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Are droughts becoming more frequent or severe in China based on the Standardized Precipitation Evapotranspiration Index: 1951–2010?

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ABSTRACT: The Standardized Precipitation Evapotranspiration Index (SPEI) was computed based on the monthly precipitation and air temperature values at 609 locations over China during the period 1951–2010.Various characteristics of drought across China were examined including: long-term trends, percentage of area affected, intensity, duration, and drought frequency. The results revealed that severe and extreme droughts have become more serious since late 1990s for all of China (with dry area increasing by ∼3.72% per decade); and persistent multi-year severe droughts were more frequent in North China, Northeast China, and western Northwest China; significant drying trends occurred over North China, the southwest region of Northeast China, central and eastern regions of Northwest China, the central and southwestern parts of Southwest China and southwestern and northeastern parts of western Northwest mainly due to a decrease in precipitation coupled with a general increase in temperature. In addition, North China, the western Northwest China, and the Southwest China had their longest drought durations during the 1990s and 2000s. Droughts also affected western Northwest, eastern Northwest, North, and Northeast regions of China more frequently during the recent three decades. The results of this article could provide certain references and triggers for establishing a drought early warning system in China.

KEY WORDS China; drought trends, severity and frequency; SPEI

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1. Introduction

Droughts are the world's most damaging and pressing natural disasters [Federal Emergency Management Agency (FEMA), 1995; Keyantash and Dracup, 2002; Svoboda *et al.*, 2002; Romm, 2011], causing tens of billions of dollars in global damages, and collectively affecting more people than any other form of devastating climate-related hazards (Wilhite, 2000). Widespread drying has occurred over Africa, East and South Asia, and other areas from 1950 to 2008, and most of this drying is due to recent warming (Dai, 2011). According to Dai (2011), the global percentage of dry areas has increased by about 1.74% per decade from 1950 to 2008. Located in East Asia, China has also suffered long-lasting and severe droughts during the second half of twentieth century, which caused large economic and societal losses (Zou *et al.*, 2005; Xin *et al.*, 2006; Zhai *et al.*, 2010a, 2010b; Stone, 2010; Lu *et al.*, 2010; Lu *et al.*, 2011a, 2011b; Wang *et al.*, 2011; Wu *et al.*, 2011). Zou *et al.* (2005) calculated the Palmer Drought Severity Index based on the monthly air temperature and precipitation during 1951–2003 and discovered significant increases of drought areas in North China, with severe and prolonged dry periods dominating since the late 1990s. The drought in 2000 damaged more than 40 million hectares large area of crops in northern China. The severe drought in 1997 over northern China resulted in 226 d of zero flow in the Yellow River along a 687 km stretch (Liu and Zhang, 2002; Xu, 2004; Cong *et al.*, 2009). Droughts also occurred frequently in the Yangtze River basin in recent decades (Su *et al.*, 2008; Zhai *et al.*, 2010a, 2010b). In 2006, the Yangtze River basin runoff reached its lowest in the last 50 years with no flood in the flood season (Dai *et al.*, 2008; Yu *et al.*, 2012). During the summer of 2006, Sichuan and Chongqin provinces (located in the upper reach of the Yangtze River basin) were hit by their most severe drought since 1891 (Hai *et al.*, 2008). The average air temperature of middle August in some regions even reached 41–44.5°C. The drought evaporated water supplies and caused a shortage of drinking water for over 16 million people and 17 million livestock. It devastated crops in more than 2.5 million hectares of farmland

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with 30% of these hectares producing no harvest at all, which caused direct economic damages of US$3.5 billion (http://www.weather.com.cn/zt/kpzt/28353.shtml). The once-in-a-century drought swept across southwest China (including Yunnan, Guizhou, Guangxi, Sichuan, and Chongqing) from summer 2009 to spring 2010. It subjected over 16 million people and 11 million livestock to water shortages, devastated crops across more than 4 million hectares of farmland and made 25% of them yield no harvest. Most rivers shrank to 30–80% of their normal volume, and some dried up completely. The Southwest drought consequently was also examined by Huang *et al.* (2011), Zhang and Bai (2011), Liu *et al.* (2011), and Lu *et al.* (2011a, 2011b). For instance, Lu *et al.* (2011a, 2011b) found the severe drought in SW China mainly contributed to much-less-than-normal precipitation and much warmer-than-normal surface temperature.

These overwhelming drought conditions have been a big concern to both the Chinese government and general public during recent decades. Many previous studies have evaluated the dryness or wetness variations over China using different drought indices (Wu *et al.*, 2001; Ma and Fu, 2003; Wang *et al.*, 2003; Zou and Zhai, 2004; Zou *et al.*, 2005; Xin *et al.*, 2006; Zhai *et al.*, 2010a, 2010b; Lu *et al.*, 2011a, 2011b; Wang *et al.*, 2011; Wu *et al.*, 2011). According to Jones and Moberg (2003), there has been a general temperature increase (0.5–2 °C) during the last 150 years, and coupled climate change models also predict a marked increase (4 °C) during the twenty-first century (IPCC, 2007). Therefore, drought indices including temperature data are preferable for these types of applications. The Palmer Drought Severity Index (PDSI) (Palmer, 1965) is one of the most widely used drought indices over the world and considers prior precipitation, moisture supply, runoff, and evaporation demand (ET). The development of the self-calibrated PDSI solved considerable deficiencies (i.e. strong influence of calibration period, limitation in spatial comparability, subjectivity in relating drought conditions to the index values etc.) that the original PDSI had; nevertheless, the main deficiency of the PDSI has not been worked out. The PDSI has unspecified, built-in time scale and autoregressive characteristics, whereby the index values are influenced by the conditions even up to 4 years in the past (Guttman, 1998). Another widely accepted drought index is the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993) due to its multi-scalar characteristic and simplicity of calculation; however, the SPI is based on precipitation only. The newly developed Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010) combines the sensitivity of the PDSI to the changes in ET (caused by air temperature fluctuations and trends) with the simplicity of calculation, but also has the robustness of the multi-temporal nature of the SPI. This study primarily attempts to provide information of drought severity and frequency over the whole nation, and representative regions within China, based on the SPEI with updated data from 1951 to 2010.

