Prolonged dry episodes over Northeast China during the period 1961–2012

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Abstract Spatial and temporal changes of prolonged dry episodes, defined by the 90th percentile of consecutive no-rain days (<1 mm/day) in both the wet (May to September) and dry seasons (October to April), were investigated using daily precipitation data of 72 meteorological stations over Northeast China from 1961 to 2012. Increasing trends are detected for the prolonged dry episode duration at 94.4 % of the stations in the wet season, and 26.5 % of these increasing trends are statistically significant at the 5 % level. In the dry season, 77.8 % of the stations show decreasing trends, and 32.1 % of these decreasing trends are significant at the 5 % level. The drought trend in the wet season detected by the prolonged dry episode duration is more prominent than that detected by the total number of no-rain days or the Standard Precipitation Index. The ratio between the prolonged dry episode duration and total number of no-rain days exhibits a significant (at the 5 % level) increase of 8.3 %/52 years in the wet season and a significant decrease (at the 5 % level) of nearly 11 %/52 years. An overall dry (before 1980), wet (during the 1980s), and dry (after 1990) tendency in the wet season is detected at the regional average level. Inter-annual variations of the prolonged dry episode duration at individual stations show four patterns. The most predominant pattern is similar to the regional average condition but with larger amplitude and mainly occurring over the northern part of Northeast China. Our study provides a more in-depth case to

monitor droughts caused by extremely long dry spells and supports studies over other regions.

1 Introduction

Characterized by long duration, large extent, and widespread impacts, drought is one of the most frequent and threatening meteorological disasters in the world (Li et al. 1996). Global climate models indicate that droughts may become more severe and longer lasting in current drought-prone regions due to enhanced evaporation (Dai et al. 1998; Gregory et al. 1997). In China, the arid area has expanded with enhancing drought tendency under the background of global warming during the past decades (She et al. 2013). Northeast China is an important agricultural area, accounting for nearly 5 % of global soybean production and nearly 50 % of the national total (FAOSTAT 2011). Adjacent to the semiarid region of northern China and the Mongolian Plateau, Northeast China is quite vulnerable to the lack of precipitation and has suffered increasing drought pressure over the past two decades (Chen et al. 2011).

A consistent framework for the description of drought is essential for any study of this phenomenon (Lloyd-Hughes and Saunders 2002). However, it is always difficult to quantify drought characteristics due to the complexities of measuring intensity, magnitude, duration, and spatial extent (Vicente-Serrano et al. 2009). Therefore, numerous indices, including the widely used Standardized Precipitation Index (SPI) (McKee et al. 1993) and Palmer Drought Severity Index (PDSI) (Palmer, 1965), have been proposed and modified for the monitoring and analysis of droughts during the last century. Most studies using these indices were based on monthly precipitation data and attributed droughts to precipitation reduction. However, droughts not only result from the lack of total precipitation but are also affected by changes in annual precipitation pattern, such as a shift in dry spells, especially those extremely long dry spells caused by the increase in consecutive no-rain days during a period. Research based solely on monthly precipitation would

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sometimes lead to incorrect results (Cindric et al. 2010). For example, a prolonged dry period followed by a heavy precipitation event might be regarded as wet at an average level (She et al. 2013). The same precipitation total and number of dry days will have quite different effects when the dry days are homogeneously distributed in time or concentrated in a few dry spells (Zolina et al. 2013). Therefore, dry spells form a useful index being helpful for a better and more comprehensive understanding of droughts and has also been widely used all over the world (Cindric et al. 2010; Deni and Jemain 2009; Deni et al. 2010; Lana et al. 2006; Lana et al. 2008; Modarres 2010; Schmidli and Frei 2005; Vargas et al. 2011). Several researches about dry spells have also been conducted over China (Gong et al. 2005; Lei and Duan 2011).

