (Fig. 6b and c). There were 15 stations (36.6%) that had significant increases, at an average rate of 1.8% per decade, and half of these stations, which are distributed across most of the country, experienced a 1.7%–2.4% per decade increase in R95pT (Fig. 6c).

The dominance of positive trends for both the R95p and R95pT indices, therefore, resulted in significant increases in the region-wide weighted average time series of R95p and R95pT of 71.4 mm and 2.9%, respectively since 1955 (Fig. 7a and b). These results indicate spatially coherent changes in precipitation extremes at local scale and the intensity of heavy precipitation events contributed an increasing fraction of the annual total precipitation. Similar increases in R95p and R95pT have been previously detected over many regions for which high-quality instrumental records were available (e.g., Alexander et al., 2006; Caesar et al., 2011; Klein Tank et al., 2006). Alexander et al. (2006) found that the R95p averaged over the global land area significantly increased by 4.68 mm per decade from 1971 to 2003. Moreover, significant positive trends in the occurrence of heavy precipitation events (top 10% by precipitation amounts) were found in the tropics for the period from 1979 to 2003, based on an analysis of two blended space-based and ground-based global precipitation data sets (Lau and Wu, 2007). When examining the data further into the tail of the precipitation distribution, significant changes were not detected for the amounts of precipitation on extremely wet days (above the 99th percentile).

Fig. 8a and b show the spatial patterns for the trends in RX1day and RX5day which represent, respectively, the maximum 1-day and 5-day rainfall totals, which can have significant impacts on society (Kenyon and Hegerl, 2010; Min et al., 2011). From Fig. 8a and b, it is evident that the RX1day and RX5day indices exhibit irregular spatial trends. The stations with a greater prevalence of positive (68.3% and 63.4%, respectively) than negative trends were observed across the country. Notable and significant coherent increases in RX1day and RX5day occurred at two stations located along the Gulf of Thailand (Fig. 8a and b). As a result of the greater fraction of positive trends and the exceptionally large significant trend magnitudes, the weighted average anomalies of the RX1day and RX5day series for Thailand as a whole displayed noticeable upward trends, with statistical significances at the 90%–95% level of confidence (Fig. 9a and b).

The varied patterns in which the number of stations with positive and negative trends was comparable to those for PRCPTOT were also observable for R20 (Fig. 8c). This pattern averaged out to a nonsignificant negative trend in R20 for Thailand as a whole (Fig. 9c). Only 22.0% of the station trends were significant at the 95% confidence level in either direction, and these trends were geographically distributed across the Central, East and Northeast (Fig. 8c).

3.4. Trends in the duration of extreme precipitation events

An analysis of the indices of the duration of extreme precipitation events also provided evidence for a widespread reduction in CWD throughout the region for the period from 1955 to 2014. Similar to RD (Fig. 4a), a large percentage of stations exhibited downward trends in CWD, with 36.6% of the stations recording significant decreases

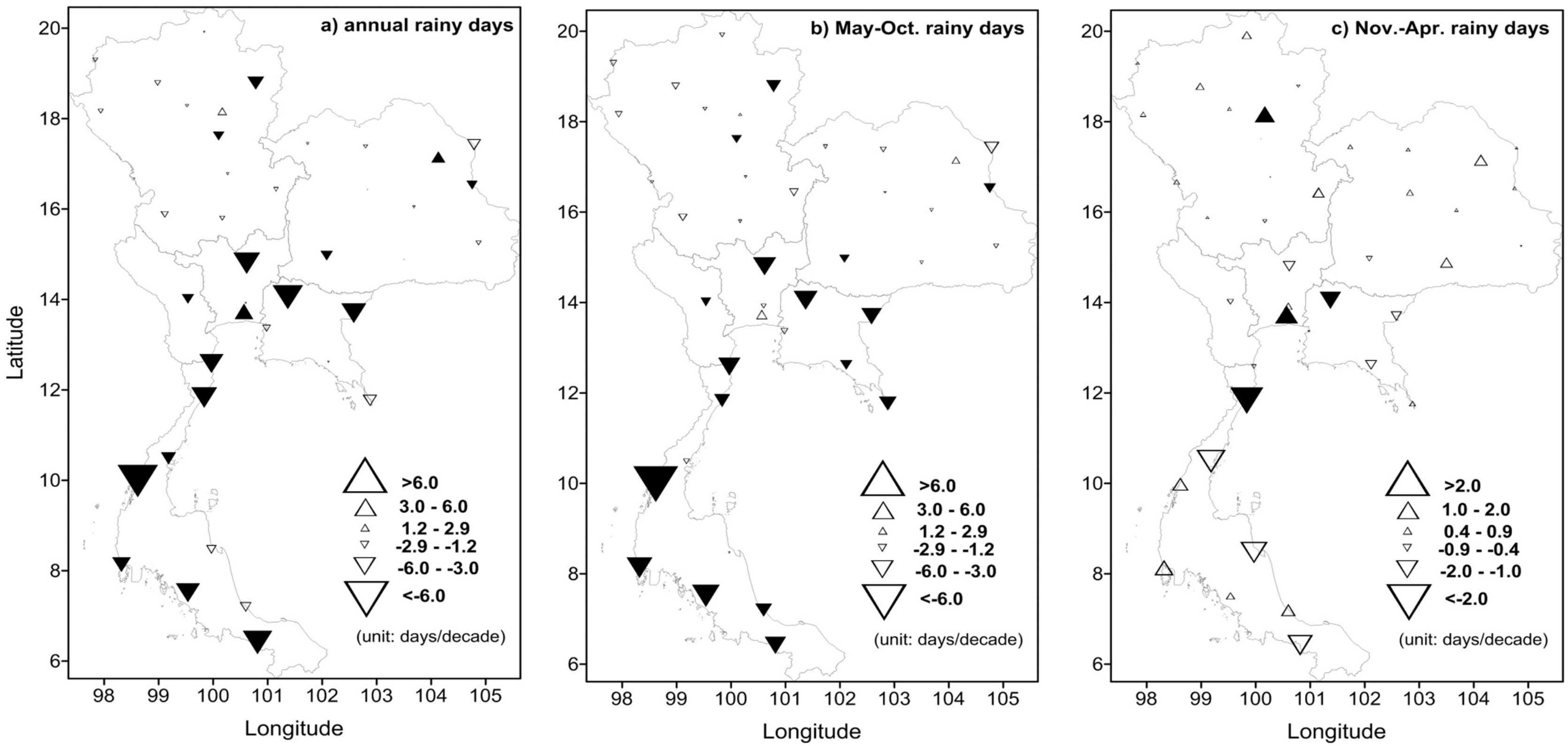

Fig. 4. Same as Fig. 2 but for (a) RD, (b) May–Oct. RD and (c) Nov.–Apr. RD. Note the different scale in (c).

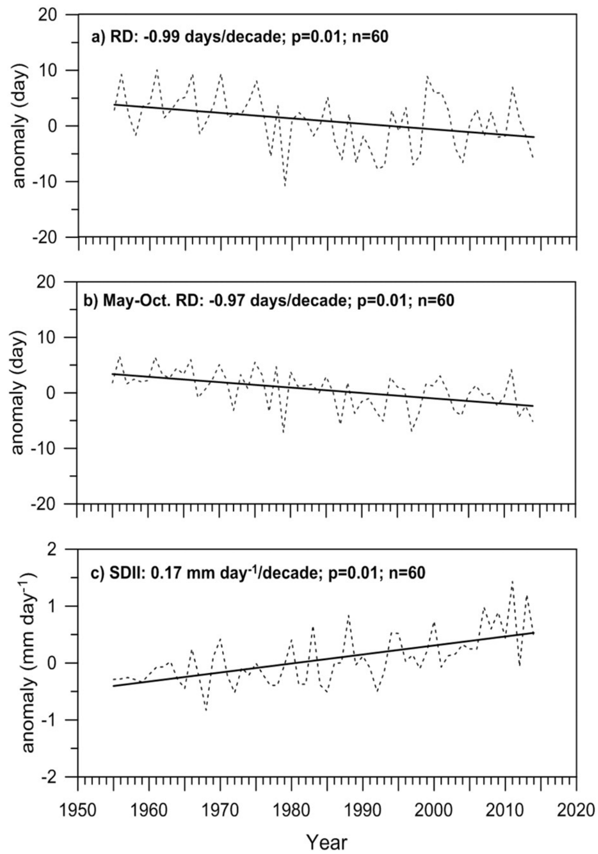

Fig. 5. Regional-average anomalies of (a) RD, (b) May–Oct. RD and (c) SDII. Solid lines represent linear trends, and the significance of the trends was assessed by Kendall's tau test. The 1971–2000 means at the individual stations for RD, May–Oct RD and SDII which the anomalies are departure from are in range of 80.5–178.7 days, 66.5–141.6 days and 9.94–28.17 mm day^{-1}, respectively.

