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PDSI-Based Variations of Droughts and Wet Spells in Thailand: 1951-2005

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Abstract

Temporal variations of droughts/wet spells in Thailand for the period 1951-2005 were examined on the basis of the gridded Palmer Drought Severity Index (PDSI) data. PDSI is the most dominant index for drought monitoring, climatology and variability across different climates. The PDSI variations in Thailand were correlated well with the annual streamflow records, indicating that PDSI is a good proxy for monitoring and assessing droughts/wet spells and it can be further used as an index of annual-mean streamflow variations. An empirical orthogonal function (EOF) analysis of PDSI revealed a linear trend and an El Niño-Southern Oscillation (ENSO)-induced mode of multi-year variations as the leading pattern. The ENSO cycle and its shift toward more warm phases after about 1976 appeared to be largely responsible for interannual variations and the recent progressive dying trend in Thailand. From 1951 to 2005, there were also large interannual/decadal variations in the occurrence frequencies in severe/extreme droughts (PDSI< -3) and very/extremely wet spells (PDSI> 3) with the coherent jump occurred in the mid 1970s. Similar to the leading PDSI EOF1 mode, these annual occurrence frequencies were closely related to ENSO events which extreme events tended to happen more frequently during ENSO years. Patterns of EOF-derived PDSI variations were consistent with the observed surface temperature warming in Thailand. These results provide evidence that Thailand will experience the increasing risks of severe and extreme droughts/floods in the near future as a result of the combined effects of a more vigorous hydrological cycle and enhanced surface drying due to anthropogenic global warming and the anomalous oscillations of ENSO.

Keywords: Palmer Drought Severity Index; droughts; wet spells; variations; Thailand

1. Introduction

Recent scientific evidence has suggested that human-driven warming of the global climate system is unequivocal (IPCC, 2007). An increase in extreme events is one of the most serious challenges in coping with anthropogenic climate change due to their significant impacts on economy, society and environment. Extreme climate events, such as droughts and floods, by their nature are rare (Dai *et al*., 1998; Meehl *et al*., 2000). Therefore, they are located at the tails of distribution of climate variables and percentage-wise will change more rapidly than the mean in a changing climate (Greenough *et al*., 2001; Trenberth *et al*., 2003). Scenario-based global climate models indicate that, in a warmer climate, droughts may become longer lasting and more severe in current drought-prone regions and precipitation events may become more intense leading to more flooding (e.g., Gregory *et al*., 1997; Cameron *et al*., 2000; Wang, 2005).

Droughts and floods are complex and recurrent climate-related phenomena which are among the world's costliest natural disasters causing social-economic damages annually and collectively affecting more people than any other forms of natural disasters (e.g., Keyantash and Dracup, 2002; Heim, 2002; Below *et al*., 2007). Given the consequences and pervasiveness of droughts and floods, it is crucially important to monitor, understand and predict their variability to better manage the associated risks. However, the precise quantification of droughts and wet spells is difficult because they are many different definitions for these extreme events (Wilhite, 2000; Keyantash and Dracup, 2002) and the criteria for determining their start and end also vary (Dai *et al*., 2004; Wells *et al*., 2004). Moreover, historical records of direct measurements of the dryness and wetness of the ground such as soil moisture content are sparse (Robock *et al*., 2000). To monitor droughts and wet spells, numerous specialized indices have been developed using readily available data such as precipitation and temperature (e.g., Palmer, 1965; McKee *et al*., 1993; Ntale and Gan, 2003).

The Palmer Drought Severity Index (PDSI) is the most prominent drought indices used today and one of the first procedures to demonstrate success at quantifying the severity of drought across different climates (e.g., Palmer 1965; Keyantash and Dracup, 2002; Dai *et al*., 2004; Wells *et al*., 2004). Besides its routine use for monitoring droughts, the PDSI has been used to study drought climatology and variability in many areas of the world (e.g., Dai *et al*., 1998; Wells *et al*., 2004; Dai *et al*., 2004). The PDSI was also used in tree-ring-based reconstruction of droughts (e.g., Li *et al*., 2007; Nicault *et al*., 2008).