2. Study area, data, and methods

2.1. Study area and data sources

The monthly precipitation (mm) and air temperature (°C) data during 1951–2010 from 752 meteorological stations in China were collected from the National Climate Center of the China Meteorological Administration (CMA). The homogeneity and reliability of the monthly meteorological data have been checked and firmly controlled by the CMA before its release. Of these, 609 stations covering most regions of China were selected for the study according to data availability criteria, and stations with less than 40 years data were rejected. For the purposes of this study, China is divided into three parts: Northern China, Southern China, and the Tibetan plateau. Northern China consists of Northeast (NE), North (N), eastern Northwest (ENW), and western Northwest China (WNW); Southern China consists of Southwest (SW), East (E), and South (S) China; the Tibetan plateau is marked by Tibet (see Figure 1). It should also be noted that due to a shortage of data in western Tibet, the time series can only represent the drought variations of eastern Tibet. The climate of China varies significantly from region to region due to its vast territory and complicated terrain (Zhai *et al.*, 2010a, 2010b). Dry climate generally dominates western and northern parts of China, while semi-humid and humid climate conditions primarily in the eastern part of China. Since the greatest part of continental China is located within the East Asian monsoon climate zone, where both winter and summer monsoons are distinctly developed, the monthly, annual and interannual variations in precipitation and air temperature are striking (Wu, *et al.*, 2011). For the Eastern part of China, semi-arid or semi-humid climate dominates the northern parts of its territory with annual precipitation ranging from 200 to 800 mm, while the southern parts have a relatively wetter climate with annual precipitation falling within 800–2000 mm (Zou *et al.*, 2005).

2.2. Calculation of the SPEI

The computation of the SPEI is as follows:

(1) Potential evapotranspiration calculation (Thornthwaite, 1948):

$$\mathrm{PET} = 16K\left(\frac{10T}{I}\right)^{m} \tag{1}$$

where T is the monthly mean temperature (°C); I is a heat index, which is calculated as the sum of 12 monthly index values; m is a coefficient depending on I: $m = 6.75 \times 10^{-7}I^{3} - 7.71 \times 10^{-5}I^{2} + 1.79 \times 10^{-2}I + 0.492$; and K is a correction coefficient computed as a function of the latitude and month.

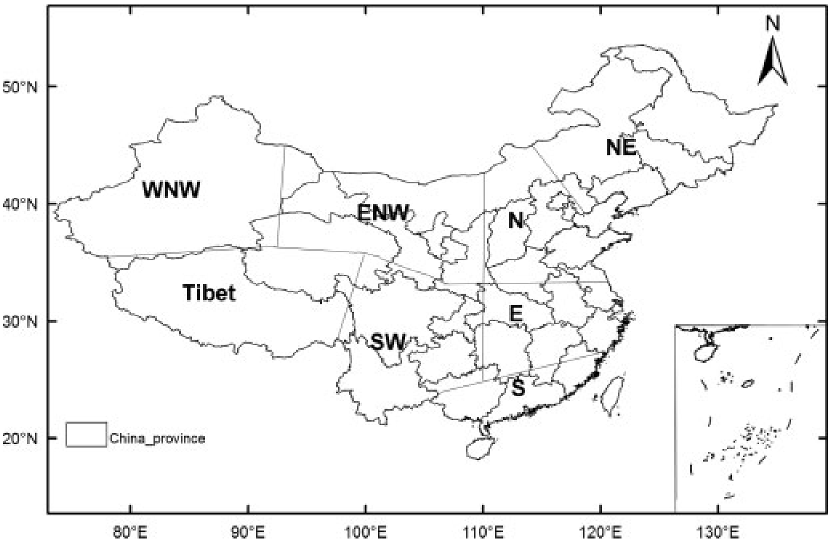

Figure 1. Locations of different regions within China.

(2) Deficit or surplus accumulation of a climate water balance at different time scales with a value for PET, the difference between the precipitation P and PET for the month i is calculated using:

$$D_i = P_i - \mathrm{PET}_i \tag{2}$$

The calculated D_i values are aggregated at different time scales, following the same procedure as that for the SPI. The difference $D_{i,j}^k$ in a given month j and year i depends on the chosen time scale k. For example, the accumulated difference for 1 month in a particular year i with a 12-month time scale is calculated using:

$$X_{i,j}^k = \sum_{l=13-k+j}^{12} D_{i-1,l} + \sum_{l=1}^{j} D_{i,l}, \text{if } j < k \text{ and}$$

$$X_{i,j}^k = \sum_{l=j-k+1}^{j} D_{i,j}, \text{if } j \geq k \tag{3}$$

where $D_{i,l}$ is the $P-\mathrm{PET}$ difference in the first month of year i, in millimetres.

(3) Normalize the water balance into a log-logistic probability distribution to obtain the SPEI index series.

The log-logistic distribution was selected for standardizing the D series to obtain the SPEI. The probability density function of log-logistic distributed variable is expressed as:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)\left[1+\left(\frac{x-\gamma}{\alpha}\right)\right]^{-2} \tag{4}$$

where α, β, and γ are scale, shape, and origin parameters respectively, for D values in the range ($\gamma > D < \infty$). The three parameters of the Pearson III distribution can be obtained following Singh *et al.* (1993).

Table 1. Categorization of dryness/wetness grade by the SPEI.

Categories	SPEI values
Extremely dryness	Less than −2
Severe dryness	−1.99 to −1.5
Moderate dryness	−1.49 to −1.0
Near normal	−1.0 to 1.0
Moderate wettness	1.0 to 1.49
Severe wettness	1.50 to 1.99
Extremely wettness	More than 2

Thus, the probability distribution function of the D series is given by:

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{5}$$

With $F(x)$ the SPEI can easily be obtained as the standardized values of $F(x)$. Following the classical approximation of Abramowitz and Stegun (1965):

$$\mathrm{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{6}$$

where $W = \sqrt{-2\ln(P)}$for$P \leq 0.5$ and P is the probability of exceeding a determination D value, $P = 1 - F(x)$. If $P > 0.5$, then P is replaced by $1 - P$ and the sign of the resultant SPEI is reversed. The constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$. Table 1 is the Categorization of dryness/wetness grade by the SPEI.

2.3. Trend analysis method

The trend tests applied in this study are the nonparametric Mann–Kendall (MK) test, which is a rank-based procedure suitable for detecting nonlinear trends (Mann, 1945; Kendall, 1975).