(Fig. 10a). Across Thailand, the statistically significant trends in CWD were geographically concentrated in the central, southern and eastern parts of the country (Fig. 10a). When averaging all stations together for the 60-year period (1955–2014), the CWD in Thailand decreased significantly by 0.27 days per decade (Fig. 11a). A significant decrease similar to that detected in Thailand was also observed for CWD averaged over the entire global land area for the period from 1971 to 2003 (Alexander et al., 2006).

The other duration indicator, CDD, generally exhibited the opposite sign compared with CWD (Fig. 10b). The result of CDD revealed a general drying pattern for the period from 1955 to 2014, with two stations having statistically significant trends (Fig. 10b). Although the spatial coverage of the increasing trends in CDD was consistent across most of the region (Fig. 10b), there was no statistically significant regional trend (Fig. 11b).

3.5. Relationships between precipitation indices and the ENSO and PDO

The Spearman's rank-order correlation coefficients calculated from the de-trended annual series of the MEI and PDOI and the region-wide weighted-average precipitation indices (Table 3) revealed significant correlations for most of precipitation indices (PRCPTOT, RD, SDII, R95p, R99p, RX1day, R20 and CDD). Correlation analysis showed that stronger relationships were observed for the indices representing the mean states of precipitation (PRCPTOT and RD) (Table 3, Fig. 12a, and b). Both of these indices were negatively correlated at the 5% significance level with the MEI and PDOI at many stations across the entire country (Figs.13a, b and 14a, b). The observed relationships indicate that positive/negative anomalies of PRCPTOT and RD on interannual-to-interdecadal time scales appear to be in phase with the cold/warm phases of the ENSO and PDO (negative/positive MEI and PDOI). During the 5 exceptionally negative values of the MEI (1956, 1974, 1975, 1999 and 2011) and the PDO cool phase from 1955 to 1976, Thailand not only tended to have greater total precipitation amounts but also received more frequent precipitation events (Figs. 15a, b and 16a, b). In contrast, negative anomalies of PRCPTOT and RD were evident during the 5 positive MEI years (1977, 1982, 1987, 1992 and 1997) and the PDO warm phase from the late 1970s to the mid 1990s (Figs. 15a, b and 16a, b). Our results are consistent with the recent study of Ouyang et al. (2014), showing that precipitation in the majority of China decreased during El Niño/PDO warm phase periods and increased during La Niña/PDO cool phase periods. Sen Roy and Sen Roy (2011) also showed that precipitation patterns in Myanmar exhibited different responses in El Niño periods during PDO warm/cool phases.

The scatter plots of the MEI versus the area-averaged PRCPTOT and RD show a tendency for asymmetries in the relationships (Fig. 15a and b). The magnitudes of El Niño years (positive MEI) exert a greater influence on these precipitation indices than the strength of La Niña years (negative MEI) does; the slopes of lines of best fit in both plots are significantly different from zero only for El Niño years (Fig. 15a and b). For RD, the asymmetric relationship with the PDOI was also observed (Fig.16b). It may indicate that the asymmetry of decadal variability in the relationship between the PDO and RD in Thailand is enhanced during the warm PDO regime and is nonexistent during the cool PDO regime. A symmetric relationship between ENSO and precipitation has been previously observed in the whole of Australia where the strength of El Niño events has little effect on precipitation across a season, whereas the magnitude of La Niña events seems to play a major role (Power et al., 2006). Our results are in line with the previous studies which demonstrated that the precipitation anomalies in Southeast Asia depend strongly on the phase of the ENSO and PDO phenomena (e.g., Juneng and Tangang, 2005; Nguyen et al., 2014; Sen Roy and Sen Roy, 2011; Singhrattna et al., 2005).

The correlations between MEI and PDOI and the other extreme precipitation indices (SDII, R95p, R99p, R20, RX1day and CDD) were generally weaker, but they were still significant when considering both Thailand as a whole (Table 3, Fig. 12c and d) and at a number of individual stations (Figs. 13c, d, 14c and 15d). It should be noted that these extreme precipitation indices had stronger relationships with the PDOI than the MEI (Table 3). The relationships between the extreme precipitation indices and the MEI and PDOI imply that for the El Niño (La Niña) years and the PDO warm (cool) regimes, the interannual-to-interdecadal variability in the frequency and magnitude of heavy and more intense precipitation events tended to be reduced (enhanced). Significant relationships between ENSO/PDO and variations of extreme rainfall events were also reported in southern México, with extreme events tending to occur more frequently during La Niña periods and during the positive phase of the PDO (Peralta-Hernández et al., 2009). The results of ENSO-extreme precipitation index relationships are in agreement with the study of Kenyon and Hegerl (2010), suggesting that the extreme values of precipitation indices (RX1day, RX5day, R95p and R99p) are much lower in Southeast Asia during an El Niño event. Consistent changes were also reported by Caesar et al. (2011), who found that extreme indices related to periods of heavy rainfall (R10 and R20) appear to be positively correlated with a La Niña-like SST pattern over the Indo-Pacific region. Note that no asymmetric relationships have been found for R20, R95p (Figs. 15c, d and 16c, d) and other extreme indices. Unlike eastern Australia, a nonlinear relationship between ENSO and extreme rainfall has been observed. That is, the strength of a La Niña episode has a much greater influence on the intensity and duration of RX5day than the magnitude of an El Niño episode (King et al., 2013). The relationships between MEI and PDOI and CDD at both national and station levels were marked by positive correlations (Table 3). That is, during La