In this study, the updated monthly gridded PDSI data were statistically examined for the Kingdom of Thailand to illustrate interannual/decadal variations and a long-term trend in droughts and wet spells and their association with the ENSO.

2. A brief review of Palmer's procedure

The PDSI was first created by Palmer who used a two-layer model for soil moisture computations and made certain assumptions concerning field capacity and transfer of moisture to and from the layers (Palmer, 1965). The other parts of the PDSI calculation account for climatic differences between locations and seasons of the year. These computations attempt to scale the PSDI index values so that they fit Palmer's 11 categories (Table 1) that allows comparisons across regions and time (Palmer, 1965; Alley, 1984; Wells *et al*., 2004).

The PDSI assumes that evapotranspiration (*ET*) occurs close to the potential *ET* (*PE*) until a certain amount of the available water is depleted after which the actual *ET* is less than *PE*. Each month of every year, four values related to the soil moisture (*ET*, recharge [*R*], runoff [*RO*] and loss [*L*]) and their complementary potential values (*PE*, potential recharge [*PR*], potential runoff [*PRO*] and potential loss [*PL*]) are computed. The water-balance coefficients or weighting factors (α, β, γ and δ) are then estimated using the four potential values to give the climatically appropriate for existing conditions (*CAFEC*) potential values (Alley, 1984; Wells *et al*., 2004), and are found in the following manner:

Table 1. Drought classification by PDSI value

PDSI value	Classification
4.00 or more	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient dry spell
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
-4 or less	Extreme drought

$$\alpha_i = \frac{\overline{ET_i}}{\overline{PE_i}}, \qquad \beta_i = \frac{\overline{R_i}}{\overline{PR_i}} \tag{1}$$

$$\gamma_i = \frac{\overline{RO_i}}{\overline{PRO_i}} \qquad \delta_i = \frac{\overline{L_i}}{\overline{PL_i}} \tag{2}$$

where *i* ranges over the months of the year. The bar over a term indicates an average value.

The potential values and water-balance coefficients are combined to form $\hat{P}$ which represents the amount of precipitation needed to maintain a normal soil moisture level for a single month:

$$\hat{P} = \alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL \tag{3}$$

The difference between the actual precipitation that falls in a specific month and $\hat{P}$ is the moisture departure, *d:*

$$d = P - \hat{P} = P - (\alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL) \tag{4}$$

$\hat{P}$ represents the water balance equations and is a hydrological factor which needs be parameterized locally. The Palmer moisture anomaly index (*Z*) is then defined as

$$Z = Kd \tag{5}$$

K acts as a climate weighting factor and is applied to yield index with comparable local significance in space and time. Palmer derived Eq. (6) for *K*:

$$K_i' = 1.5\log_{10}\left[\frac{\frac{\overline{PE_i} + \overline{R_i} + \overline{RO_i}}{\overline{P_i} + \overline{L_i}} + 2.8}{\overline{D_i}}\right] + 0.5 \tag{6}$$

The *Z* index is used to calculate the PDSI value for a given month using the general formula:

$$X_i = 0.897X_{i-1} + (\frac{1}{3})Z_i . \tag{7}$$

For example, to calculate the current value of X_i, 0.897 times the previous PDSI value X_{i-1} is added to one-third of the current moisture anomaly Z_i. Palmer called the values 0.897 and 1/3 the duration factors. Three PDSI values are actually computed each month: X_1, X_2 and X_3. The values of X_1 and X_2 are the severity of a wet or dry spell, respectively. While, X_3 is the severity of a wet or dry spell that is currently established.

3. Data used and analytical methods

The updated 2.5° x 2.5° gridded PDSI data were used in this study. The dataset was developed by Dai *et al*. (2004) and is available via the web site, http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html. These data consist of monthly PDSI over global land areas from 1870 to 2005 derived using historical precipitation and temperature records. We selected the PDSI at eight grid cells in the region of 7.50-20.00 °N, 98.25-102.50 °E, covering most areas of Thailand (Fig. 1). At these locations, the PDSI data extends from 1951 to 2005, without missing value.