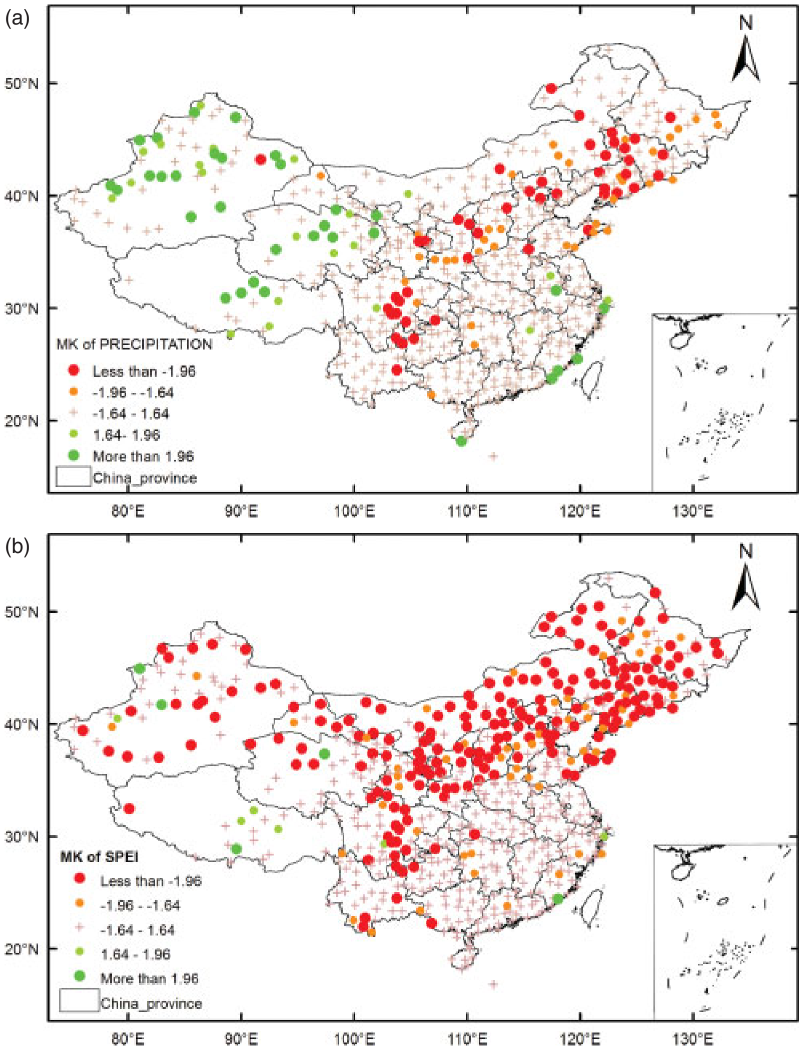

Figure 2. Trend variations of annual precipitation and SPEI over China (a) annual precipitation and (b) annual SPEI.

The MK method, assumes that the time series is $x_1, x_2, x_3, \ldots, x_N$, on the condition that the original time series was random and independent, and m_i denotes the cumulative total of samples so that $x_i > x_j (1 \le j \le i)$, where N is the number of the sample.

The definition of the statistical parameter d_k is as follows:

$$d_k = \sum_{i}^{k} m_i \; (2 \le k \le N) \tag{7}$$

The mean and variance of d_k are defined as:

$$E\,[d_k] = \frac{k\,(k-1)}{4} \text{and}$$
$$var\,[d_k] = \frac{k\,(k-1)\,(2k+5)}{72} 2 \le k \le N \tag{8}$$

Under the above assumption, the definition of the statistic index Z_k is calculated as:

$$Z_k = \frac{d_k - E\,[d_k]}{\sqrt{var\,[d_k]}} \; (k = 1, 2, 3, \ldots, N) \tag{9}$$

Z_k follows the standard normal distribution. In a two-sided test for trend, the null hypothesis is rejected at the significance level of α if $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. In this article, the significance levels of $\alpha = 5\%, 10\%$ are discussed respectively.

2.4. Data processing

The SPEI was calculated for the 12-month (for drought trends and drought area analysis) and 3-month (for drought duration and drought frequency analysis) time scales respectively by using monthly precipitation and air temperature data from the period 1951–2010 at 609 station locations. The MK trend test was applied for the existence of a possible tendency of annual dry conditions (based on the computed SPEI). Trends in annual precipitation and the relationship of trend variations between the annual SPEI and the annual precipitation were investigated thereafter. Considering the spatial variability of underlying conditions, the study area was divided into grids by Inverse Distance Weighting interpolation method with a chosen size of 0.5 square

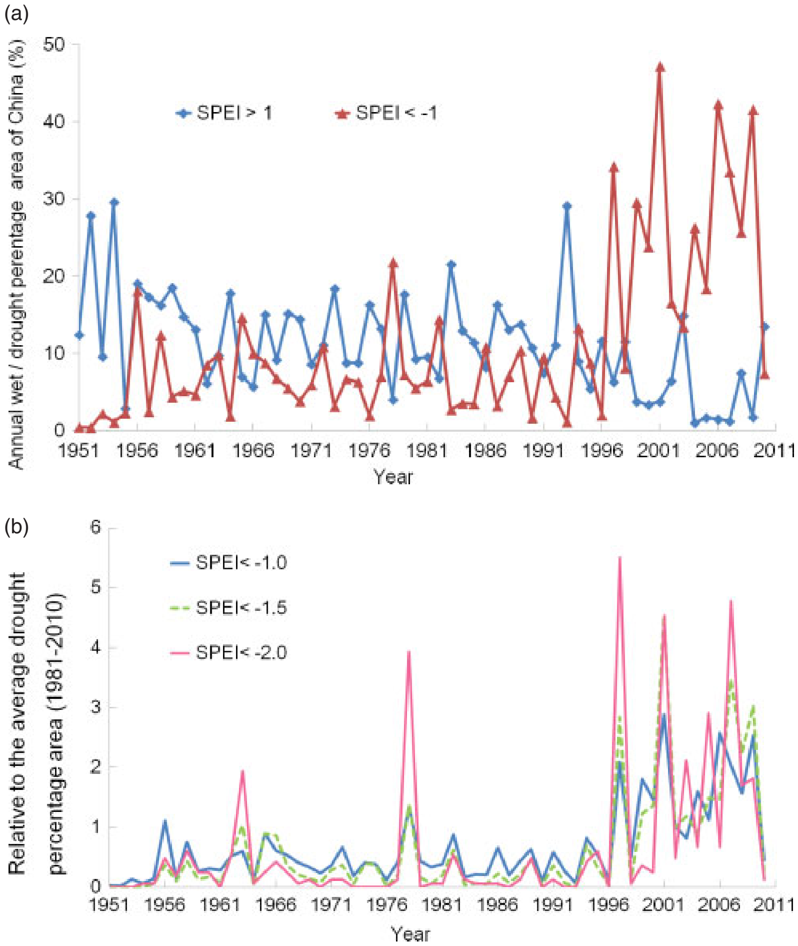

Figure 3. Temporal variations of annual percentage areas in drought conditions over the whole of China. (a) Temporal variations of percent area of China experiencing annual dry (SPEI < -1) and wet (SPEI > 1) conditions for 1951–2010. (b) Temporal variations of annual drought area relative to 1981–2010 mean values.

degrees for the drought area analysis. Time series of annual drought/wet percentage of area for all of China (and various regions within) were calculated based on the ratio of the number of grid points with SPEI < -1.0 to the related total number of grid points in China or the regions. Relative values of annual drought percentage area to the 1981–2010 average with SPEI < -1.0, SPEI < -1.5, and SPEI < -2.0, respectively, were also carried out and compared for all of China. To analyse the variations of the drought areas, the MK test and linear regression method were used to detect the changing trend of the annual drought/wet percentage area at different significance levels for the mainland China. Variations of drought areas were also plotted and investigated by different regions. In addition, the spatial and temporal variations of drought duration, which is defined as the longest period of consecutive months with SPEI < -1 over the period 1951–2010, were explored. Finally, based on the computed frequency of 3-month SPEI values falling in different ranges, frequency curves were plotted for different sub-periods at different regions within the whole of China and their changing patterns were investigated.