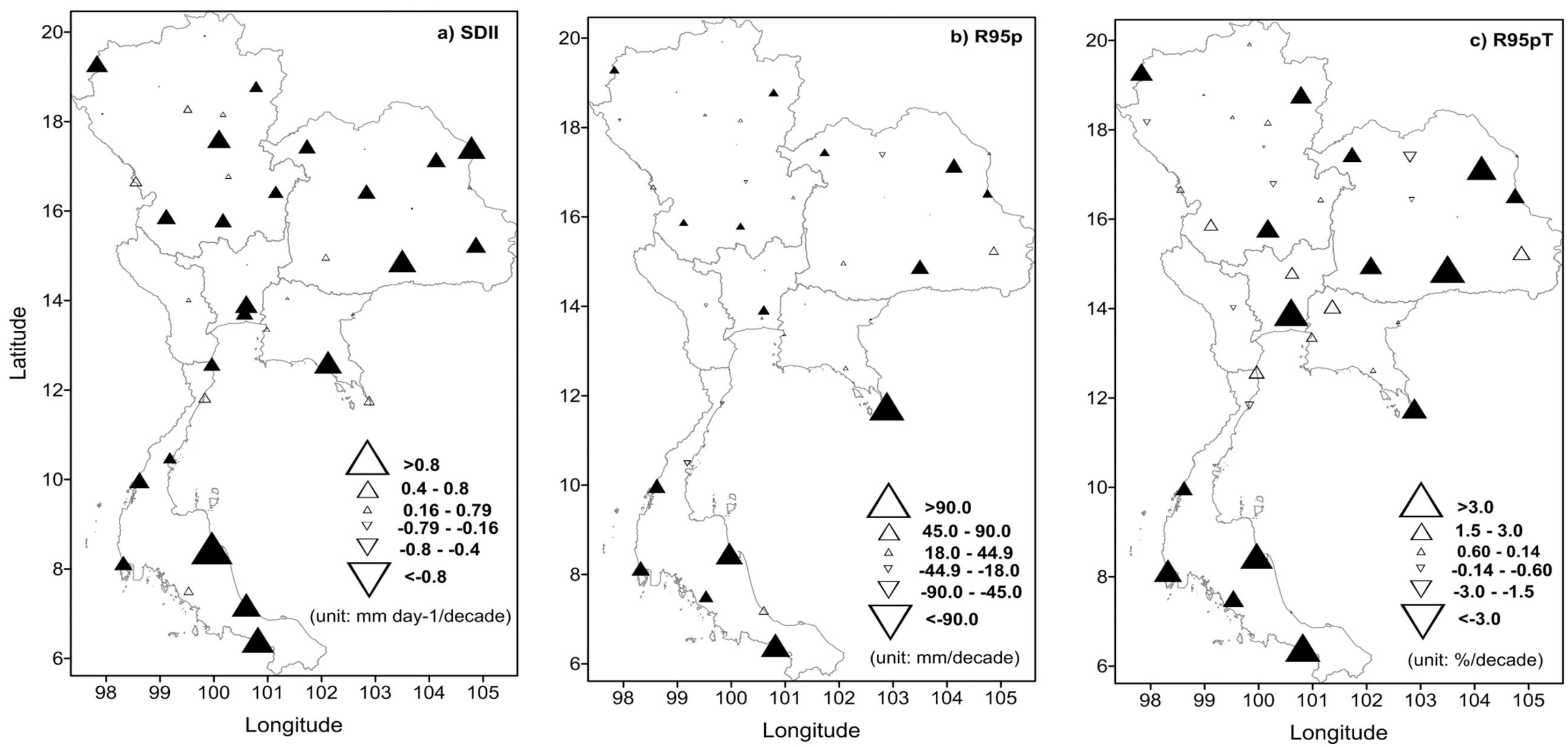

Fig. 6. Same as Fig. 2 but for (a) SDII, (b) R95p and (c) R95pT.

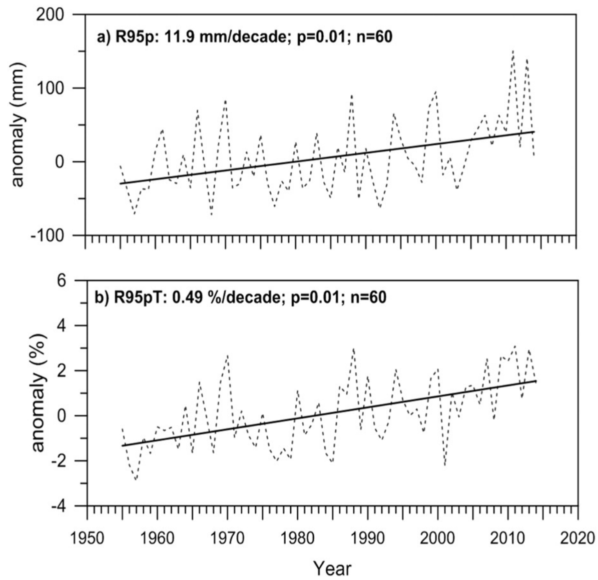

Fig. 7. Same as Fig. 5 but for (a) R95p and (b) R95pT. The 1971–2000 means at the individual stations for R95p and R95pT which the anomalies are departure from are in range of 248.4–1261.1 mm and 22.4%–32.0%, respectively.

Niña (El Niño) years and the PDO cool (warm) phases, the annual number of periods with consecutive dry days in Thailand tended to be shorter (longer) than normal, similar to what has been observed in the Hawaiian Islands (Chu et al., 2010).

4. Discussions and conclusions

This study examined the variability and trends of a set of indices mainly describing changes in total and extreme precipitation in Thailand for the period from 1955 to 2014. The indices represent a number of statistical-based characteristics that are both convenient and easy-to-understand tools available to policy makers and non-specialists (Peterson and Manton, 2008; Klein Tank et al., 2009; Zhang et al., 2011). This detection method is also helpful for providing an important context for the interpretation of individual, complex-driven extreme events and for evaluating the ability of models to simulate events that are affected by a number of different mechanisms (Peterson et al., 2012).

Analysis of numerous series at a station scale can uncover some interesting characteristics of ENSO- and PDO-related interannual-to-interdecadal variability in total and extreme precipitation in Thailand and also assess the significant, coherent long-term trends. From a long-term perspective, the results indicate that while precipitation has become less frequent in most parts of Thailand with a significant reduction in the occurrence of consecutive wet days, precipitation events have become more intense. The indices that measure the amount of intense precipitation contributed by very wet day events and the maximum single-day precipitation amounts also indicated a trend toward wetter conditions (Figs. 6b, 7a, 8a and 9a), with heavy precipitation events contributing an increasing fraction of annual totals (Figs. 6c and 7b). One consequence of changes in these indices is the increased frequency and severity of flash floods, as recently evidenced in many parts of Thailand (CRED, 2014; Dartmouth Flood Observatory, 2014; GISTDA, 2014). Of the eleven indices examined for the period from 1955 to 2014, the PRCPTOT during the Nov.–Apr. period, RD, SDII, R95p, R95pT, RX1day and CWD demonstrated spatially coherent patterns, with the regional-average annual series exhibiting significant trends (Figs. 2c, 3b, 4–7, 8a, 9a, 10a and 11a). The changes in precipitation extremes reported in this study are generally consistent with the regional results observed for the Asia-Pacific Network and Indo-Pacific regions (Caesar et al., 2011; Choi et al., 2009; Cinco et al., 2014; Endo et al., 2009). Compared with the regional studies of Endo et al. (2009), Caesar et al. (2011) and Choi et al. (2009), however, this study provides a more detailed picture of the spatially coherent trends in precipitation extremes at a sub-national scale, and documents the more recent changes that have occurred in the twenty-first century, which will help inform decisions concerning effective management strategies based on recent conditions.

On interannual-to-interdecadal timescales, observed significant relationships between precipitation indices and the MEI and PDOI were found (Table 3), providing additional evidence that large-scale climate phenomena in the Pacific Ocean are remote drivers of variability in Thailand's total and extreme precipitation. These results also support previous statements that ENSO activity is the principal large-scale forcing of the year-to-year precipitation variability in the Indo-Pacific (e.g., Juneng and Tangang, 2005; Kenyon and Hegerl, 2010; Caesar et al., 2011; Nguyen et al., 2014; Villafuerte et al., 2014). The negative correlations between various precipitation indices and the MEI and PDOI imply that Thailand tends to have abundant precipitation and more extreme events in La Niña years and the PDO cool phase, whereas there is a lower-than-normal amount of precipitation and fewer extreme events during El Niño years and the PDO warm phase. It has been suggested that shifts in the Walker circulation induced by anomalous SST conditions in the eastern Pacific appear to be the dominant mechanism whereby ENSO events alter the convergence of atmospheric moisture and convective cells in the Indo-Pacific sector and, consequently, influence precipitation in Southeast Asia (Juneng and Tangang, 2005; Nguyen et al., 2014; Singhrattna et al., 2005). Changes in the large-scale vertical atmospheric motion associated with ENSO events have also been reported to play an important role in weakening monsoons and reducing precipitation over Thailand (Juneng and Tangang, 2005; Singhrattna et al., 2005; Wang et al., 2003). A La Niña-related increase in the formation of tropical cyclones and changes in the storm tracks of the western Pacific is a possible explanation for the increase in heavy precipitation days across the Indo-Pacific region (Caesar et al., 2011). Interannual variations in extreme precipitation indices in the Philippines were found to be influenced greatly by the ENSO, and El Niño (La Niña) events were associated with statistically significant drier (wetter) conditions (Villafuerte et al., 2014). Krishnamurthy and Krishnamurthy (2014) found that changes in the Walker circulation over the Pacific and Indian Oceans also depend on the phase of the PDO. As a consequence, the mechanism by which the PDO affects the Indian summer monsoon rainfall is determined by the associated Hadley circulation in the monsoon region (Krishnamurthy and Krishnamurthy, 2014). To extend our knowledge of the influences of large-scale remote forcing on interannual-to-interdecadal variations in total and extreme precipitation within the local contexts to which Thai societies need to adapt, however, further investigation of physical mechanisms underlying the ENSO- and PDO-extreme precipitation linkage is required. Interdecadal modulations of the ENSO-extreme precipitation teleconnections related to SST patterns associated with the PDO are not studied here but require further investigation as well.