In order to identify an overall spatial structure of PDSI variations in Thailand, empirical orthogonal function (EOF) analysis was performed based on the covariance matrix calculated from the eight PDSI series. The EOF technique is multivariate statistics among the most widely and extensively methods used in meteorology/oceanography data analysis (e.g., Preisendorfer, 1988; Jolliffe, 2002; Hannachi *et al*., 2007). The method is in essence an exploratory tool, which allows a time display and a space display of the space-time field. In practice, EOF technique aims at finding a new set of variables that capture most of the observed variance from the data through linear combination of the original variables. It involves decomposition of a multivariate data set into its orthogonal (uncorrelated) principal components. Time-series of the PDSI can be represented by a linear combination of the eigen-function (F_n) as equation (8)

$$T(x,t) = \sum_{n=1}^{N} a_n(t) F_n(x) \quad (8)$$

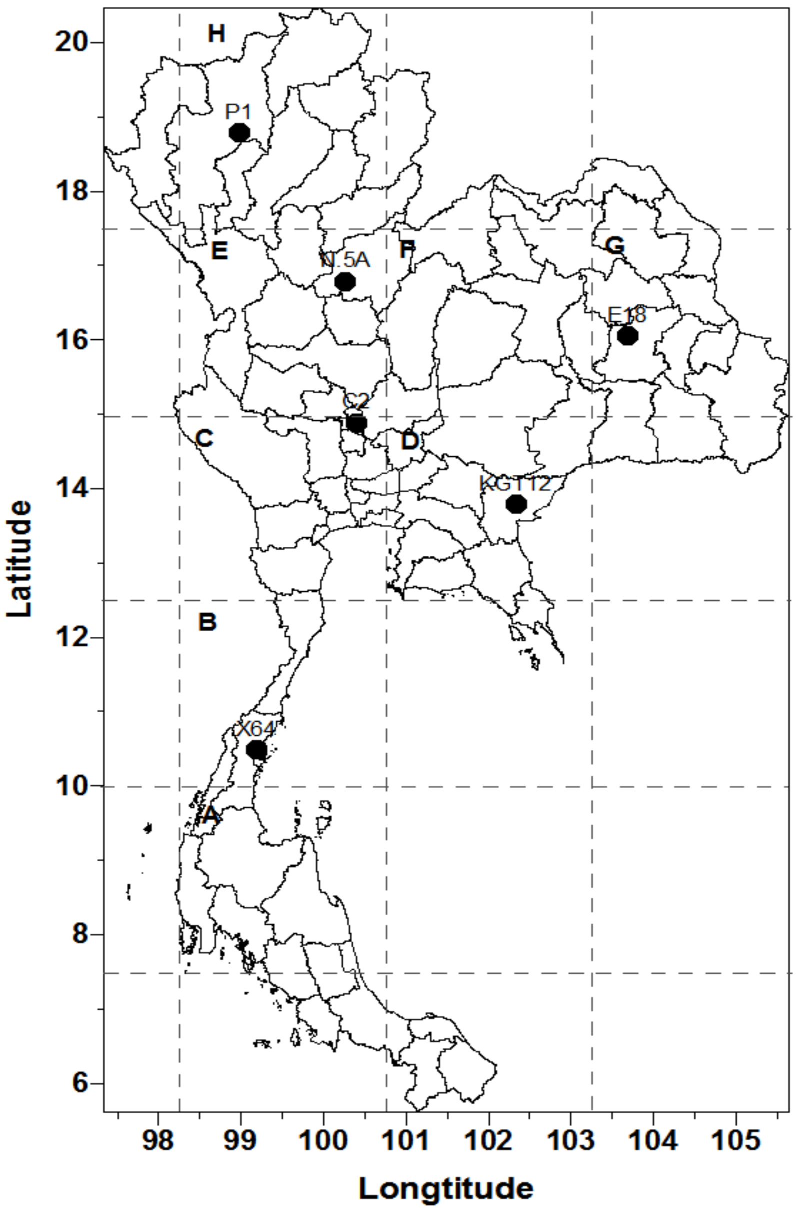

Figure 1. Eight grid cells of the monthly PDSI data used in this study. The selected PDSI extends from 1951 to 2005 and in the region of 7.50-20.00 °N, 98.25-102.50 °E covering most areas of Thailand.

where F_n (eigenvector) represents orthogonal spatial EOF pattern and a_n is the time-dependent amplitude or the EOF expansion coefficient which carries information about the temporal variance of the data set along F_n.

