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Research article

Change in rainfall seasonality in Thailand during 1955-2018

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Abstract

Spatiotemporal changes in Thailand were analyzed in rainfall seasonality for long-term data (1955–2018). The results showed that the dimensionless rainfall seasonality index (*DSI*) and relative entropy (*RE*) in Thailand ranged from rather seasonal with a short drier season to markedly seasonal with a long drier season. In addition, climatology of the *DSI* and *RE* captured the dominant feature of Thailand's rainfall pattern which is under the influence of phase reversals between the Southwest and Northeast monsoons and topographical effects. From a long-term perspective, the *DSI* in Thailand showed a significant decreasing trend, indicating a tendency for the annual rainfall to be more spread out over the months. Furthermore, the decrease in the *RE* was more attributable to the observed decreasing trend in the *DSI* than normalized mean annual rainfall. Similar to the *DSI*, the timing of peak rainfall significantly decreased, suggesting a delay in the peak rainfall of 1.2 d per decade. In contrast, the rainfall duration significantly increased at the rate of 0.61 d per decade, highlighting a lengthening of the rainfall season. Therefore, these observations provide an indication of an earlier onset or a delayed withdrawal or both, as well as a shift in its associated rainfall peak for the summer monsoon in Thailand. These changes in rainfall seasonality will have profound socioeconomic implications for Thailand, especially with the on-going warmer background. To better understand short-term variations in Thailand's rainfall seasonality, their relationship with regional and global natural climate modes needs to be further elaborated.

Introduction

Rainfall seasonality and its associated variations in magnitude, timing and duration of the wet and dry seasons is an important abiotic driver of ecosystem processes and society as it directly affects water availability and timing which are key factors controlling biogeochemical cycles, primary productivity and the phenology of growth and reproduction (Borchert, 1998; Austin et al., 2004; Feng et al., 2013; Berghuijs et al., 2014; Zhang et al., 2018), alters fire regimes (Chen et al., 2014) and influences crop and livestock production (Richardson and Hahn, 2007; Tedesco et al., 2008). Substantial change in rainfall seasonality with its associated drought and flood risks can have a great impact on the economies of many countries and pose huge challenges to local populations (Petrow and Merz, 2009; Feng et al., 2013; Pascale et al., 2015; Sahany et al., 2018). Rainfed agriculture which is widely practiced in Asia, Africa and Latin America depends critically on rainfall seasonality (Wani et al., 2009) which consequently has gained much scientific attention in recent years. The growing concern regarding the increasing effect of anthropogenic climate change further emphasizes the need for better understanding changes in rainfall seasonality and its mechanisms and ecological and socioeconomic consequences.

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Accumulated evidence has revealed changes in rainfall seasonality over different parts of the world (Kanellopoulou, 2002; Pryor and Schoof, 2008; Feng et al., 2013; Guhathakurt and Saji, 2013; Patil, 2015; Gitau, 2016; Pascale et al., 2015; 2016; Sahany et al., 2018; Sharma and Singh, 2019). For example, Feng et al. (2013) found increases in the interannual variability of seasonality over many parts of the dry tropics, indicating increasing uncertainty in the intensity, timing and duration of seasonal rainfall over the past century. Change in rainfall seasonality and a significant decrease in rainfall frequency have been detected in East Asia, especially in China (Ding et al., 2007; Piao et al., 2010). More recently, Deng et al. (2019) have shown that rainfall seasonality across China increased from 1961 to 2012, indicating changes in the magnitude, timing or duration of the wet season. Significant decreasing trends in seasonality coupled with decreasing rainfall have been identified over parts of central India, the Indo-Gangetic plains and parts of western Ghats (Sahany et al., 2018). Under a high greenhouse gas emissions scenario, rainfall seasonality has been projected to increase over Mediterranean-type regions and the areas of South and Central America, implying an increase in the number of dry days by up to 1 mth by the end of the twenty-first century (Pascale et al., 2016).

Seasonality in rainfall regimes is typically quantified based on a simple index which analyzes monthly distribution of rainfall climatology using variables such as relative length and rainfall amount in wet and dry seasons for specific locations. A novel rainfall seasonality index has been recently introduced by Feng et al. (2013) based on the concept of relative entropy quantifying the differences between the monthly fraction of the annual rainfall and the uniform rainfall sequence and has been applied to detect changes in rainfall seasonality in tropical regions. This approach has provided new, well-defined metrics for evaluating rainfall seasonality as it does not rely on specific assumptions or on arbitrary thresholds. Therefore, this work applied the dimensionless rainfall seasonality index (*DSI*) proposed by Feng et al. (2013) based on mutual information and entropy to the near-surface weather observation data in Thailand to analyze the climatology and spatiotemporal changes.

Materials and Methods

Data sources and quality control checks

Daily rainfall data were used that had been routinely recorded at the main surface weather stations of the Thai Meteorological Department (TMD) distributed across Thailand. The data were chosen first based on their record length being available from 1955 to 2018 and on their completeness, with missing data less than 1%. Based on these criteria, 44 stations were selected for a further statistical quality control algorithm. Commonly used objective approaches were applied to assess the quality of data, including tests of outliers, data missing interpolation and homogeneity checks (Feng et al., 2004; Wang et al., 2007). Where missing data were minimal (less than 1% of the total number of data points), linear regression was applied to fill in the missing values using data from the nearest neighboring stations (Feng et al., 2004).