Another noteworthy feature observed from this study is that Bangkok Metropolis has experienced wetter and more intense conditions and a concomitant increase in the frequency and magnitude of heavy precipitation events (Figs. 2a, 6 and 8). Similar increases in precipitation and predominant changes in extreme precipitation events have been documented in several urban areas across the globe, such as large cities in the USA and India (Mishra and Lettenmaier, 2011; Kishtawal et al., 2010; Pingale et al., 2014), Beijing, China (Wang et al., 2009b), São Paulo, Brazil (Silva Dias et al., 2012) and Tokyo (Sato and Takahashi, 2000). For example, Kishtawal et al. (2010) found a significantly increasing trend in the frequency of heavy rainfall events over urban regions of India during the monsoon season. Several factors, including alternations in the hydro-meteorological and thermodynamic conditions of urban environments, changes in the convective available potential energy and urban heat island effects have been suggested as

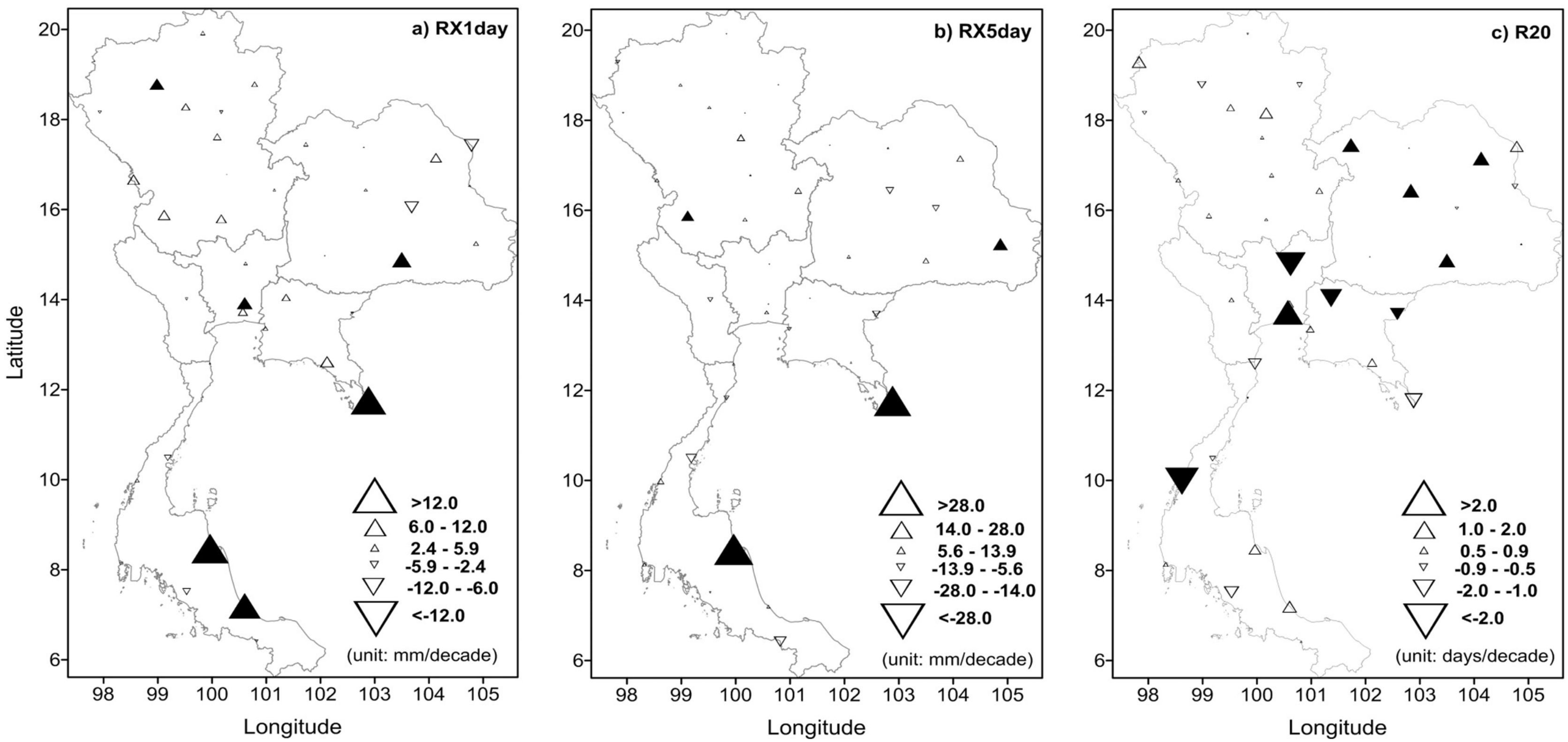

Fig. 8. Same as Fig. 2 but for (a) RX1day, (b) RX5day and (c) R20.

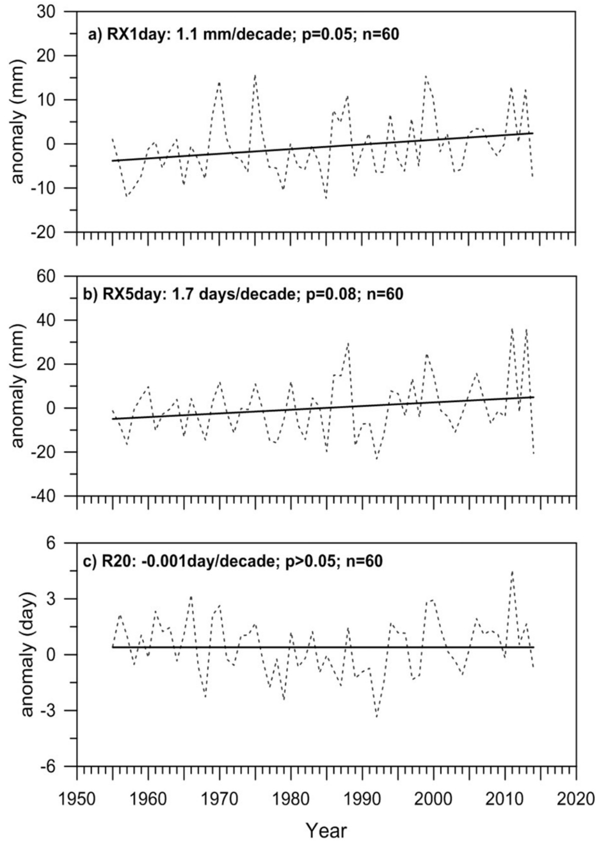

Fig. 9. Same as Fig. 5 but for (a) RX1day, (b) RX5day and (c) R20. The 1971–2000 means at the individual stations for RX1day, RX5day and R20 which the anomalies are departure from are in range of 67–254 mm, 120–561 mm and 14.6–68.8 days, respectively.

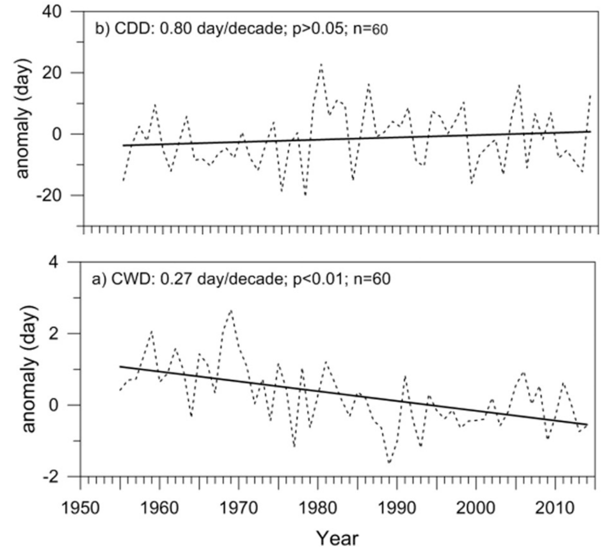

Fig. 11. Same as Fig. 5 but for (a) CWD and (b) CDD. The 1971–2000 means at the individual stations for CDD and CWD which the anomalies are departure from are in range of 24.2–111.7 and 6.4–28.2 days, respectively.

possible causes of the impacts of urbanization on precipitation (e.g., Shepherd, 2005; Kishtawal et al., 2010). While the mechanisms underlying the enhancement of precipitation in Bangkok Metropolis require further study, the results indicate that this low-lying mega city is likely to be at a greater risk of disasters associated with increased precipitation extremes, including coastal and flash floods.