3. Results and discussion

3.1. Variations of drought changing trend

The spatial distributions of the MK trend statistic of annual precipitation and annual SPEI over China are shown in Figure 2. The positive and negative trends, which represent trends towards wetter and drier conditions, respectively, were detected. From Figure 2(a) it can be seen that the annual precipitation presented remarkable spatial variations in patterns, i.e. a significant downward trend (drying) dominates the east of China, whilst a significant upward trend (wetting) is observed in western China. For instance, significant downward trends (significant at 5 and 10% confidence level, respectively) of annual precipitation were found in the southwestern part of NE, central part of the N, southeastern part of the ENW, and central and southern parts of SW China (SW) respectively; whereas significant upward trends (significant at 5 and 10% confidence level, respectively) of annual precipitation were detected mainly in Xinjiang, Qinhai, eastern Tibet, and some small areas in the South and East China. The wetting trend is consistent with the recent study by Wang *et al.* (2011) and Wu *et al.* (2011).

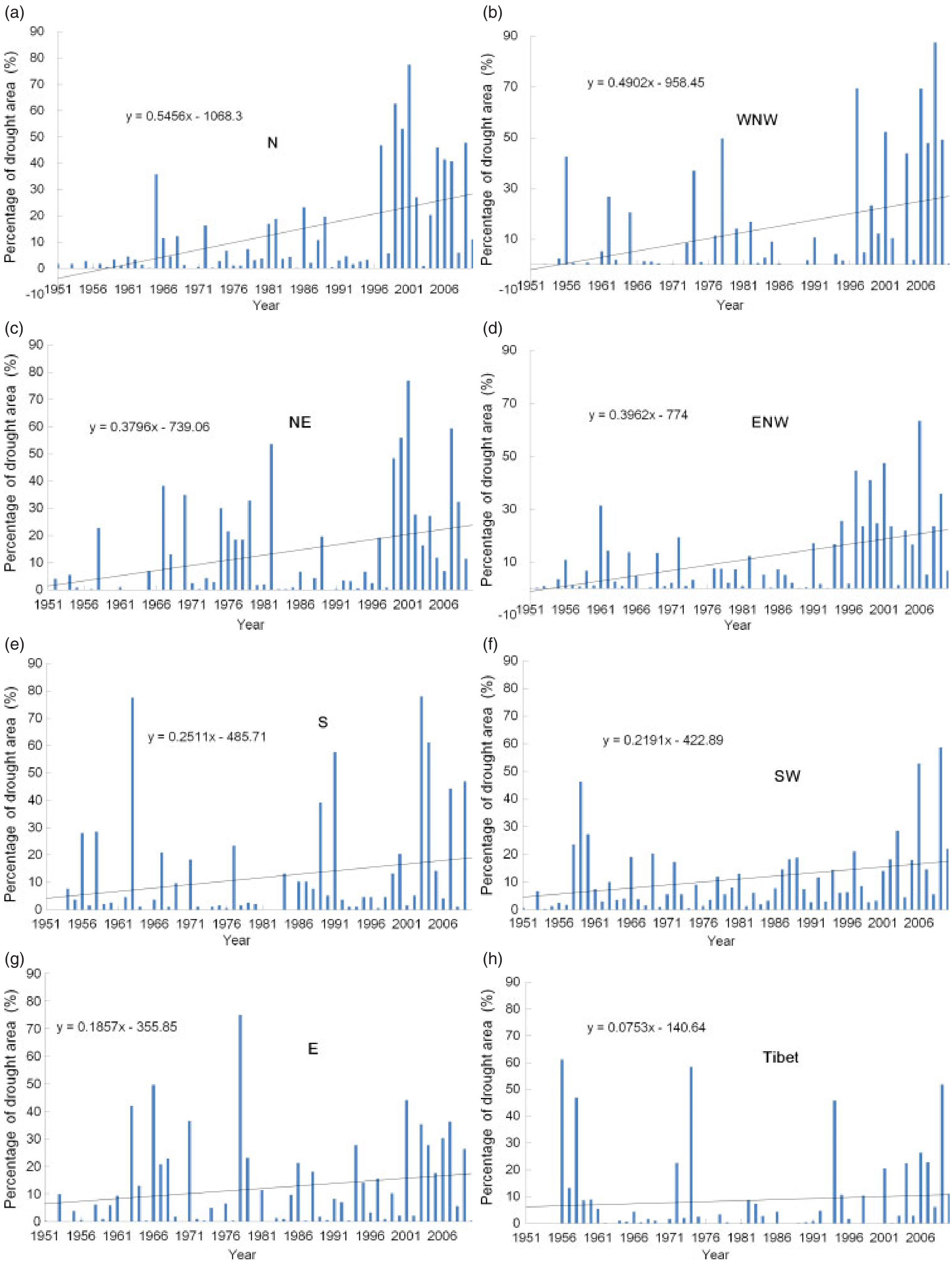

Figure 4. Changes and linear trends in dry areas (SPEI < −1) during 1951–2010 over different regions of China (a) N, (b) WNW, (c) NE, (d) ENW, (e) S, (f) SW, (g) E, and (h) Tibet.