To further examine temporal variability, a linear trend was first analyzed for the PDSI EOF1 coefficient time series by using a non-parametric Kendall's tau based slope estimator (Aguila *et al*., 2005). This method is resistant to the effect of outliers in the series. The significance of the trends was determined using Kendall's test, since this approach does not assume an underlying probability distribution of the data series resulting robust significant trends. The PDSI EOF1 coefficient time series was further considered interannual (11-term smoothed series) and decadal (60-term smoothed series) timescales. The two different timescales were chosen on the basis that the separated interannual/decadal variability corresponds to short and long-term behavior of the ENSO phenomenon. To compare the PDSI EOF1 coefficient time series on interannual/decadal time-scales with the well-known

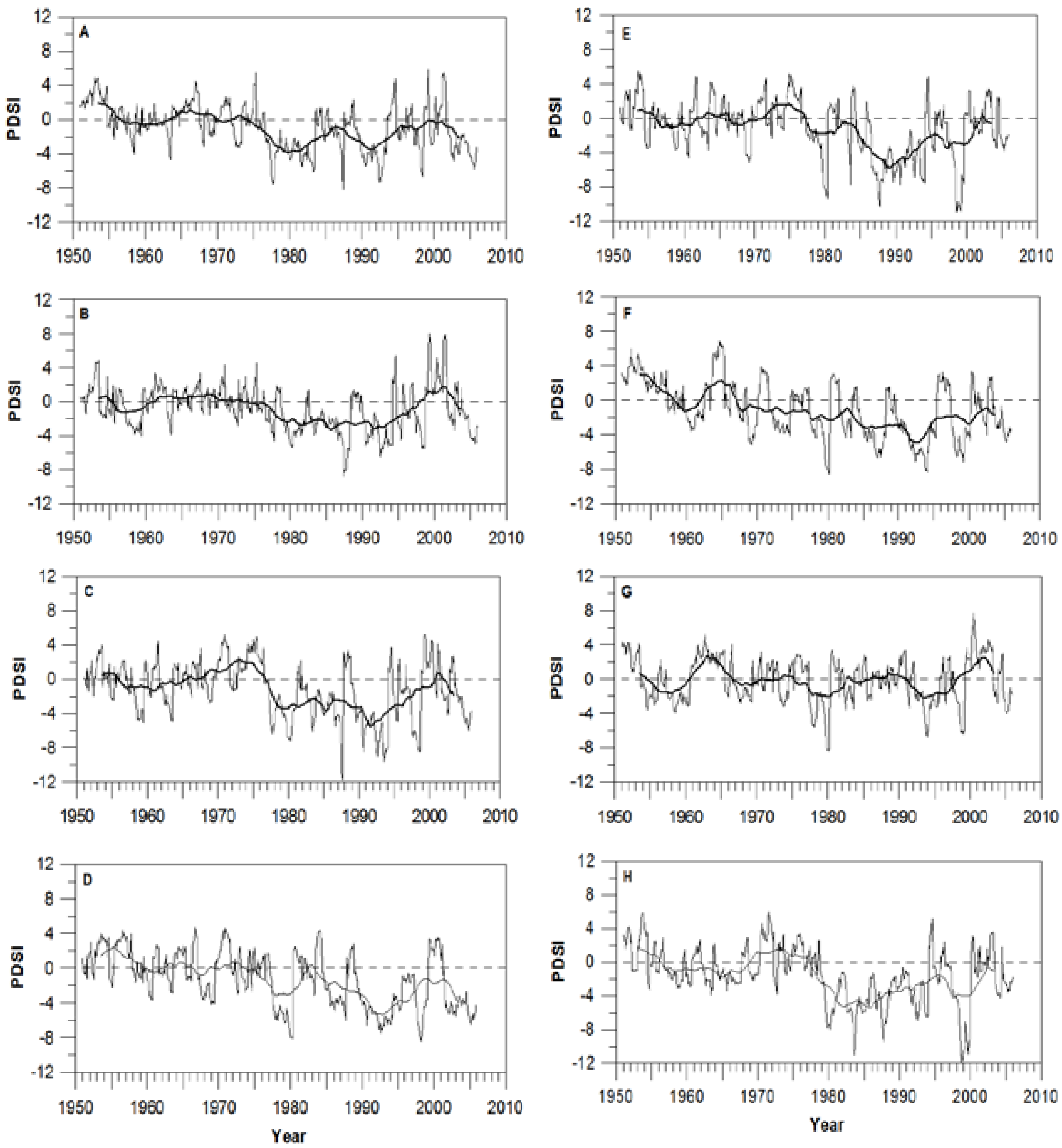

Figure 2. Monthly PDSI time series plots at each grid cell shown in Fig. 1. Solid lines denote 60-term running means representing decadal variations.

mode of global climate variability, we examined 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). Since the MEI integrates more information than other indices, it fully reflects the nature of the coupled ocean–atmosphere system and thereby is better for monitoring the ENSO phenomenon including, for instance, world-wide correlations with surface temperatures and rainfall than the SOI or SST-based indices (Wolter and Timlin, 1998).