The results also revealed that in 2011, when Thailand experienced the worst and most extensive flooding during the 60-year record examined, it was a year of exceptionally extreme precipitation events (Figs. 3a, 5c, 7 and 9). van Oldenborgh et al. (2012) examined the variations in precipitation in the middle and upper Chao Phraya basin

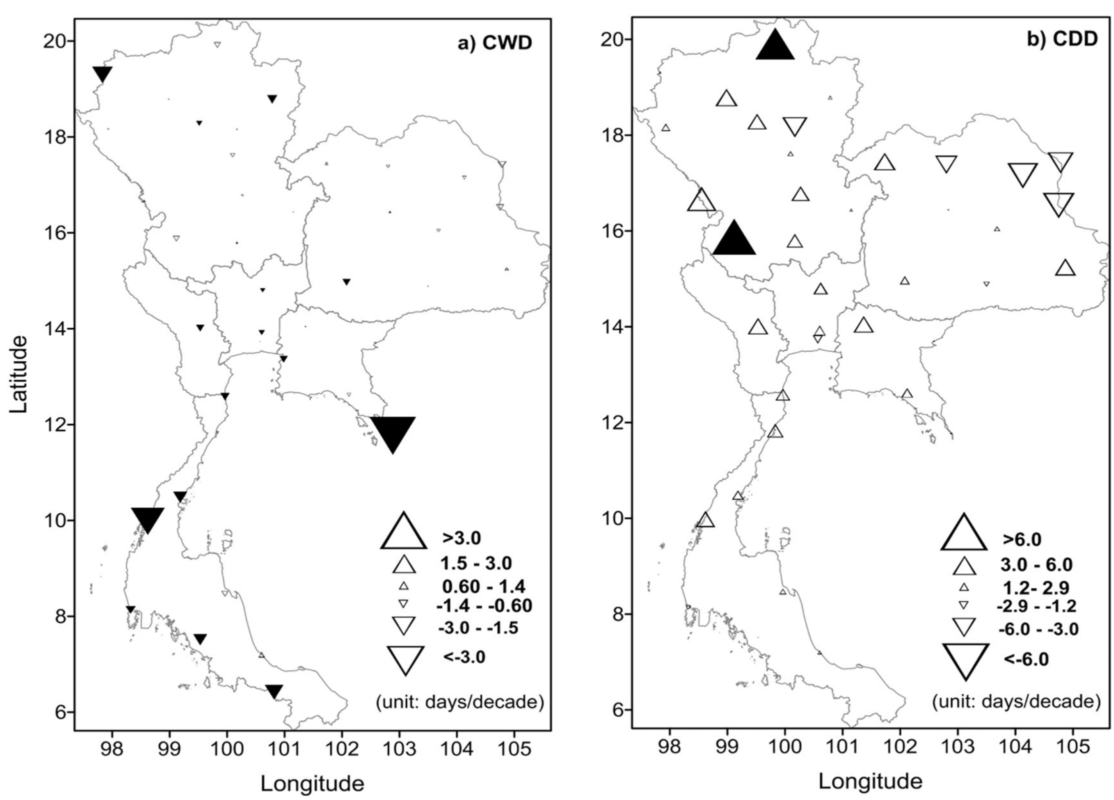

Fig. 10. Same as Fig. 2 but for (a) CWD and (b) CDD.

Table 3
The Spearman's rank correlation coefficients between the de-trended annual series of the Multivariate ENSO Index (MEI), PDO index (PDOI) and those of the all-station weighted averages of precipitation indices.

	MEI	PDO
PRCPTOT	−0.48**	−0.48**
RD	−0.50**	−0.49**
SDII	−0.25*	−0.26*
R95p	−0.36*	−0.40**
R99p	−0.25*	−0.30*
RX1day	−0.30*	−0.38**
RX5day	−0.22	−0.11
R20	−0.41**	−0.43**
CWD	−0.05	−0.17
CDD	0.35*	0.40**

The sample size for each series used for correlation analyses = 60.
* Significant at the 5% level.
** Significant at the 1% level.

during 1915–2011 and found that the monsoon season in 2011 was the wettest on record. The total rainfall in the Chao Phraya River watersheds during the 2011 rainy season was 143% of the 1982–2002 average (Komori et al., 2012), resulting from persistent monsoonal rains combining with the remnants of a series of tropical storms and strong low-pressure systems (Kure and Tebakari, 2012). The increased rainfall doubled runoff which was over the total reservoir capacity of the gigantic Bhumipol and Sirikit dams (Kure and Tebakari, 2012; Komori et al., 2012). This flood caused tremendous damage, including seven industrial estates and 804 companies with inundation damage, and total losses estimated at 1.36 trillion baht (Komori et al., 2012). Remarkable increases in precipitation extremes in combination with other non-meteorological factors, such as changes in the hydrology and land use of the area as well as the reservoir operation policies, appear to be key factors in determining the unprecedented scale of the 2011 Thailand flood disaster. van Oldenborgh et al. (2012) pointed out that anthropogenic climate change was not a significant factor in the 2011 Thailand floods. However, simulations by high-resolution regional climate models may help to reveal the physical mechanisms underlying past changes and to project future trends in precipitation extremes. Such attribution studies will provide scientific information in support of a master plan on climate-induced flood management, in which the Thai government will invest at least 10 billion USD in upcoming years (NESDB, 2012).

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References

Aguilar, E., Auer, I., Brunet, M., Peterson, T.C., Wieringa, J., 2003. Guidelines on climate metadata and homogenization. Report WMO-TD 1186. World Meteorological Organization, Geneva, Switzerland (50 pp.).
Aguilar, E., et al., 2005. Changes in precipitation and temperature extremes in Central America and northern South America. J. Geophys. Res. 110, D23107–2003. http://dx.doi.org/10.1029/2005JD006119.
Alexander, L.V., et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res. 111, D05109. http://dx.doi.org/10.1029/2005JD006290.
Allan, R.P., Soden, B.J., 2008. Atmospheric warming and the amplification of precipitation extremes. Science 321, 1481–1484. http://dx.doi.org/10.1126/science. 1160787.
Barretta, C.B., Santos, P., 2014. The impact of changing rainfall variability on resource-dependent wealth dynamics. Ecol. Econ. 105, 48–54. http://dx.doi.org/10.1016/j.ecolecon.2014.05.009.
Caesar, J., et al., 2011. Changes in temperature and precipitation extremes over the Indo-Pacific region from 1971 to 2005. Int. J. Climatol. 31, 791–801. http://dx.doi.org/10.1002/joc.2118.
Cao, L.-J., Yan, Z.-W., 2012. Progress in research on homogenization of climate data. Adv. Clim. Chang. Res. 3, 59–67. http://dx.doi.org/10.3724/SP.J.1248.2012.00059.
Choi, G., et al., 2009. Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. Int. J. Climatol. 29, 1906–1925. http://dx.doi.org/10.1002/joc.1979.
Chu, P.-S., Chen, Y.R., Schroeder, T.A., 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. J. Clim. 23, 4881–4900. http://dx.doi.org/10.1175/2010JCLI3484.1.
Cinco, T.A., de Guzman, R.G., Hilario, F.D., Wilson, D.M., 2014. Long-term trends and extremes in observed daily precipitation and near surface air temperature in the Philippines for the period 1951–2010. Atmos. Res. 145–146, 12–26. http://dx.doi.org/10.1016/j.atmosres.2014.03.025.
Coumou, D., Rahmstorf, S., 2012. A decade of weather extremes. Nat. Clim. Chang. 2, 491–496. http://dx.doi.org/10.1038/NCLIMATE1452.
CRED, 2014. The International Disaster Database, Center for Research on the Epidemiology of Disasters (Available online http://www.emdat.be/ (accessed on 1 September 2014)).
Domonkos, P., 2011. Homogenising time series: beliefs, dogmas and facts. Adv. Sci. Res. 6, 167–172. http://dx.doi.org/10.5194/asr-6-167-2011.