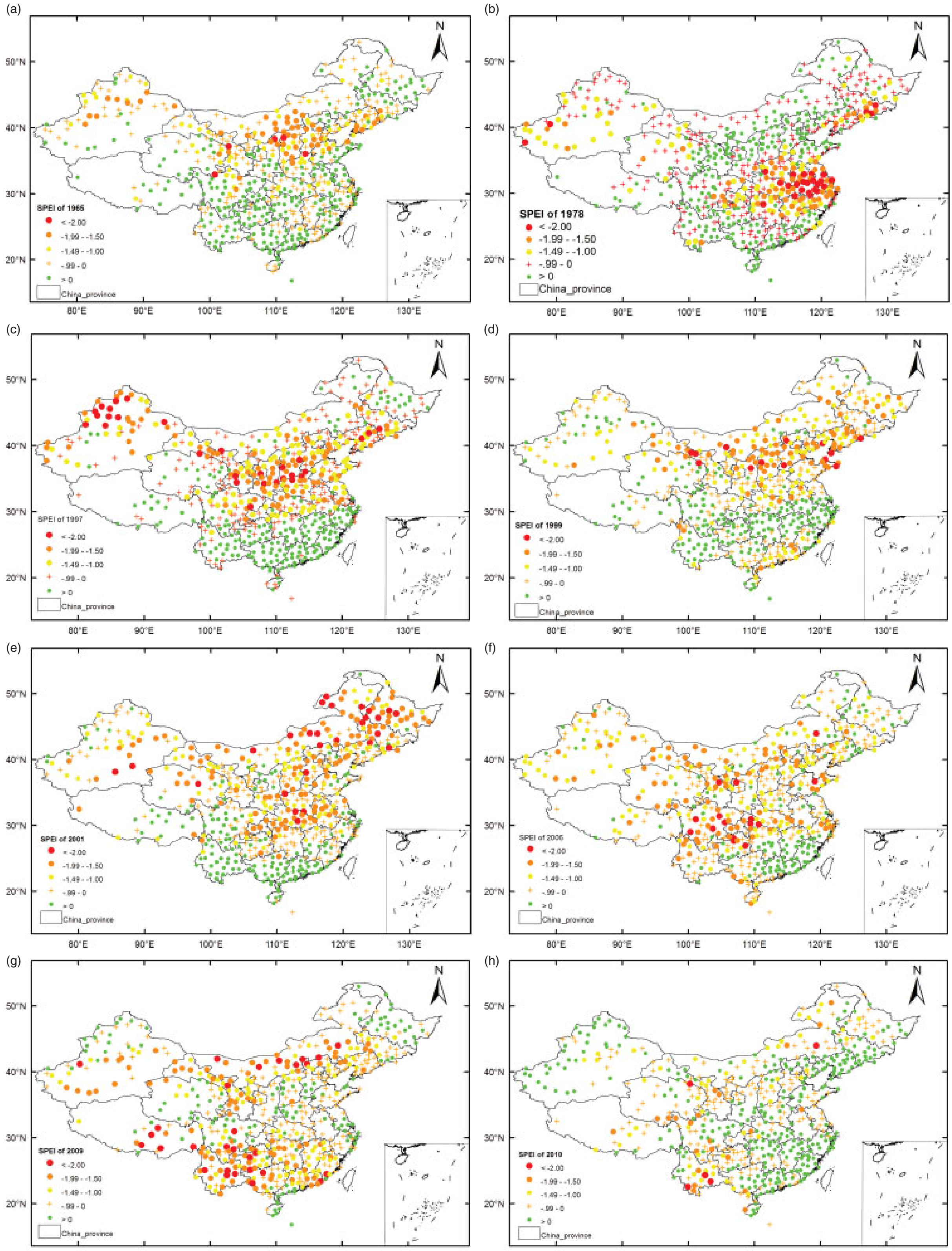

Figure 5. Severe (SPEI < −1.5) and extremely (SPEI < −2.0) drought events during 1951–2010 (a) 1965, (b) 1978, (c) 1997, (d) 2001, (e) 2003, (f) 2006, and (g) 2009.

Table 2. Drought area trends for China and different provinces.

	Trends (SPEI < −1)							
Regions	Liaoning	Hebei/Beijir	Shanxi	Sichuan	Yunnan	Inner Mongolia	Xinjiang	All China
MK values	2.83	2.7***/2.60**	2.65***	2.19**	2.02**	4.55***	2.99***	3.92***
%/10 years	4.67	4.79/6.50	3.94	2.32	3.22	6.71	4.94	3.72
Drought years	7	8/8	7	2	4	8	9	

Drought year is defined as the year with drought area more than 40%; *** and **are statistically significant at 1%, 5% confidence level respectively.

On the basis of soil moisture obtained from hydrological models they found wetting trends occurred over most of Xinjiang, Qinhai, and eastern part of Tibet.

Similarly, Figure 2(b) shows significant trends towards drier conditions (passing the 5 and 10% confidence level, respectively) of the annual SPEI in N China (i.e. Hebei, Shanxi, Shandong, and Mogonlia provinces), the southwestern part of NE China (i.e. Liaoning, Jilin, and Heilongjiang provinces), central and eastern of ENW China (i.e. Shaanxi, Gansu, Qinhai, and Ningxia provinces), central and southwestern parts of SW China (i.e. Sichuan and Yunnan provinces), and the southwestern and northeastern reaches of WNW China (i.e. most part of Xinjiang province). Significant trends towards wetter conditions (passing the 5 and 10% confidence level, respectively) were detected in eastern parts of the Tibetan plateau along with some small areas in Xinjiang, Qinhai, and Fujian provinces. Cook *et al.* (2010) investigated the climatic change over the 'Third Pole' by utilizing long tree-ring paleo-records, and concluded that the eastern Tibetan plateau is becoming wetter mainly due to melting of the Himalayas glaciers, which is likely being induced by rapid global warming.

In general, the annual SPEI and the annual precipitation both depicted the most significant drying areas, which indicated that the drying trend is mainly attributed to the significant reduction in precipitation. However, variations in the pattern of the annual SPEI were notably different from those of the annual precipitation. For example, 244 stations showed significant drying trends at the 90% confidence level for annual SPEI, with the ratio to the total stations of ∼40%, while merely 82 stations showed the same trend for annual precipitation, with the ratio of ∼13%. Only 11 stations had a significant wetting trend at the 90% confidence level for the annual SPEI, with the ratio to the total stations of ∼2%, whereas 53 stations showed a similar trend for annual precipitation, with the ratio of ∼9%. The analysis above suggests that although precipitation played an important role in the drying trend, recent warming (as represented by the temperature-based ET component of the SPEI) has also increased atmospheric moisture levels along with subsequent demand by evapotranspiration, with both contributing to the overall drying. Hence, air temperature must be taken into consideration in the context of warming in order to assess the drying trend more objectively.

3.2. Variations of drought/wet percentage area

Figure 3(a) shows the temporal variations of the percent area of China experiencing annual dry (SPEI < −1) and wet (SPEI > 1) conditions during 1951–2010. It can be seen that relatively large dry areas occurred in the middle of the 1950s, 1960s, late 1970s, early 1980s, and very large dry areas in late 1990s until 2010. It should be noted that the information from the early 1950s might not be as reliable due to limited availability of meteorological stations/data during that time. For all of China, the long-term increasing trend of dry areas was relatively large (3.7%/10 years, computed from linear regression) during the 60 years studied and was statistically significant at the 99% confidence level. In contrast to the drought areas, the temporal variations of annual wet percentage areas showed a less remarkable decreasing trend (−1.70%/10 years), but also statistically significant at the 99% confidence level, i.e. the larger the dry percentage area, the smaller the wet percentage area with the lowest values occurring from late 1990s to present.

Figure 3(b) shows the temporal variations of relative values of annual drought area to the mean values during 1981–2010 for different levels of drought severity (with SPEI classes of < −1.0, −1.5, and −2.0, respectively). In general, drought areas with different severity had similar patterns of variation with relatively large values of drought area occurring in the early 1960s, late 1970s, and late 1990s until present. The fluctuations of relative values corresponds very well with the annual drought percentage area (SPEI < −1.0) (Figure 3(a)), with the most pronounced fluctuations in relative drought area being depicted with SPEI < −2.0, and the least with SPEI < −1.0 (Figure 3(b)). Before the late 1990s, the relative values of SPEI < −2.0 were lower than those with SPEI < −1.0 and SPEI < −1.5 in general except in 1963 and 1978 due to severe drought events; however, the average relative values with SPEI < −2.0 became the highest thereafter. Nevertheless, the relative values of severe and extreme droughts even reached three to five times the mean average of 1981–2010 in many years since the late 1990s. This indicates that severe drought areas, particularly extreme drought, have increased dramatically since the late 1990s.