4. Results and Discussions

4.1. PDSI variations

Fig. 2 shows the PDSI time series of each grid cell in Thailand. During 1951-2005, PDSI values typically ranged from -11.97 to 7.98. As can be seen, each series exhibited irregular oscillations in which prominent year-to-year variations were superimposed on long-term trends with time-scales of a few to multi years (Fig. 2).

4.2. PDSI versus river flow

Annual river flow rates at selected five stations across Thailand (Fig. 1) and the PDSI at grid cell B, C, D, E, G and H that have long records ranging from 1973-2005, 1956-2005, 1967-2005, 1954-2005 and 1951-2005 respectively were compared (Fig. 3). Both the PDSI and annual streamflow rates in Thailand have large multi-year and decadal variations, and they covaried reasonably as correlation coefficient for each grid cell was in range of 0.41 – 0.70 with all significant at 95% level. Thailand PDSI-streamflow relationships are strong in the North and South and become low over the Central, East and Northeast. This may be due to the fact that more rainfall evaporates instead of going into streamflow in these rapid land-use changes. Based on the results, it is reasonable to suggest that the PDSI is a good proxy of both surface moisture conditions and streamflow in Thailand, and they are consistent with the previous studies showing coherent variations with comparable magnitudes between the two in many parts of the world (Dai *et al*., 1998; 2004).