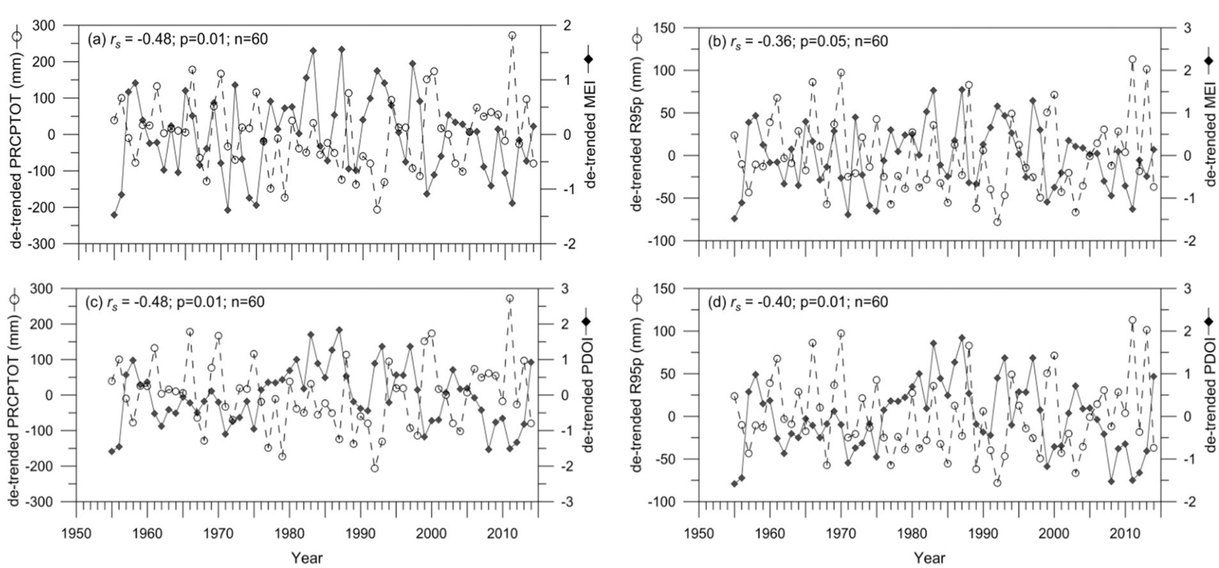

Fig. 12. De-trended annual time series plots between (a) PRCPTOT and MEI, (b) R95p and MEI, (c) PRCPTOT and PDOI and (d) R95p and PDOI. Note that PRCPTOT and R95p are all-station weighted averages series.

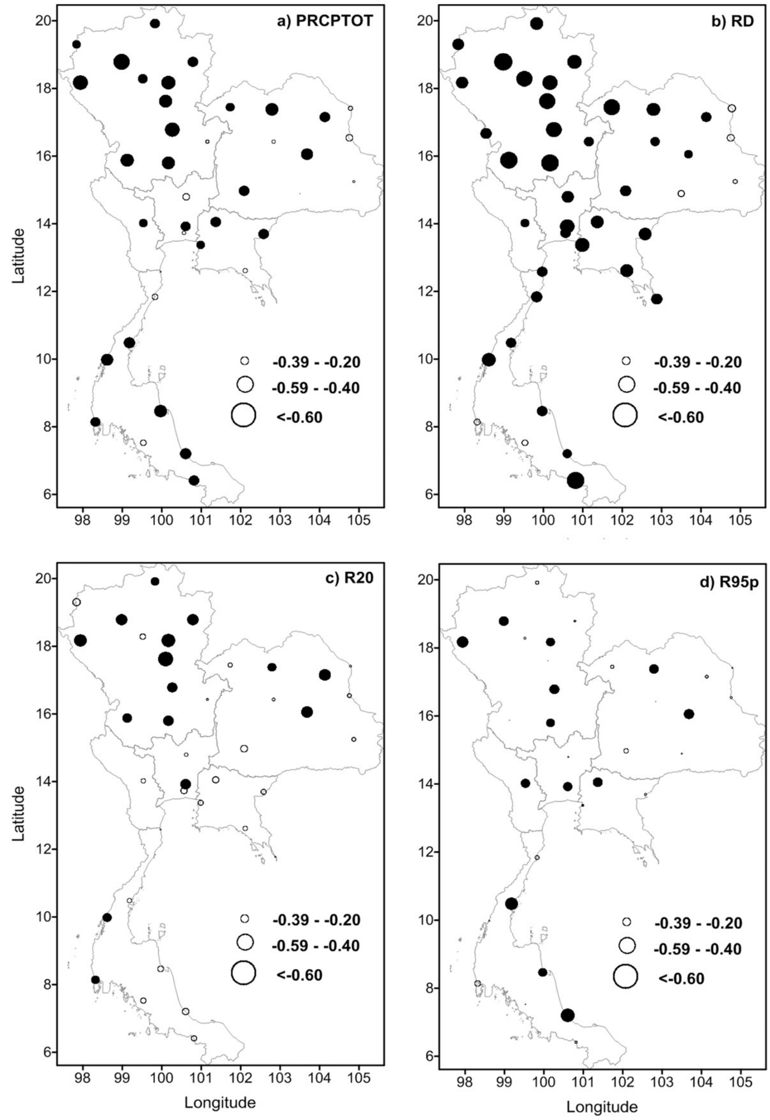

Fig. 13. Station-by-station Spearman's rank correlation coefficients between de-trended annual series of the Multivariate ENSO Index (MEI) and those of (a) PRCPTOT, (b) RD, (c) R20 and (d) R95p. Significant changes at the 5% level are indicated by filled black circles.

Donat, M.G., et al., 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J. Geophys. Res. Atmos. 118, 1–16. http://dx.doi.org/10.1002/jgrd.50150.

Donat, M.G., et al., 2014. Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. Int. J. Climatol. 34, 581–592. http://dx.doi.org/10.1002/joc.3707.

Endo, N., Matsumoto, J., Lwin, T., 2009. Trends in precipitation extremes over Southeast Asia. SOLA 5, 168–171. http://dx.doi.org/10.2151/sola.2009-043.

Flood Observatory, Dartmouth, 2014. Active Archives of Large Floods, 1985–Present (Available online http://www.dartmouth.edu/~floods/Archives/index.html (accessed on 1 September 2014)).

GISTDA, 2014. Thailand Flood Monitoring System, Geo-Informatics and Space Technology Development Agency (Available online http://flood.gistda.or.th/ (accessed 1 September 2014)).

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., Prince, K.X., 2006. Increasing trend of extreme rain events over India in a warming environment. Science 314, 1442–1445.

Griffiths, M.L., Bradley, R.S., 2007. Variation of twentieth-century temperature and precipitation extreme indicators in the Northeast United States. J. Clim. 20, 5401–5417. http://dx.doi.org/10.1175/2007JCLI1594.1.

Guan, K., Good, S.P., Caylor, K.K., Sato, H., Wood, E.F., Li, H., 2014. Continental-scale impacts of intra-seasonal rainfall variability on simulated ecosystem responses in Africa. Biogeosciences 11, 6939–6954. http://dx.doi.org/10.5194/bg-11-6939-2014.

Hoerling, M., Eischied, J., Perlwitz, J., 2010. Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. J. Clim. 23, 2131–2145. http://dx.doi.org/10.1175/2009JCLI3420.1.

Hong, C.-C., Li, T., 2009. The extreme cold anomaly over Southeast Asia in February 2008: roles of ISO and ENSO. J. Clim. 22, 3786–3801. http://dx.doi.org/10.1175/2009JCLI2864.1.

Juneng, L., Tangang, F.T., 2005. Evolution of ENSO-related rainfall anomalies in Southeast Asia region and its relationship with atmosphere–ocean variations. Clim. Dyn. 25, 337–350. http://dx.doi.org/10.1007/s00382-005-0031-6.

Kenyon, J., Hegerl, G.C., 2010. Influence of modes of climate variability on global precipitation extremes. J. Clim. 23, 6248–6262. http://dx.doi.org/10.1175/2010JCLI3617.1.

King, A.D., Alexander, L.V., Donat, M.G., 2013. Asymmetry in the response of eastern Australia extreme rainfall to low-frequency Pacific variability. Geophys. Res. Lett. 40, 1–7. http://dx.doi.org/10.1002/grl.50427.

Kishtawal, C.M., Niyogi, D., Tewari, M., Pielke, R.A. Sr, Shepherde, J.M., 2010. Urbanization signature in the observed heavy rainfall climatology over India. Int. J. Climatol. 30, 1908–1916. http://dx.doi.org/10.1002/joc.2044.

Klein Tank, A.M.G., et al., 2006. Changes in daily temperature and precipitation extremes in central and south Asia. J. Geophys. Res. 111, D16105. http://dx.doi.org/10.1029/2005JD006316.

Klein Tank, A.M.G., Zwiers, F.W., Zhang, Z., 2009. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. WMO-TD No. 1500 (56 pp. (WCDMP-72, WMO-TD/No. 1500)).

Komori, D., et al., 2012. Characteristics of the 2011 Chao Phraya River flood in Central Thailand. Hydrol. Res. Lett. 6. http://dx.doi.org/10.3178/HRL.6.41.

Krishnamurthy, L., Krishnamurthy, V., 2014. Influence of PDO on South Asian summer monsoon and monsoon–ENSO relation. Clim. Dyn. 42, 2397–2410. http://dx.doi.org/10.1007/s00382-013-1856-z.