Figure 4 also presented the changes and linear trends in dry areas (SPEI < −1) during 1951–2010 over different regions of China. The most significant increasing trend of dry area was found in N China with a rate

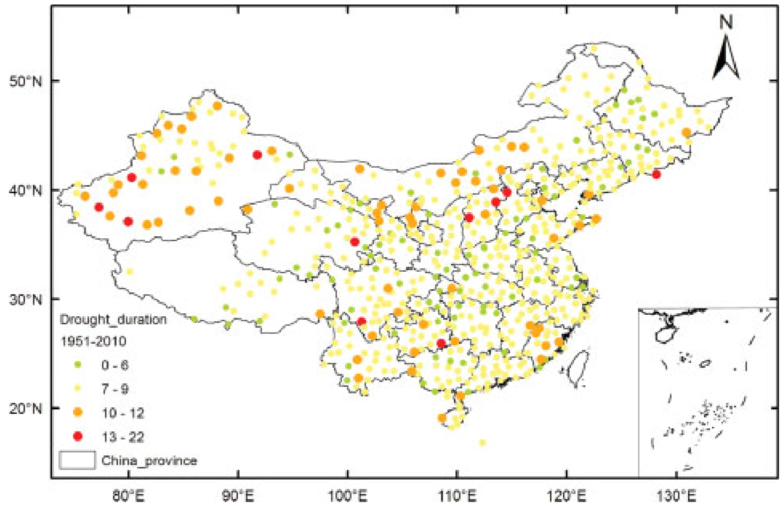

Figure 6. Spatial distribution of drought duration (number of months) over China during 1951–2010.

of 5.46%/10 years (Figure 4(a)). Widespread and large droughts occurred frequently in 1997, 1999, 2000, 2001, 2005, 2006, 2007, and 2009 with the percentages areas in drought condition of 47, 63, 53, 77, 46, 41, 41, and 48% respectively. It indicated that the successive severe droughts began in recent two decades in N China. Striking drying trend also occurred in WNW China with a rate of 4.90%/10 years (Figure 4(b)). Persistent multi-year droughts dominated in last two decades in WNW with percentage area over 40% in five consecutive years in 2000s. The percentage area of drought condition even reached almost 90% during 2008, and nearly 70% both in 1997 and 2006. Obvious increases of dry area were also detected in NE China and ENW China, with a rate of 3.80% per decade and 3.96% per decade, respectively (Figure 4(c) and (d)). Large drought area covered the NE in 1982, 1999, 2000, 2001, and 2006 respectively, with its most extensive drought in 2001 with nearly 80% percentage drought area in the region. Weaker upward trends were observed in S, SW, and E China, with a rate of 2.51%/10 years, 2.19%/10 years, and 1.86 %/10 years, respectively. Almost no remarkable upward trend was found in Tibet.

To better investigate the spatial variations of severe drought, the representative severe drought events discussed above are plotted in Figure 5. The 1965 drought affected central N China, central ENW China, and the northwest part of WNW China. The 1978 drought was mostly contained within the eastern reaches of E China while small drought area appeared over the southern part of NE China and western parts of the WNW. The 1997 drought was clearly divided into two centres, one located over N China and the other over northern Xinjiang province. Following on directly after the droughts of 1999 and 2000, the 2001 drought was one of the most severe droughts in terms of the drought area, duration, and agricultural and economical losses. The drought was mainly located to the north of the Yangtze River, i.e. NE, N, the northern part of E, ENW, and the southeastern part of WNW. In spring and summer of 2003, regions to the south of the Yangtze River in China were hit by severe droughts, particularly in Fujian and Zhejiang provinces (Wu, 2005; Xu, 2005) (http://www.weather.com.cn/zt/kpzt/1244106.shtml). During the summer and autumn 2006, the 1-in-100 year Chuan (Sichuan)-Yu (Chongqin) drought was mainly located in the upper reaches of the Yangtze River basin. Some people attributed the severe drought to the construction of the Three Gorges Dam (the largest dam on the Yangtze River started operation since 2003); however, other factors, such as extensive land reclamation and excessive pumping of groundwater are significant contributors to the droughts (Lu *et al.*, 2011a, 2011b). The 2009/2010 Southwest China drought can be seen in Figure 5. Yunnan province, which is in the subtropics, was hit the hardest and resembled a desert during the drought among the Yunnan, Guizhou, Guangxi, Sichuan, and Chongqing five provinces. The dried up lakes revealed desiccated aquatic animals. It was reported by the Yunnan Province Information Office that the drought continued till 26 March and caused water shortages for 8.2 million people and 3.1 million hectares of crops (Lu *et al.*, 2011a, 2011b).

From Figure 5 it can be concluded that severe droughts mostly occurred in N, NE, WNW, and SW. To better examine the drought conditions in those regions, annual drought percentage area in these main provinces were further analysed (see Table 2). It can be seen that the drought area of all the provinces showed significant ascending trends and all passed the 95% confidence level. In the meantime, secular trends of drought area were very large over all the provinces. Drought years, which were defined as years with drought percentage area being more than 40% (Lu *et al.*, 2010), showed different variation patterns in different regions. Liaoning, Heibei, Beijing, Tianjin, Shanxi, Inner Mongolia, and Xinjiang provinces, which were located in N, NE China, and WNW China respectively, had seven to nine drought