The next step evaluated the data for homogeneity based on the penalized *t*-test (Wang et al., 2007) and the penalized maximal *F*-test (Wang, 2008). 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). Monthly total rainfall series were used to analyze homogeneity, based on the relative test described in more detail in Limsakul and Singhruck (2016). Homogeneity testing identifies one station with significant step changes in its monthly total series. No further attempt is made to adjust the data because the adjustment of non-homogeneous daily rainfall data is a complex problem with a number of uncertainties (Domonkos, 2011), and a conservative approach is taken to exclude any non-homogenous data. Based on the quality control procedures, a set of 43 high-quality records of rainfall for the period 1955 to 2018 was obtained (Fig. 1) for further analysis.

Dimensionless rainfall seasonality index

The entropy-based metrices proposed by Feng et al. (2013) were used to analyze rainfall seasonality over Thailand. For each station, long-term mean monthly rainfall accumulation was computed and normalized using the mean annual rainfall accumulation (*R*), resulting

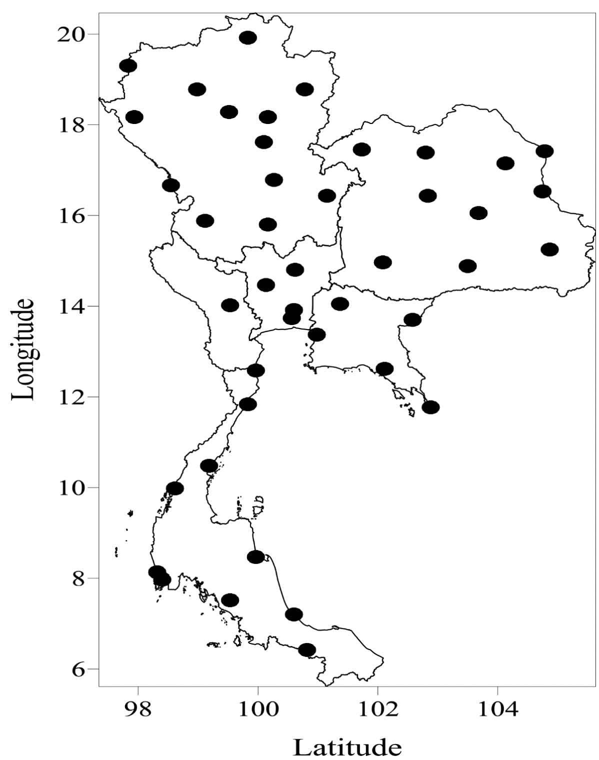

Fig. 1 Geographical distribution of main surface weather stations of Thai Meteorological Department having long-running, quality controlled, daily rainfall records (1955–2018)

in a monthly rainfall probability distribution (p_m) for each month. The relative entropy of p_m (*RE*) which is a measure of the extent of rainfall concentration in the wet season was calculated using Equation 1 which identifies the departure of p_m with respect to a uniform rainfall sequence (q_m, m=1,…,12) for which each month has a value of 1/12. This is a positive, semi-definite measure for the distance between the observed p_m and the q_m (Feng et al., 2013; Pascale et al., 2015). The *DSI* for each station was then computed by multiplying its *R* normalized value by the observed maximum mean annual rainfall in the data set, R_{max}, with the corresponding relative entropy as shown in the Equation 2:

$$RE = \sum_{m=1}^{12} p_m \log_2(p_m/q_m) \quad (1)$$

$$DSI = RE \cdot \frac{R}{R_{max}} \quad (2)$$

Note that the R_{max} of the data set over the whole period 1955–2018 equals 6,463 mm per year at the Klong Yai station. On the basis of Equation 2, the *DSI* is zero when either *R* (completely dry location) or *RE* (*R* distributed uniformly throughout the year) is zero and attains its maximum value at $\log_2 12$ (3.585) when the mean annual rainfall is concentrated in a single month. A low *DSI* can be caused by a reduction in either the rainfall amount or its relative entropy.

For each station, the centroid C_k (timing of the peak rainfall) and the spread Z_k (duration of the wet season) were computed based on daily rainfall data for each year ($R_{k,d}$) using the first and second moments of ($R_{k,d}$), specifically,

$$C_k = \frac{1}{R_k} \sum_{d=1}^{365} d R_{k,d} \quad (3)$$

$$Z_k = \sqrt{\frac{1}{R_k} \sum_{d=1}^{365} [d - C_k]^2 R_{k,d}} \quad (4)$$

The centroid is an integral measure of the timing of the wet season and it is related to the time of the year around which most of the annual rainfall is distributed. Therefore, it cannot provide information about the beginning and the end of the wet season associated with the onset and retreat of monsoons (Kitoh et al., 2013; Sperber et al., 2013; Hasson et al., 2014).

Statistical analysis

The RHtestsV4 software was used to analyze the inhomogeneity of the data series (Zhang, 2019). Whereas, trend analysis was done using the JMP data analysis software (version 3.2.2; SAS Institute Inc., USA). A trend was taken to be statistically significant when the probability was at $p < 0.05$).