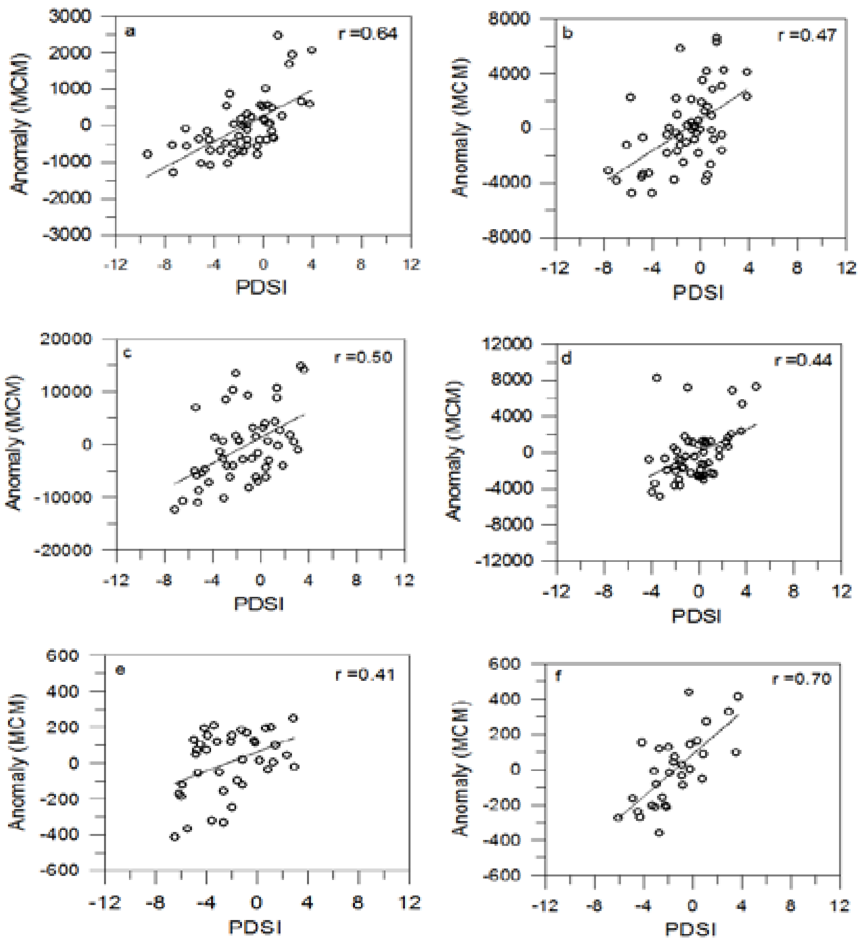

Figure 3. Scatter plots of PDSI and annual anomalies of streamflow rates for P1 (a), N.5A (b), C2 (c), E18 (d), KGT12 (e) and X64 (f). Locations of annual streamflow records used are shown in Fig. 1.

Table 2. Spearman correlation coefficients (r_s) between MEI and 11-term and 60-term smoothed PDSI EOF1

Variables	*N*	N_{eff}	r_s	*p value*
11-term smoothed PDSI EOF1 & MEI	650	89	0.59	<0.01
60-term smoothed PDSI EOF1 & MEI	600	59	0.88	<0.01

N and N_{eff} are the number of data points in each series and the effective number of independent observation. Significant levels of computed r_s were assessed by calculating the effective number of independent observations (N_{eff}) following the approach of Emery and Thomson (1997).

4.3. A leading EOF mode of Thailand's PDSI

The EOF analysis of monthly PDSI from 1951-2005 revealed that the leading mode accounted for 62% of the total variance. The principal component time series of the first EOF represented multi-timescale changes ranging from interannual/decadal variations to a long-term trend (Fig. 4). From a long-term perspective, there was a declining trend towards remarkable drying over Thailand for period 1951-2005. The results are in line with the previous studies showing the significant surface warming, the unusual and persistent deficit in rainfall and a concomitant reduction of rainy days observed in Thailand over the last three decades (Limsakul *et al*., 2007; Limsakul and Goes, 2008). These changes are expected to be a major cause for the progressive and widespread drying over the region, as clearly evidenced from the PDSI and rainfall records. In addition, an abrupt shift from mild wet spells to remarkable drying was identified in the mid 1970s (Fig. 4), consistent with the well-known climatic regime shift occurred in 1976/1977 with coherent atmosphere-ocean changes and far-reaching impacts in many parts of the world (e.g., Trenberth and Hurrell, 1994; Mantua *et al*., 1997; Zhang *et al*., 1997; McGowan *et al*., 1998). On interannual/decadal basis, the principal component time series of PDSI EOF1 correlated significantly with ENSO events (Table 2). This is not surprising in view of the well documented changes in the distributions of rainfall, droughts and floods throughout the world during the warm and cold phases of ENSO. Dai *et al*. (2004) pointed out that the second EOF of global PDSI highly correlated with ENSO, since it was mainly induced by the precipitation anomalies associated with ENSO, rather than ENSO-driven temperature anomalies. Limsakul *et al*. (2007) further demonstrated that the recent drought-like condition in Thailand has been closely associated with the shift in the ENSO towards more El Niño events since the late 1970s, and coincided with the high global mean temperature.