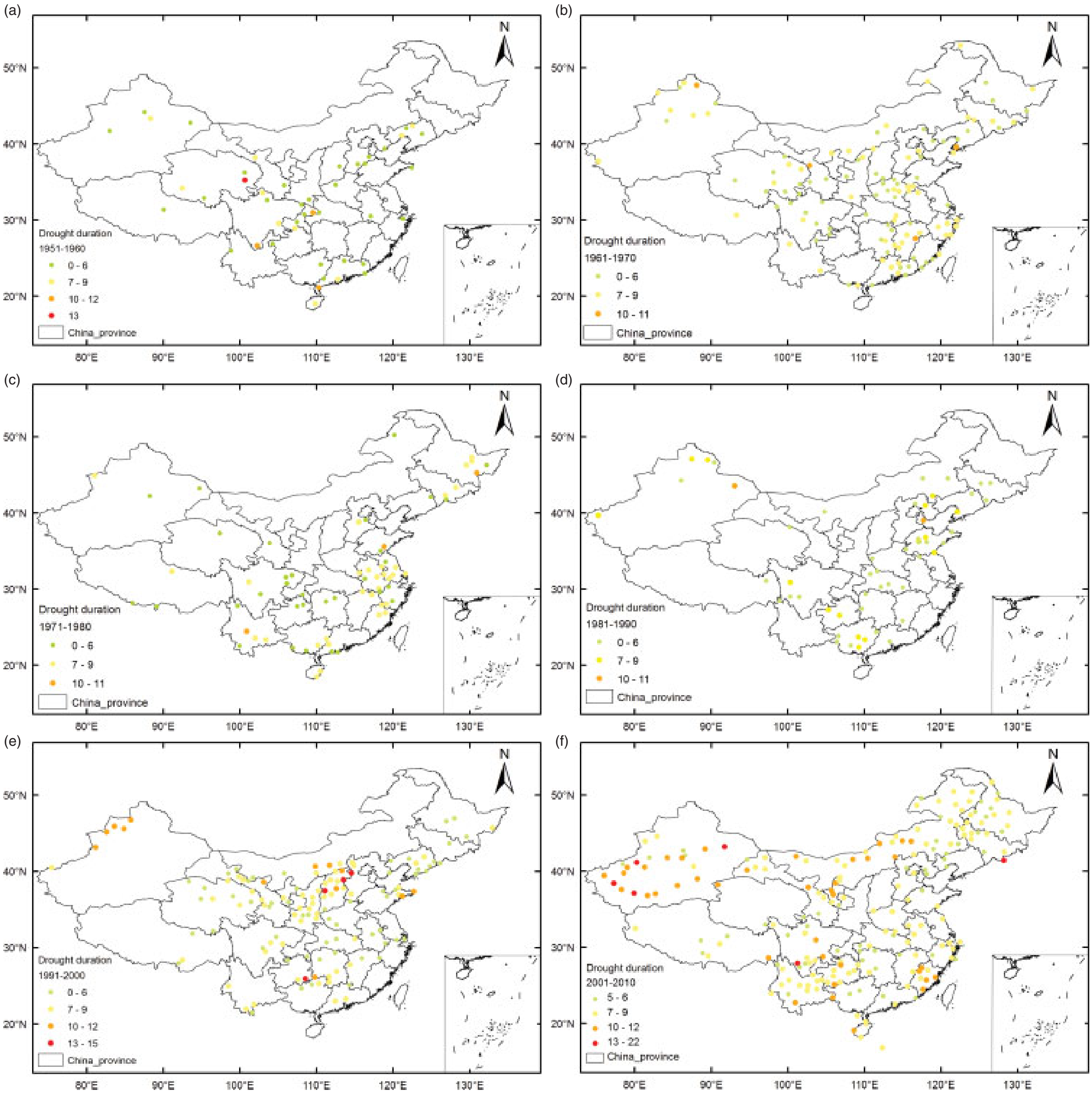

Figure 7. Decadal spatial distributions of drought duration (number of months) over China (a) 1950s, (b) 1960s, (c) 1970s, (d) 1980s, (e) 1990s, and (f) 2000s.

years, while Sichuan and Yunnan provinces, which were situated in SW China had 2 and 4 years, respectively. This revealed that multiple-year persistent severe droughts (SPEI < -1.5) were more likely to occur in N, NE, and WNW during 1951–2010.

3.3. Variations of drought duration

Variations of drought duration over China were also studied in addition to drought percentage areas. Figure 6 presents the spatial distribution of drought duration over China during 1951–2010. Drought duration here was defined as the longest consecutive months with 3-month SPEI < -1. It can be seen that droughts in N China, WNW, SW China, small area in NE, and Fujian province had their longest drought duration with more than 10 months. The longest drought duration in SW mainly occurred during the 2006 Chuan-Yu drought and the 2009/2010 Southwest drought, while that in Fujian was due to the 2003 severe drought in spring and summer (see Figure 5). The decadal spatial distribution of drought duration illustrated further that droughts in those area were stricken by their longest drought duration mostly in 1990s and 2000s (Figure 7).

3.4. Variations of drought frequency

Due to the atmosphere–ocean climate system shift-Pacific Decadal Oscillation over the North Pacific Ocean during the 1976/1977 winter season (Graham, 1994; Miller *et al.*, 1994; Mantua *et al.*, 1997; IPCC, 2007; Li *et al.*, 2011), the variations of precipitation and air temperature in China were also considerably affected (Zhou and Huang, 2003). Thus, it is necessary to divide the