Results and Discussion

Climatology of Thailand's rainfall seasonality metrics

The *DSI* for all stations during 1955–2018 was in range 0.04–0.83 with the values lower than 0.2 and between 0.2–0.5 accounting for 70% and 28% of the total data, respectively (Fig. 2). These results suggested that the mean annual rainfall at almost all stations in Thailand had an equitable distribution throughout the year to definite wetter and drier seasons. Based on Fig. 2, there was a low *DSI* at the stations having a high *RE* and a low normalized mean annual rainfall ($\frac{R}{R_{max}}$) and vice versa, whereas there was a high *DSI* at stations with intermediate or high values of both parameters.

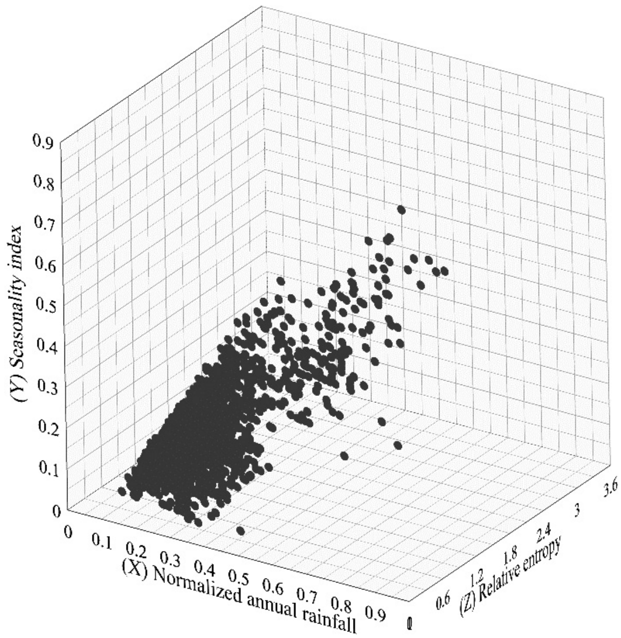

Fig. 2 Dimensionless rainfall seasonality index in Thailand for all stations during 1955–2018 as a function of normalized annual rainfall and relative entropy

Station-by-station climatological means (1955–2018) of the *DSI*, *RE* and normalized mean annual rainfall in Thailand are shown in Fig. 3. From a climatological perspective, the *DSI* at most stations was below 0.2 with a few stations showing clearly higher values (Fig. 3A). The three highest *DSI* values were at stations in the South, East and Northeast (Fig. 3A) and could be attributed to the rainfall distribution being concentrated in a few months and to a high annual rainfall, most of which occurred during the summer monsoon season. Pascale et al. (2015) reported a relatively high *DSI* in some parts of Southeast Asia where both the total annual rainfall and the *RE* are high. The climatological mean range of the *RE* was from 0.41 to 0.98 (Fig. 3B). Based on the *RE* classes and their associated seasonality rainfall regime suggested by Patil (2015) and Sharma and Singh (2019), the climatological means of the *RE* in Thailand can be classified from rather seasonal with a short drier season such as for stations in the South to markedly seasonal with a long drier season such as for stations in the North, Northeast and Central regions (Fig. 3B).

The long-term average normalized mean annual rainfall was relatively high in the South and for a few stations in the East and Northeast, and moderate-to-low at most stations in the North, Central and Northeast regions (Fig. 3C). It should be noted that the climatology of the rainfall seasonality metrics captures the general feature of the monsoon region and depicts the dominant picture of Thailand's rainfall pattern which is strongly influenced by seasonally reversing surface circulations associated with phase reversals between the Southwest summer monsoon and the Northeast winter monsoon (Limsakul et al., 2010a). However, there were large *DSI* values at some isolated stations (Ranong Station, Klong Yai Station and Nakhon Phanom Station), as shown in Fig. 3A which were mainly due to normalized annual rainfall (Fig. 3C). These results suggest a local effect arising from topography on the *DSI* in Thailand in addition to large-scale climate phenomena.

Trend in Thailand's dimensionless rainfall seasonality index

Fig. 4 illustrates the station-by-station trends in the *DSI* in Thailand during 1955–2018 calculated using the Mann-Kendall nonparametric trend test which has been widely used to evaluate randomness against trend in hydrology and climatology (Sen, 1968). It is a non-parametric ranked based procedure which is robust to the influence of extremes, and is good for use with skewed variables and is highly resistant to the effects of outliers (Hamed and Rao, 1998). Of note from Fig. 4 is a general decrease in the *DSI*, indicating that there has been a tendency for the annual rainfall in Thailand to be more spread out over the months. Nearly 80% of the total stations recorded a decrease in the *DSI*, with 23% having significant ($p < 0.05$) negative trends. The stations with these decreasing trends ranging from (-0.011) – (-0.0044) per decade were generally located in the North, Central region and along the Andaman Sea with a few stations observed in the East and Northeast (Fig. 4). It should be noted that the stations between the west and east coasts in southern Thailand displayed opposite trends in the *DSI* (Fig. 4). This pattern of changes agreed well with the results of Limsakul et al. (2010b) who found notable contrasting changes in rainfall extreme events between the Andaman Sea coast (ASC) and the Gulf of Thailand's Coast (GoT). Wetter conditions and increases in the magnitude and frequency of intense rainfall events as observed along the GoT are consistent with prolonged strengthening of the Northeast winter monsoon (Limsakul et al., 2010b). Therefore, weakening and strengthening of the Southwest summer monsoon and the Northeast winter monsoon acting as a primary climatic force in southern Thailand are believed to have different influences on the *DSI* between the ASC and GoT. When considering Thailand as a whole, the all-station average anomalies of the *DSI* displayed a significant ($p < 0.05$) trend of -0.002 per decade (Fig. 5). A further examination indicated that the decrease in the *RE* was more attributable to the observed decreasing trend of the *DSI* than to the normalized mean annual rainfall. However, significant decreasing trends in rainfall seasonality observed over parts of central India and the western Ghats during 1901–2013 were caused mainly by the decreasing trend in the normalized mean annual rainfall (Sahany et al., 2018), whereas, a marked reduction in rainfall seasonality in western Africa and central Brazil was due mainly to decreases in their rainfall amounts and distribution, respectively (Feng et al., 2013). Goswami et al. (2006) reported a significant decrease in rainfall seasonality over parts of central India that coincided with a significant