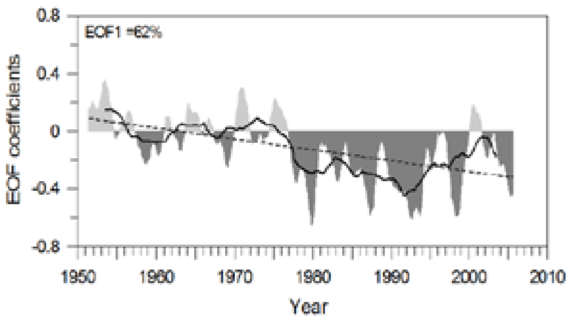

Figure 4. The PDSI EOF1 principal component time series. The bar charts denote interannual variability while the solid and dash lines represent decadal variability and a long-term trend, respectively

4.4. Temporal frequencies of severe/extreme droughts and very/extremely wet spells

We also estimated occurrence frequencies in severe/extreme droughts (PDSI <-3) and very/extremely wet spells (PDSI >3) for 1951-2005. This was done by counting the annual occurrence frequencies at each grid cell and summing all to represent an overall temporal change over Thailand. Figs. 5-7 show the annual occurrence frequencies in severe/extreme droughts, very/extremely wet spells and the sum of the two respectively, together with estimated linear trends. It can be seen that the multi-year and decadal variations of the annual occurrence frequencies in severe/extreme droughts, very/extremely wet spells and the sum of the two were very large. In the second half of 20th century, the annual occurrence frequencies in severe/extreme droughts in Thailand has more than doubled with a large jump in the mid 1970s (Fig. 5) as a result of rainfall decrease (Limsakul *et al*., 2007) and subsequent expansion primarily due to surface warming (Limsakul and Goes, 2008). Coinciding with increased occurrence frequency in severe/extreme droughts over 55 years, very/extremely wet spell frequency gradually declined by 2.5% per year as compared with the 1951-2005 mean (Fig. 6). Together, the sum of the annual occurrence frequencies in severe/extreme droughts and very/extremely wet spells increased by 2% per year relative to the long-term mean. This finding agrees well with the study of Dai *et al*. (2004). They found that global very dry areas defined as PDSI< -3 have more than doubled since the 1970s with a large shift in the early

1980s due to ENSO-induced precipitation decrease and surface warming, while global very wet areas (PDSI> 3) declined slightly during the 1980s. Overall, the global land areas in either very dry or very wet condition have increased from about 20% to 38% since 1972.

An additional analysis further shows significant correlations between the annual occurrence frequencies in severe/extreme droughts, very/extremely wet spells and the sum of the two and the MEI (Table 3). It is suggested that severe/extreme droughts and very/extremely wet spells tended to occur more frequently during either El Niño or La Niña phase of ENSO years. The results show good correspondence to Limsakul *et al*. (2007) and Limsakul and Goes (2008) who indicated that temperature and rainfall in Thailand were higher (lower) and lower (higher) than average during El Niño (La Niña) events, respectively. On basis of the previous results in combination additional evidence from this study, it is obvious that ENSO cycle is the most prominent driving force of interannual climate variability and associated extreme events in Thailand.

5. Summary and concluding remarks

Temporal variations in droughts and wet spells and associated extreme frequencies in Thailand for the period 1951-2005 were examined on the basis of the updated monthly gridded PDSI data on a 2.5° grid extracted from global dataset. The PDSI is a water-budget-based drought index that uses a two-layer model with incorporation of evapotranspiration as a measure of water demand. The extracted gridded PDSI was compared with annual streamflow records at selected five stations across Thailand. The PDSI variations in Thailand were correlated well with those in the observed annual streamflow rates. This suggests that the PDSI is a good proxy for monitoring and assessing droughts/wet spells and surface moisture conditions in Thailand and it can be further used as an index of annual-mean streamflow variations. However, the PDSI recalculation using a high spatial-temporal dataset and further modification (where necessary) will produce more realistic results that provide a useful resource for quantifying and evaluating both the regional vulnerability to droughts and wet spells and the seasonal monitoring and predictability of the phenomenon.