Kure, S., Tebakari, T., 2012. Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. Hydrol. Res. Lett. 6, 53–58. http://dx.doi.org/10.3178/HRL.6.53.

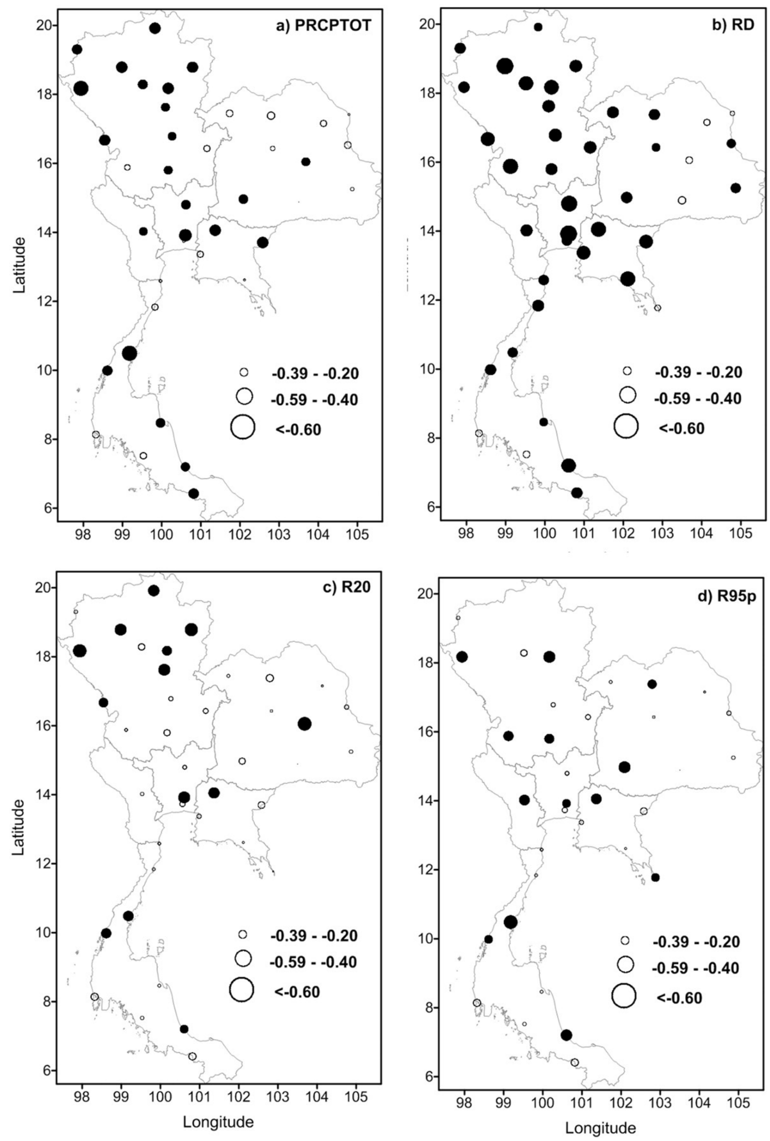

Fig. 14. Same as Fig. 13 but for PDOI.

Lau, K.-M., Wu, H.-T., 2007. Detecting trends in tropical rainfall characteristics, 1979–2003. Int. J. Climatol. 27, 979–988. http://dx.doi.org/10.1002/joc.1454.

Limjirakan, S., Limsakul, A., Sriburi, T., 2010. Trends in temperature and rainfall extremes in Bangkok Metropolitan area. J. Environ. Res. 32, 31–48.

Limsakul, A., Limjirakan, S., Suthamanuswong, B., 2007. Spatio-temporal changes in total annual rainfall and the annual number of rainy days in Thailand. J. Environ. Res. 29, 1–21.

Limsakul, A., Limjirakan, S., Sriburi, T., 2010. Observed changes in daily rainfall extremes along Thailand's coastal zone. J. Environ. Res. 32, 49–68.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.W., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. 78, 1069–1079.

Maraun, D., Osborn, T.J., Gillett, N.P., 2008. United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. Int. J. Climatol. 28, 833–842. http://dx.doi.org/10.1002/joc.1672.

McGree, S., et al., 2014. An updated assessment of trends and variability in total and extreme rainfall in the western Pacific. Int. J. Climatol. 34, 2775–2791. http://dx.doi.org/10.1002/joc.3874.

Min, S.-K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470, 378–381. http://dx.doi.org/10.1038/nature09763.

Mishra, V., Lettenmaier, D.P., 2011. Climatic trends in major U.S. urban areas, 1950–2009. Geophys. Res. Lett. 38, L16401. http://dx.doi.org/10.1029/ 2011GL048255.

Misra, V., DiNapoli, S., 2014. The variability of the Southeast Asian summer monsoon. Int. J. Climatol. 34, 893–901. http://dx.doi.org/10.1002/joc.3735.

Moberg, A., Jones, P.D., 2005. Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–99. Int. J. Climatol. 25, 1149–1171.

Moberg, A., et al., 2006. Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J. Geophys. Res. Atmos. 111, D22106. http://dx.doi.org/10.1029/2006JD007103.

NESDB, 2012. The master plan for water resource management of Thailand. Office of the National Economic and Social Development Board (Available online http:// http://ka.mahidol.ac.th/ (accessed 30 January 2015)).

Nguyen, D.-Q., Renwick, J., McGregor, J., 2014. Variations of surface temperature and rainfall in Vietnam from 1971 to 2010. Int. J. Climatol. 34, 249–264. http://dx.doi.org/10.1002/joc.3684.

Ouyang, R., et al., 2014. Linkages between ENSO/PDO signals and precipitation, streamflow in China during the last 100 years. Hydrol. Earth Syst. Sci. 18, 3651–3661. http://dx.doi.org/10.5194/hess-18-3651-2014.

Peralta-Hernández, A.R., Balling Jr., R.C., Barba-Martínez, L.R., 2009. Comparative analysis of indices of extreme rainfall events: variations and trends from southern México. Atmosfera 22, 219–228.

Peterson, T.C., Manton, M.J., 2008. Bull. Am. Meteorol. Soc. 89, 1266–1271. http://dx.doi.org/10.1175/2008BAMS2501.1.

Peterson, T.C., et al., 1998. Homogeneity adjustments of in situ atmospheric climate data: a review. Int. J. Climatol. 18, 1493–1517.

Peterson, T.C., Stott, P.A., Herring, S., 2012. Explaining extreme events of 2011 from a climate perspective. Bull. Am. Meteorol. Soc. 93, 1041–1067. http://dx.doi.org/10.1175/BAMS-D-12-00021.1.

Pielke Jr., R.A., Downton, M.W., 2000. Precipitation and damaging floods: trends in the United States, 1932–97. J. Clim. 13, 3625–3637.

Pingale, S.M., Khare, D., Jat, M.K., Adamowski, J., 2014. Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. Atmos. Res. 138, 73–90. http://dx.doi.org/10.1016/j.atmosres.2013.10.024.

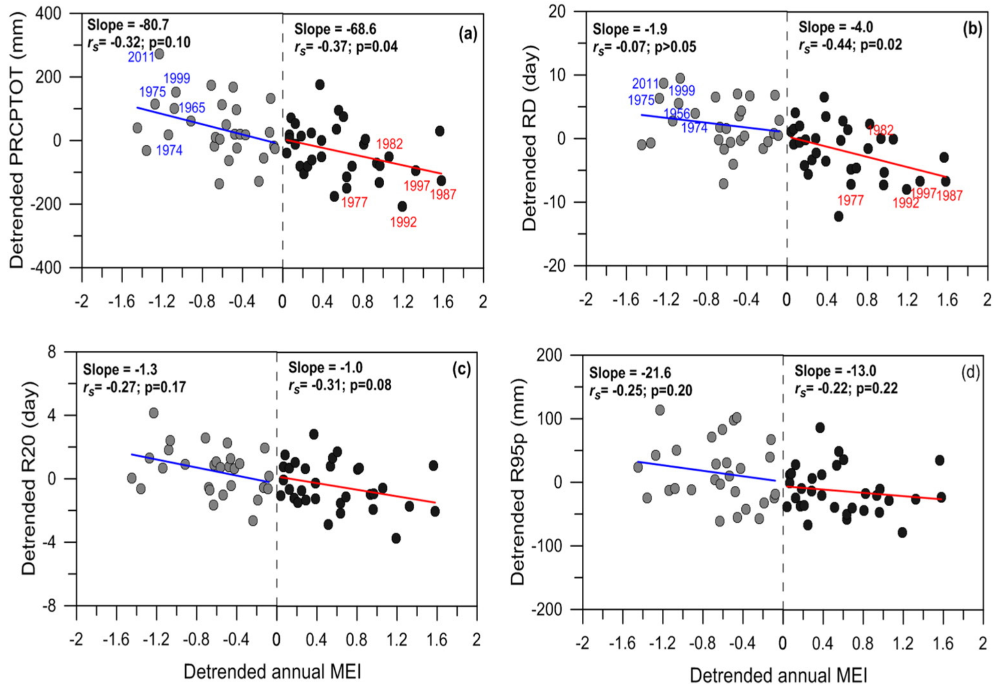

Fig. 15. Scatter plots for de-trended annual series of the MEI and de-trended annual area-average anomalies during 1955–2014 for (a) PRCPTOT, (b) RD, (c) R20 and (d) R95p.