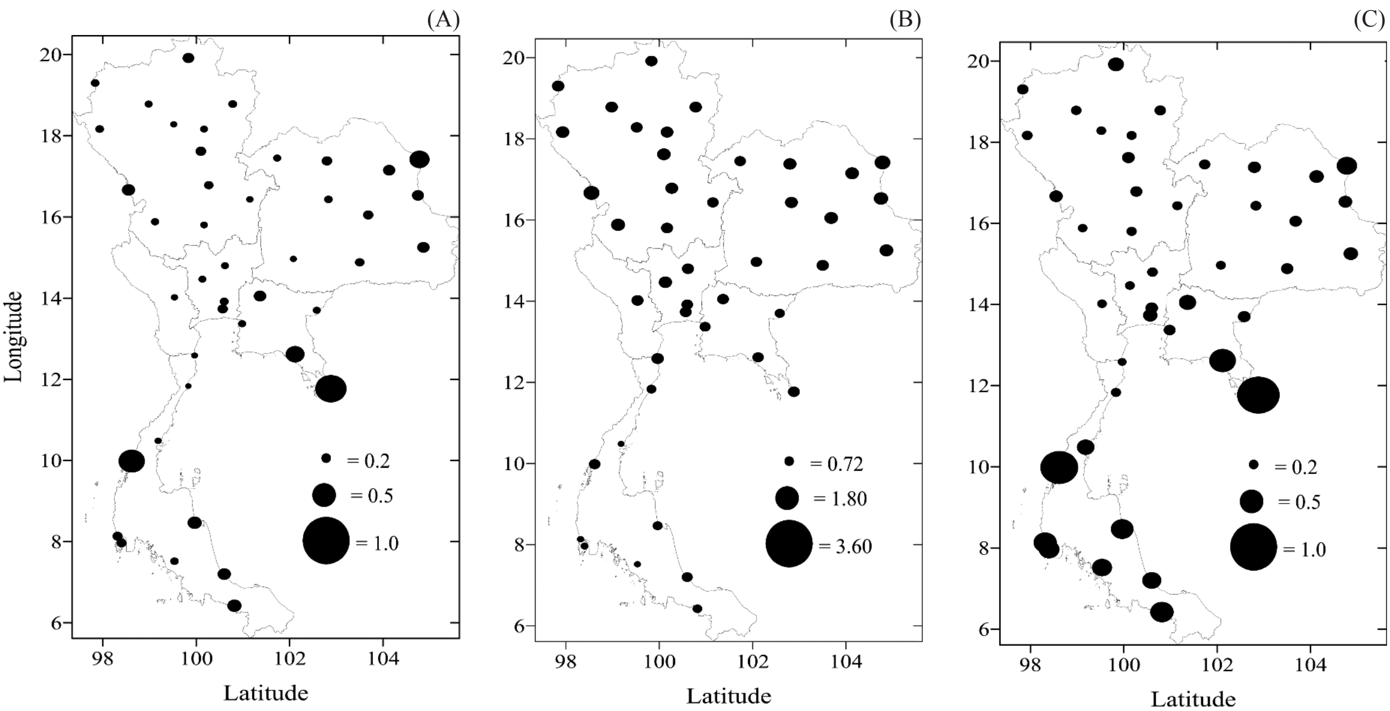

Fig. 3 Climatology for data 1955–2018: (A) dimensionless rainfall seasonality index; (B) relative entropy; (C) normalized annual rainfall

increasing trend of the summer-monsoon-season (June–September) variance of daily rainfall during 1951–2000 (Sahany et al., 2018). Goswami et al. (2006) showed that the long-term increase in daily rainfall variance was related to the increase in large-scale moisture availability, which in turn was due to a gradual warming trend for the tropical Indian Ocean sea surface temperature. Based on the results of Goswami et al. (2006) and Sahany et al. (2018), it is suggested that rainfall seasonality including its variance and extremes over India is under the strong influence of large-scale climate forces. The opposite trends between the decreased *DSI* and the increased variance of daily rainfall were also observed in Thailand (Figs. 5 and 6). The annual coefficient of variability (defined as the ratio of the standard deviation to the mean of daily rainfall) averaged over all stations in Thailand showed an increasing trend of 10.2% per decade with significance at the 99% confidence level. These results may provide additional evidence supporting that annual rainfall in Thailand is distributed over the months with daily rainfall amounts having recently become more widely experienced, especially those associated with high and extreme values.