The EOF analysis of the PDSI revealed a fairly linear trend resulting from a combination of rainfall and surface temperature trends and an ENSO-induced mode of large interannual/decadal variations as the leading pattern. The ENSO cycle and its shift toward more warm phases after about 1976 which has been linked to decadal changes in climate throughout the Pacific basin (e.g., Mantua *et al*., 1997; Zhang *et al*., 1997) and is very unusual given the records of previous 100 years (Trenberth and Hoar, 1996) appears to be largely responsible for interannual variations and the recent progressive dying trend in Thailand. From

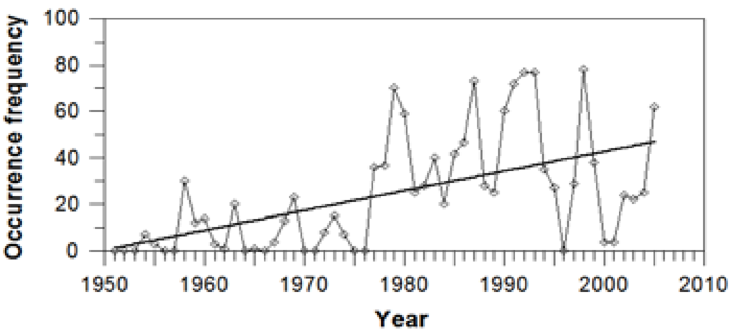

Figure 5. The annual occurrence frequency in severe/extreme drought (PDSI< -3) summing for all grid cells.

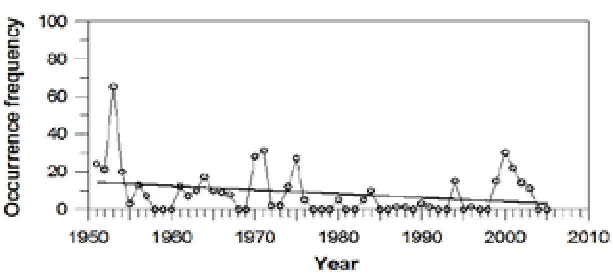

Figure 6. The annual occurrence frequency in very/extremely wet spells (PDSI> 3) summing for all grid cells.

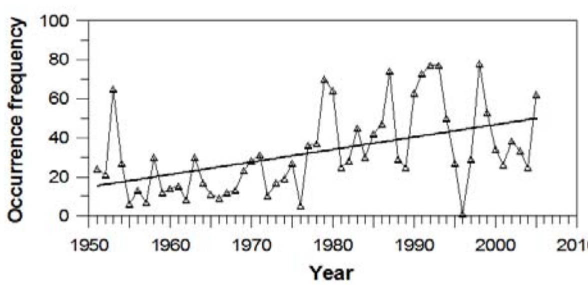

Figure 7. The annual occurrence frequency in severe/extreme drought + very/extremely wet spells summing for all grid cells.

Table 3. Spearman correlation coefficients (r_s) between MEI and the annual occurrence frequencies in severe/extreme droughts, very/extremely wet spells and the sum of the two. N and N_{eff} are the same as Table 2.

Variables	N	N_{eff}	r_s	*p value*
Severe/extreme drought (PDSI< -3) & MEI	55	50	0.58	<0.01
Very/extremely wet spells (PDSI> 3) & MEI	55	42	-0.45	<0.01
The sum of the two	55	43	0.45	<0.01

1951 to 2005, there were also large multi-year to decadal variations in the occurrence frequencies in severe/extreme droughts (PDSI< -3) and very/extremely wet spells (PDSI> 3) with the coherent jump occurred in the mid 1970s while an increased trend is still discernable. Similar to the leading PDSI EOF1 mode, the annual occurrence frequencies in severe/extreme droughts and very/extremely wet spells were closely related to ENSO events which extreme events tended to happen more frequently during ENSO years.

Patterns of EOF-derived PDSI variations and their extreme frequencies are consistent with surface temperature warming in Thailand with a pronounced increase after 1970s (Limsakul and Goes, 2008), similar to the global trend which has been attributed to human-forced climate change arising primarily from increased greenhouse gases. Higher temperatures increase the water-holding capacity of the atmosphere and thus increased potential evapotranspiration (Dai *et al*., 2004). Hence recent global and regional warming not only promotes a more vigorous hydrological cycle but also enhances drying near the surface as is captured by the PDSI. Moreover, some global climate models indicate a more El Niño-like superposed on top of more general warming with increased greenhouse gases (e.g., Meehl and Washington, 1996; Knutson *et al*., 1997). If this is the case, Thailand as one of climate change and ENSO-sensitive regions will experience the increasing risk of severe and extreme droughts/floods in the years to come as anthropogenic global warming progresses and produces increased temperatures and the anomalous oscillations of ENSO.

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