Power, S., Haylock, M., Colman, R., Wang, X., Clim, J., 2006. The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. J. Clim. 19, 4755–4771. http://dx.doi.org/10.1175/JCLI3868.1.

Queralt, S., Hernández, E., Barriopedro, D., Gallego, D., Ribera, P., Casanova, C., 2009. North Atlantic Oscillation influence and weather types associated with winter total and extreme precipitation events in Spain. Atmos. Res. 94, 675–683. http://dx.doi.org/10.1016/j.atmosres.2009.09.005.

Sato, M., Takahashi, M., 2000. Long-term changes in the properties of summer precipitation in the Tokyo area. Tenki 47, 643e648.

Sen Roy, S., Sen Roy, N., 2011. Influence of Pacific decadal oscillation and El Niño Southern oscillation on the summer monsoon precipitation in Myanmar. Int. J. Climatol. 31, 14–21. http://dx.doi.org/10.1002/joc.2065.

Shepherd, J.M., 2005. A review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interact. 9, 1–27.

Silva Dias, M.A.F., Dias, J., Carvalho, L.M.V., Freitas, E.D., Silva Dias, P.L., 2012. Changes in extreme daily rainfall for São Paulo, Brazil. Clim. Chang. 116, 705–722. http://dx.doi.org/10.1007/s10584-012-0504-7.

Singhrattna, N., Rajagopalan, B., Kumar, K.K., Clark, M., 2005. Interannual and interdecadal variability of Thailand summer monsoon season. J. Clim. 18, 1697–1708.

Takahashi, H.G., Yasunari, T., 2006. Climatological monsoon break in rainfall over Indochina—a singularity in the seasonal march of the Asian summer monsoon. J. Clim. 19, 1545–1556.

Takahashi, H.G., Yasunari, T., 2008. Decreasing trend in rainfall over Indochina during the late summer monsoon: impact of tropical cyclones. J. Meteorol. Soc. Jpn. 86, 429–438.

Tangang, F.T., et al., 2008. On the roles of the northeast cold surge, the Borneo vortex, the Madden–Julian Oscillation, and the Indian Ocean Dipole during the extreme 2006/2007 flood in southern Peninsular Malaysia. Geophys. Res. Lett. 35, L14S07. http://dx.doi.org/10.1029/2008GL033429.

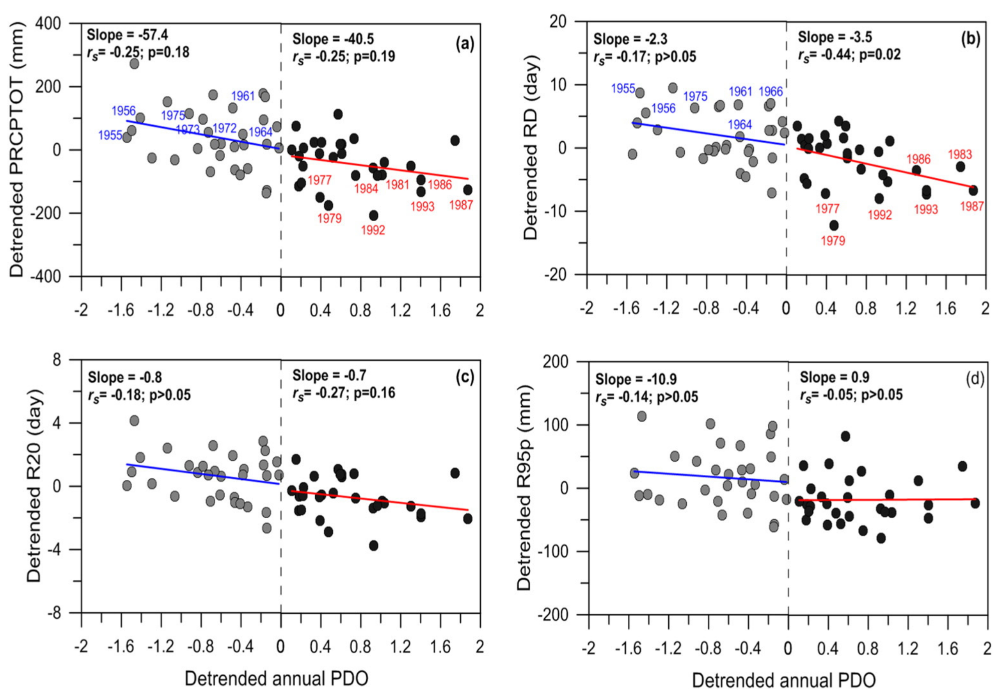

Fig. 16. Same as Fig. 15 but for PDOI.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. 84, 1205–1217. http://dx.doi.org/10.1175/BAMS-84-9-1205.
van Oldenborgh, G.J., van Urk, A., Allen, M., 2012. The absence of a role of climate change in the 2011 Thailand floods. Bull. Am. Meteorol. Soc. 93, 1047–1049. http://dx.doi.org/10.1175/2008BAMS2501.1.
Villafuerte II, M.Q., Matsumoto, J., Akasaka, I., Takahashi, H.G., Kubota, H., Cinco, T.A., 2014. Long-term trends and variability of rainfall extremes in the Philippines. Atmos. Res. 137, 1–13. http://dx.doi.org/10.1016/j.atmosres.2013.09.021.
Wang, X.L., 2008. Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F test. J. Appl. Meteorol. Climatol. 47, 2423–2444. http://dx.doi.org/10.1175/2008JAMC1741.1.
Wang, B., Wu, R., Li, T., 2003. Atmosphere–warm ocean interaction and its impacts on Asian–Australian monsoon variation. J. Clim. 16, 1195–1211.
Wang, X.L., Wen, Q.H., Wu, Y., 2007. Penalized maximal *t* test for detecting undocumented mean change in climate data series. J. Appl. Meteorol. Climatol. 46, 916–931. http://dx.doi.org/10.1175/JAM2504.1.
Wang, X.Q., Wang, Z.F., Qi, Y.B., Guo, H., 2009a. Effect of urbanization on the winter precipitation distribution in Beijing area. Sci. China Ser. D Earth Sci. 52, 250–256.
Wang, L., Chen, W., Zhou, W., Huang, R., 2009b. Interannual variations of East Asian Trough Axis at 500 hPa and its association with the East Asian winter monsoon pathway. J. Clim. 22, 600–614. http://dx.doi.org/10.1175/2008JCLI2295.1.
Wangwongchai, A., Sixiong, Z., Qingcun, Z., 2005. A case study on a strong tropical disturbance and record heavy rainfall in Hat Yai, Thailand during the winter monsoon. Adv. Atmos. Sci. 22, 436–450.
Wolter, K., Timlin, M.S., 1998. Measuring the strength of ENSO—how does 1997/98 rank. Weather 53, 315–324.
Zhang, Y., Wallace, J.M., Battisti, D.S., 1997. ENSO-like interdecadal variability: 1900–93. J. Clim. 10, 1004–1020.
Zhang, X., et al., 2005. Trends in Middle East climate extreme indices from 1950 to 2003. J. Geophys. Res. 110, D22104. http://dx.doi.org/10.1029/2005JD006181.
Zhang, X., Wang, J., Zwiers, F.W., Groisman, P.Y., 2010. The influence of large-scale climate variability on winter maximum daily precipitation over North America. J. Clim. 23, 2902–2915. http://dx.doi.org/10.1175/2010JCLI3249.1.
Zhang, X., et al., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. WIREs Clim. Chang. 2 (6), 851–870. http://dx.doi.org/10.1002/wcc.147.