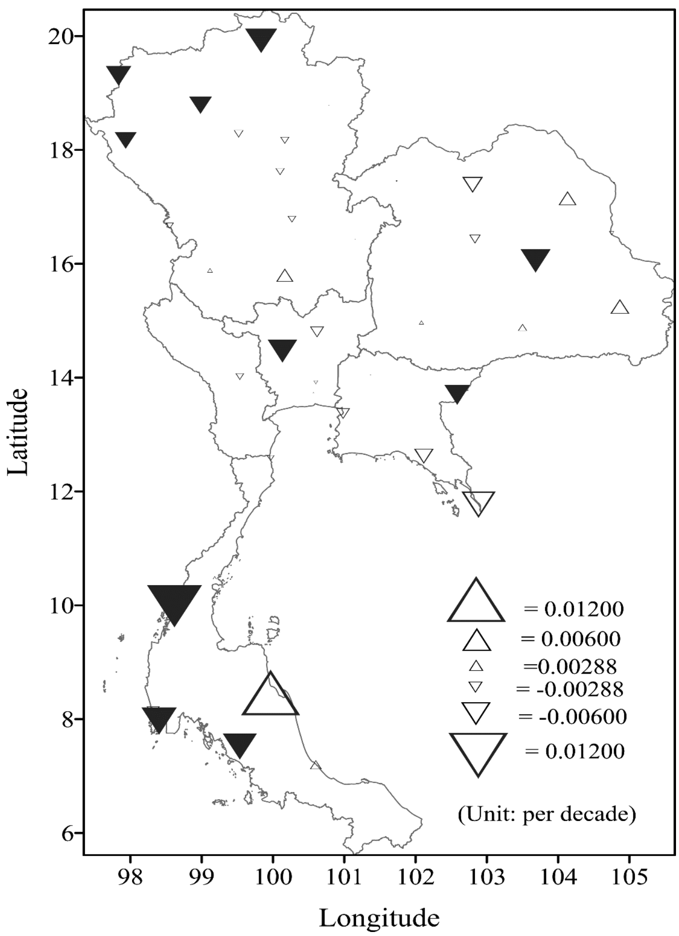

Fig. 4 Trend in station-by-station dimensionless rainfall seasonality index in Thailand during 1955–2018, where significant trends at the 5% level are indicated by filled black triangles

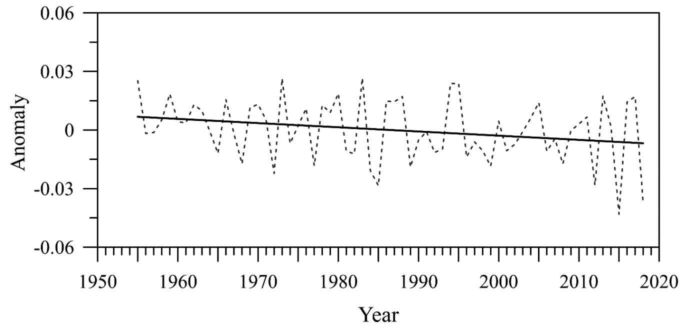

Fig. 5 All-station averaged anomalies of dimensionless rainfall seasonality index in Thailand, indicating trend of -0.002 per decade ($p < 0.05$, n = 64)

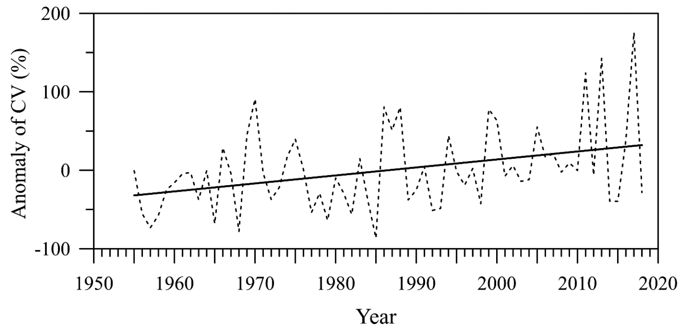

Fig. 6 Annual coefficient of variability (CV) defined as the ratio of the standard deviation to the mean of daily rainfall expressed as a percentage, indicating a trend of 10.2% per decade ($p < 0.01$, n = 64)

Trends in Thailand's rainfall magnitude, timing and duration

The mixture of drying and wetting trends as the dominant pattern of annual rainfall accumulation observed in this study (Fig. 7C) was consistent with previous studies in Thailand (Limsakul and Singhruck, 2016) and other Southeast Asia countries (Caesar et al., 2011; Nguyen et al., 2014; Sein et al., 2018). Nearly one-third of the total stations recorded significant ($p < 0.05$) decreasing and increasing trends in annual rainfall accumulation during 1955–2018. The stations with significant increasing trends were generally located in the South, Northeast and Bangkok Metropolis (Fig. 7C). No significant trend was observed in the all-station averaged anomalies of annual rainfall accumulation series (Fig. 8A) due to large interannual and interdecadal variations (Limsakul and Singhruck, 2016).