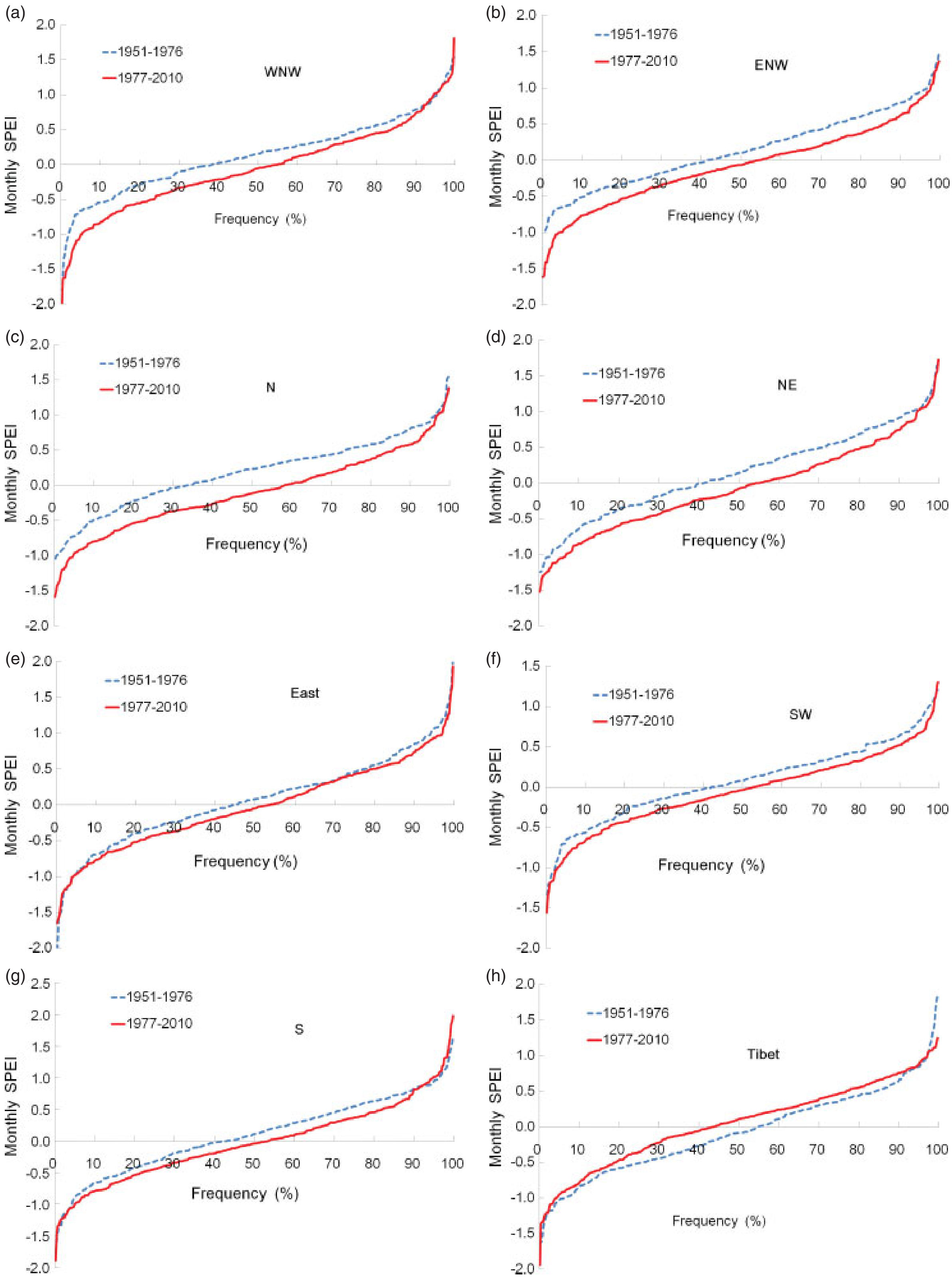

Figure 8. Drought frequency distributions for different regions within China (a) WNW, (b) ENW, (c) N, (d) NE, (e) E, (f) SW, (g) S, and (h) Tibet.

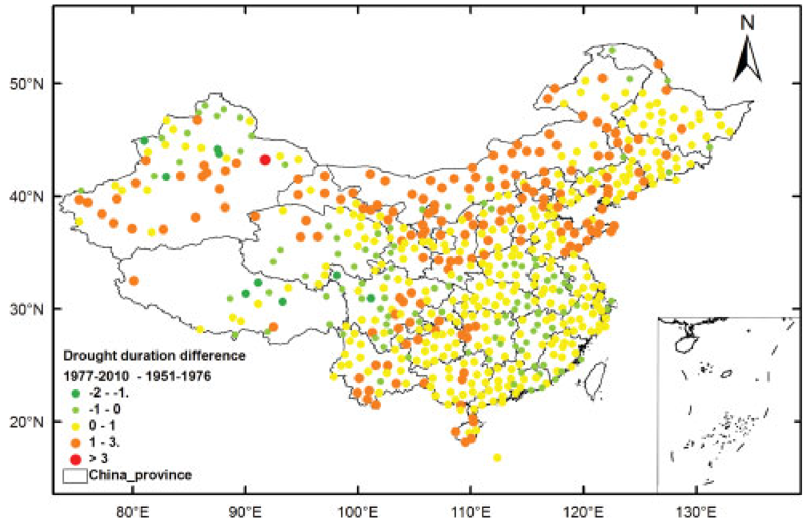

Figure 9. Spatial distributions of drought frequency between 1977–2010 and 1951–1976 over China, where drought frequency is defined as the difference in the mean annual number of drought months with SPEI < -1 (1977–2010 minus 1951–1976).

whole study period into two sub-periods (i.e. 1951–1976 and 1977–2010, respectively) to explore the variation of drought frequency patterns across China. In this study, drought frequency was investigated for several different regions (see Figure 8) and for China as a whole (see Figure 9).

Figure 8 illustrates drought frequency variations within separate regions for both sub-periods. In WNW China, the drought frequency with an SPEI of < -1 increased to 4.91% during 1977–2010 from 1.92% over the period of 1951–1976, with the ratio to the value of 1.92% being 2.56. In ENW China, the drought frequency with an SPEI of < -1 also rose rapidly to 4.00% during 1977–2010 from a value of only 0.32% over the 1951–1976 phase, with the ratio being 12.5. In N China, the drought frequency increased significantly to 4.91% over the 1977–2010 period from a value of 0.64% over 1951–1976, with the ratio being 7.67. In NE China, the drought frequency increased to 6.88% during 1977–2010 from the 2.80% observed during 1951–1976, with the ratio being 2.46. This demonstrates that droughts have hit the regions of WNW, ENW, N, and NE China more frequently during the past 30 years. The drought frequency in E China remained almost the same over 1977–2010 and 1951–1976 periods with the values both of 4.18 %. However, in looking at the two frequency curves of E China it can be seen that the percentage of dry conditions increased while that of wet conditions were generally reduced. In SW China, the drought frequency with SPEI < -1 increased to 2.95% during 1977–2010 from 1.99 % over the period 1951–1976, with a ratio of 1.50, which might be explained mainly by the contributions of the large severe droughts in 2006, and 2009/2010. In S China, drought frequency reached 4.95% over the period of 1977–2010 up from 4.47% over the period of 1951–1976, with the ratio being 1.11. That the frequency curve of 1977–2010 was mostly above that of 1951–1976 shows that the percentage of dry conditions decreased in the eastern Tibetan Plateau while that of wet conditions increased, which indicates that the climate in the eastern Tibetan Plateau is becoming wetter. The reduced the drought frequency of eastern Tibet from 6.50 % over 1951–1976 period to 4.42% over 1977–2010 also demonstrated the same result. The decreased wet percentage with SPEI > 1 with different extents over different regions also demonstrates that the climate is becoming less wet over all of China except for eastern Tibet.

The analysis above reveals that drought occurrences have become more frequent in WNW, ENW, N, and NE regions over China during the recent three decades; droughts in E, SW, and S regions also increased to a lesser extent, but not significantly; the climate in the eastern Tibetan Plateau is growing wetter.

Similar conclusions could also be obtained from Figure 9. It can be found that increased drought months occurred primarily in N, ENW, south and central parts of WNW, and southwest part of NE and SW China. The drought duration difference is small in most regions in E and S China. However, drought months decreased in some stations in WNW and eastern Tibet. This result is corresponding with the analysis carried out by Zou *et al.* (2005) based on PDSI.

4. Conclusions

This paper investigated the dryness/wetness variation patterns over China based on the SPEI. The results can be summarized as follows: (1) A significant upward trend of dry conditions occurred in N China, southwest parts of NE China, the central and east reaches of ENW China, the central and southwest parts of SW China, and southwest and northeast parts of WNW China; while significant trends towards wetter conditions occurred in eastern parts of the Tibetan plateau. (2) Comparison of the analysis of trends of annual precipitation and SPEI suggest that these changes are associated with changed in the temperature-based ET component. (3) Severe and extreme drought areas have increased since the late 1990s by ∼3.72% per decade. In addition, persistent, multiple-year severe droughts have occurred more frequently in N, NE, and WNW during the period 1951–2010. (4) N, WNW, and SW China had their longest drought durations occurring mostly in the 1990s and 2000s. (5) Drought occurrences have become much more frequent in WNW, ENW, N, and NE regions over China during the past 30 years and droughts in the E, SW, and S regions also increased to a lesser degree.

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