Similar to the *DSI*, the centroid for the timing of the peak rainfall showed a general reduction throughout Thailand (Fig. 7B). The majority of stations had a decreasing trend in the timing of the peak rainfall, with 23.3% of the stations recording a significant ($p < 0.05$) decrease ranging from -3.14 to -0.60 d per decade. The statistically significant trends in the timing of peak rainfall were geographically concentrated in the central and northern parts of the country (Fig. 7B). However, an exception was the station located in the GoT which had the opposite trend to those in the central and northern parts. Distinction of rainy seasons which in most of Thailand occur during May-October but the wettest months are November–February of the next year for the GoT (Limsakul and Singhruck, 2016) is believed to give rise to such a difference. Therefore, the dominance of a negative trend for the timing of the peak rainfall resulted in a significant decrease in its all-station averaged time series (Fig. 8B). This decreasing trend indicated a delay in the peak rainfall of 1.2 d per decade. Sahany et al. (2018) found that the timing of peak season rainfall over parts of central India and the southern Indo-Gangetic plains was delayed at a comparable rate (approximately 1–2 d per decade) as detected in the current study. A delay in the timing of peak rainfall with smaller decreasing rates was also reported in western and central Africa (Feng et al., 2013).

In contrast, the rainfall duration during 1955–2018 was marked by positive trends across most of Thailand (Fig. 7C). Significant increasing trends in the rainfall duration, ranging from 1.1 to 2.58 d per decade, were observed at 12 (27.9%) stations that were geographically concentrated in the South, North and Central regions (Fig. 7C). Considering Thailand as a whole from the long-term perspective, the rainfall duration has significantly increased at a rate of 0.61 d per decade (Fig. 8C). This trend indicates that rainfall duration in Thailand is lengthening. Increases in the rainfall duration with comparable rates compared with the current study have been reported in northeast Brazil and northern Australia (Feng et al., 2013).

On the basis of this analysis, the trends in timing and duration together suggest delayed peaking of the rainfall combined with an increase in duration, providing an indication of the earlier onset or the delayed withdrawal or both as well as a shift in its associated rainfall peak of the summer monsoon in Thailand. This interpretation has been supported by multi-model projections illustrating that monsoon onset dates will come earlier or not change much while monsoon retreat dates will be delayed, resulting in a lengthening of the monsoon season in many regions (Christensen et al., 2013).

Conflict of Interest

The author declares that there are no conflicts of interest.

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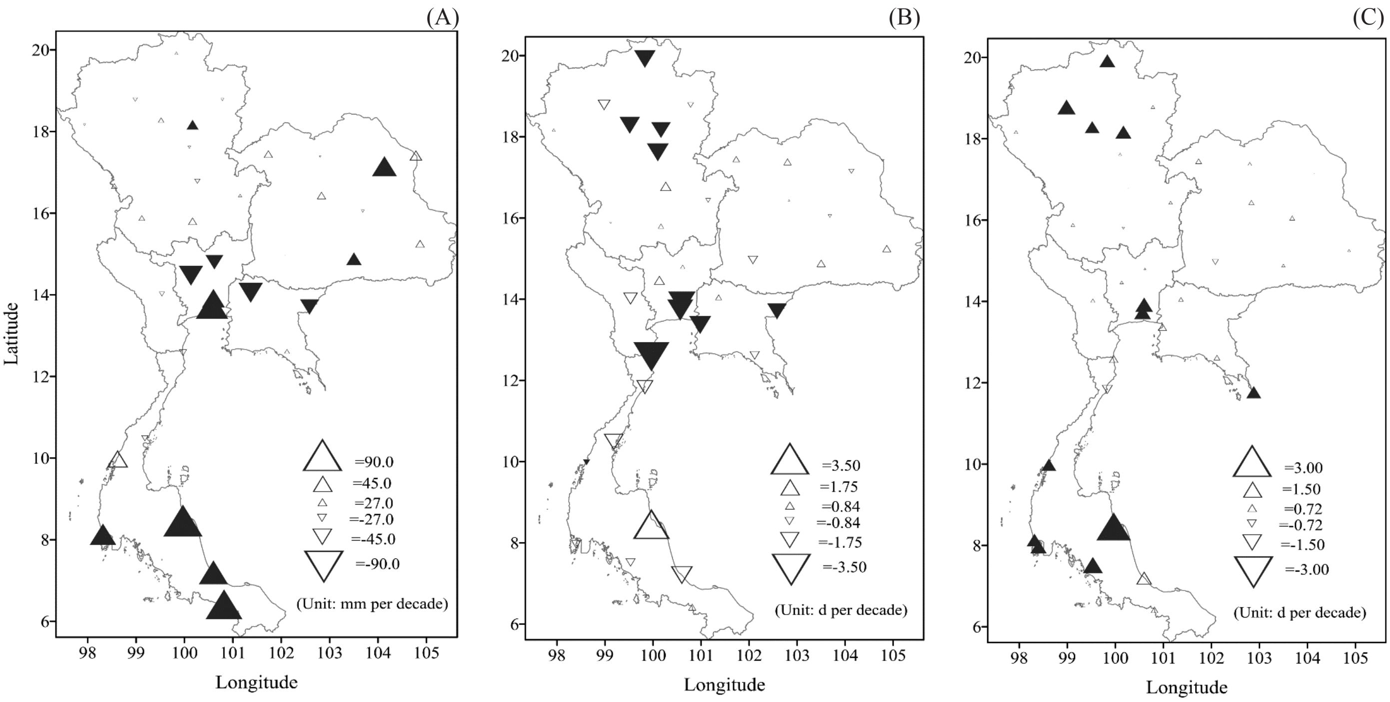

Fig. 7 Climatology for data 1955–2018, where significant trends at the 5% level are indicated by filled black triangles: (A) annual rainfall total; (B) rainfall timing; (C) rainfall duration

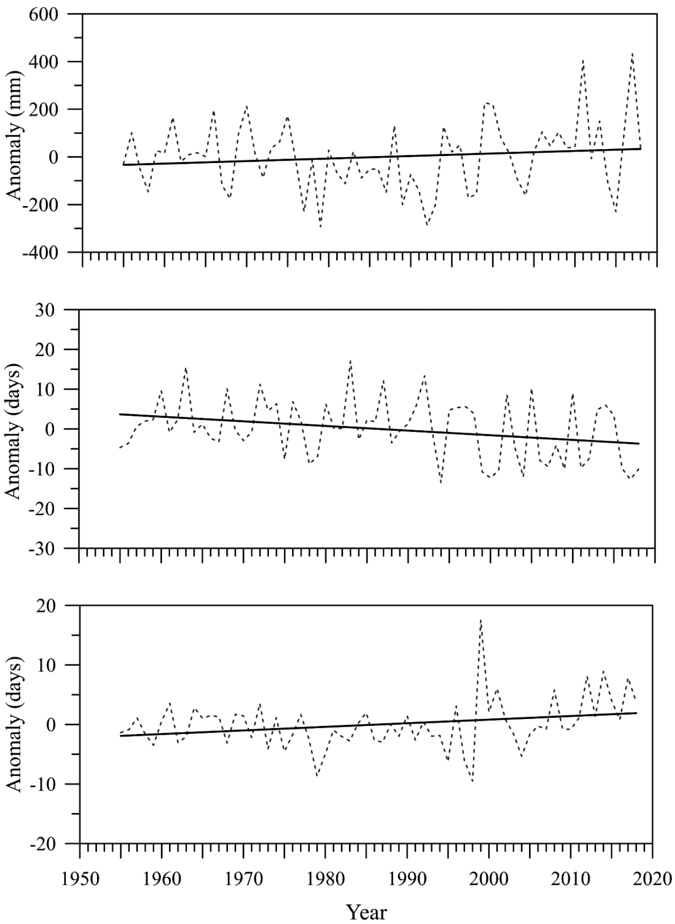

Fig. 8 All-station averaged anomalies: (A) total annual rainfall, indicating trend of 9.8 mm per decade (p = 0.33, n = 64); (B) rainfall timing, indicating trend of -1.2 d per decade (p = 0.03, n = 64); (C) rainfall duration, indicating trend of 0.61 d per decade (p = 0.04, n = 64)

References

Austin, A.T., Yahdjian, L., Stark, J.M., Belnap, J., Porporato, A., Norton, U., Ravetta, D.A. Schaeffer, S.M. 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141: 221–235. doi: 10.1007/s00442-004-1519-1

Berghuijs, W., Sivapalan, M., Woods, R., Savenije, H. 2014. Patterns of similarity of seasonal water balances: A window into streamflow variability over a range of time scales. Water Resour. Res. 50: 5638−5661. doi.org/10.1002/2014WR015692

Borchert, R. 1998. Responses of tropical trees to rainfall seasonality and its long-term changes. Clim. Change 39: 381–393. doi.org/10.1023/A:1005383020063

Caesar, J., Alexander, L.V., Trewin, B., et al. 2011. Changes in temperature and precipitation extremes over the Indo-Pacific region from 1971 to 2005. Int. J. Climatol. 31: 791–801. doi.org/10.1002/joc.2118

Chen, F., Niu, S., Tong, X., Zhao, J., Sun, Y., He, T. 2014. The impact of precipitation regimes on forest fires in Yunnan Province, Southwest China. Sci. World J. 2014: 1–9. doi.org/10.1155/2014/326782

Christensen, J.H., Kumare, K.K., Aldrian, E., et al. 2013. Climate phenomena and their relevance for future regional climate change. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK, pp. 1217–1308.

Deng, S., Yang, N., Li, M., Cheng, L., Chen, Z., Chen, Y., Chen, T., Liu, X. 2019. Rainfall seasonality changes and its possible teleconnections with global climate events in China. Clim. Dyn. 53: 3529–3546. doi: 10.1007/s00382-019-04722-3

Ding, Y.H., Ren, G.Y., Zhao, Z.C., Xu, Y., Luo, Y., Li, Q., Zhang, J. 2007. Detection, causes and projection of climate change over China: An overview of recent progress. Adv. Atmos. Sci. 24: 954–971. doi.org/10.1007/s00376-007-0954-4

Domonkos, P. 2011. Homogenising time series: Beliefs, dogmas and facts. Adv. Sci. Res. 6: 167–172. doi: 10.5194/asr-6-167-2011

Feng, S., Hu, Q., Qian, W. 2004. Quality control of daily metrological data in China, 1951–2000: A new dataset. Int. J. Climatol. 24: 853–870. doi.org/10.1002/joc.1047

Feng, X., Porporato, A., Rodriguez-Iturbe, I. 2013. Changes in rainfall seasonality in the tropics. Nat. Clim. Change. 3: 811–815. doi.org/10.1038/nclimate1907

Gitau, M. 2016. Long-term seasonality of rainfall in the southwest Florida Gulf coastal zone. Clim. Res. 69: 93–105. doi.org/10.3354/cr01399

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., Xavier, P.K. 2006. Increasing trend of extreme rain events over India in a warming environment. Science 314: 1442–1445. doi: 10.1126/science.1132027

Guhathakurta, P., Saji, E. 2013. Detecting changes in rainfall pattern and seasonality index vis-`a-vis increasing water scarcity in Maharashtra. J. Earth Syst. Sci. 122: 639–649. doi.org/10.1007/s12040-013-0294-y

Hamed, K.H., Rao, A.R. 1998. A modified Mann-Kendall trend test for autocorrected data. J. Hydrol. 204: 182–196. doi.org/10.1016/S0022-1694(97)00125-X

Hasson, S., Lucarini, V., Pascale, S., Böhner, J. 2014. Seasonality of the hydrological cycle in major South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments. Earth Syst. Dyn. 5: 67–87. doi:10.5194/esd-5-67-2014

Kanellopoulou, E.A. 2002. Spatial distribution of rainfall seasonality in Greece. Weather. 57: 215–219. doi.org/10.1256/004316502760053576

Kitoh, A., Endo, H., Kumar, K.K., Cavalcanti, I.F.A., Goswami, P., Zhou, T. 2013. Monsoons in a changing world: A regional perspective in a global context. J. Geophys. Res. 118: 3053–3065. doi.org/10.1002/jgrd.50258

Limsakul, A., Limjirakan, S., Suttamanuswong, B. 2010a. Asian summer monsoon and its associated rainfall variability in Thailand. Environment Asia 3: 79–89. doi: 10.14456/ea.2010.27

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

Limsakul, A., Singhruck, P. 2016. Long-term trends and variability of total and extreme precipitation in Thailand. Atmos. Res.169: 301–317. doi: 10.1016/j.atmosres.2015.10.015

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. doi.org/10.1002/joc.3684

Pascale, S., Lucarini, V., Feng, X., Porporato, A., Hasson, S. 2015. Analysis of rainfall seasonality from observations and climate models. Clim. Dyn. 44: 3281–3301. doi.org/10.1007/s00382-014-2278-2

Pascale, S., Lucarini, V., Feng, X., Porporato, A., Hasson, S. 2016. Projected changes of rainfall seasonality and dry spells in a high greenhouse gas emissions scenario. Clim. Dyn. 46: 1331–1350. doi.org/10.1007/s00382-015-2648-4

Patil, M.K. 2015. Change in seasonality index of rainfall in Sangli District. ISRJ. 5: 1–7.

Petrow, T., Merz, B. 2009. Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. J. Hydrol. 371: 129–141. doi.org/10.1016/j.jhydrol.2009.03.024

Piao, S., Ciais, P., Huang, Y., et al. 2010. The impacts of climate change on water resources and agriculture in China. Nature 467: 43–51. doi.org/10.1038/nature09364

Pryor, S., Schoof, J.T. 2008. Changes in the seasonality of precipitation over the contiguous USA. J. Geophys. Res. 113: 1–15. doi.org/10.1029/2008JD010251

Richardson, F., Hahn, B. 2007. A short-term mechanistic model of forage and livestock in the semi-arid Succulent Karoo: 2. Evaluation and application. Agric. Syst. 95: 62–75. doi.org/10.1016/j.agsy.2007.04.003

Sahany, S., Mishra, S.K., Pathak, R., Rajagopalan, B. 2018. Spatiotemporal variability of seasonality of rainfall over India. Geophys. Res. Lett. 45: 7140–7147. doi.org/10.1029/2018GL077932

Sein, K.K., Chidthaisong, A., Oo, K.L. 2018. Observed trends and changes in temperature and precipitation extreme indices over Myanmar. Atmosphere 9: 1–21. doi:10.3390/atmos9120477.

Sen, P.K. 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63: 1379–1389.

Sharma, S., Singh, P.K. 2019. Spatial trends in rainfall seasonality: A case study in Jharkhand, India. Weather 74: 31–39. doi.org/10.1002/wea.3231

Sperber, K.R., Annamalai, H., Kang, I.S., Kitoh, A., Moise, A., Turner, A., Wang, B., Zhou, T. 2013. The Asian summer monsoon: An intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Clim. Dyn. 41: 2711–2744. doi.org/10.1007/s00382-012-1607-6

Tedesco, P.A., Hugueny, B., Oberdorff, T., Durr, H.H., Merigoux, S., de Merona, B. 2008. River hydrological seasonality influences life history strategies of tropical riverine fishes. Oecologia 156: 691−702. doi.org/10.1007/s00442-008-1021-2

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. Meteor. Climatol. 47: 2423–2444. doi.org/10.1175/2008JAMC1741.1

Wang, X.L., Wen, Q.H., Wu, Y. 2007. Penalized maximal *t*-test for detecting undocumented mean change in climate data series. J. Appl. Meteor. Climatol. 46: 916–931. doi.org/10.1175/JAM2504.1

Wani, S.P., Rockstrom, J., Oweis, T. 2009. Rainfed Agriculture: Unlocking the Potential. CABI International. Oxford, UK.

Zhang, W., Brandt, M., Tong, X., Tian, Q., Fensholt, R. 2018. Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel. Biogeosciences 15: 319–330. doi: 10.5194/bg-2017-331

Zhang, X. 2019. RHtestsV4 software. Expert Team on Climate Change Detection and Indices (ETCCDI). http://etccdi.pacificclimate.org/software.shtml, 18 January 2019.