Over Northeast China, many previous studies have investigated drought variations using different indices. Zou et al. (2005) applied the PDSI to study drought variations over China from 1951 to 2003, finding a successive expansion of dry areas (PDSI <1.0) in Northeast China (5.41 %/10 years) and increasing drought occurrences in the eastern and southern parts of Northeast China. Yu et al. (2014a, b) focused on the temporal and spatial variation of drought occurrence during the crop-growing season (May to September) and summer (June to August) in Northeast China using the SPI. Their results showed that regional mean precipitation had decreased significantly from 1960 to 2009 and drought occurrence and severity had been enhanced since 1996. Based on the Standardized Precipitation Evapotranspiration Index (SPEI), Yu et al. (2014a, b) investigated the dryness/wetness variation patterns over China and found a significant upward trend of dry conditions in Northeast China where persistent and multiple-year severe droughts have occurred more frequently during the period 1951–2010. Zhai et al. (2010) calculated the frequency of dry and wet years using the PDSI and SPI, indicating upward dry tendencies for three northeastern basins during the period 1961–2005. Using the spring-composite index, Song et al. (2014) investigated the spatial and temporal variations of spring drought in Northeast China from 1959 to 2010. However, regional studies focusing on dry spells are still lacking for Northeast China. Furthermore, researches on the extremely long dry spells are more important than that on dry spells of average duration, for the sake of drought monitoring and analysis (She et al. 2013). Therefore, this paper focuses on the spatial and temporal changes of prolonged dry episode duration over Northeast China during the period 1961–2012.

2 Materials and methods

2.1 Data

A daily precipitation dataset along with detailed metadata covering Northeast China (including Heilongjiang, Jilin, and

Liaoning provinces) for the period 1961–2012 was used in this study. The precipitation dataset was provided by the National Climate Center of the China Meteorological Administration (<http://www.nmic.gov.cn/>) and had been subjected to the quality control procedures of the Climate Data Center before release. The 52-year period was selected to avoid inhomogeneities from non-climatic factors as much as possible, since most stations are free of missing values after 1961.

2.2 Methods

In this study, dry spells were quantified as consecutive no-rain days with daily precipitation values less than 1 mm (Groisman and Knight 2008). The DPs90th index denotes the 90th percentile threshold of the durations of dry spells during the period 1961–2012. Then, the prolonged dry episode duration (PDED) index is defined as the sum of days within those dry spells longer than the DPs90th to quantify the drought pressure derived from those extremely long dry periods. Additionally, the TNND index represents the total number of no-rain days and is used to measure the drought pressure from a total level.

Missing values of daily precipitation may bring serious problems in the statistical analysis of uninterrupted dry strings (Groisman and Knight 2008). According to the sensitivity experiments by Zolina et al. (2010), the unbiased estimation of wet and dry spell durations requires records with missing daily data less than 10 %. Of the 87 meteorological stations available over Northeast China, 72 stations satisfied this requirement and were used in this study (Fig. 1). For these 72 stations, years with total annual missing day count greater than 20 would be dropped as well. The count of the duration of dry spells was allowed to be temporarily suspended when encountering one missing day and thereafter continue until the next rain day with daily precipitation above 1 mm. Furthermore, analyses were conducted at the seasonal scale for the wet (May to September) and dry season (October to April). Dry spells at the season boundaries were allocated to the season within which they started. Trends of TNND and PDED were detected using the Mann–Kendall test (Kendall 1975) and Sen's slope estimates (Sen 1968).

3 Results and discussions

3.1 Climatology of the DPs90th, TNND, and PDED

Climatologies of the DPs90th and means of the TNND and PDED in the wet and dry seasons during the period 1961–2012 are shown in Fig. 2. The DPs90th exhibits a variation ranging from 7 to 13 days in the wet season and 15 to 90 days in the dry season. The TNND generally varies from 95 to

Fig. 1 Locations of the 72 meteorological stations over Northeast China

125 days in the wet season and 175 to 200 days in the dry season. The PDED is predominantly characterized by 32 to 48 days in the wet season and 65 to 85 days in the dry season. The spatial patterns of these three indices are similar to each other in both the wet and dry seasons, showing a clearly increasing gradient from east to west. The similar spatial patterns of these three indices also indicate a positive correlation among them, i.e., a larger TNND generally correspond to higher values of DPs90th and PDED.

3.2 Trends of the TNND, PDED, and regional means of TNND and PDED

Trend test results of the TNND and PDED are provided in Table 1 and Fig. 3. The trend of annual TNND over Northeast China was analyzed by Wang et al. (2013), who found a slight regional increasing trend (non-significant) of 0.6 days per decade. However, the trend analysis of TNND at the seasonal scale is not addressed in previous researches. In the wet season, the change of TNND is from -8 to 12 days/52 years. Increasing trends are detected at 83.3 % of the stations, and 15 % of these increasing trends are significant at the 5 % level and mainly located in the eastern part of Northeast China. In the dry season, the change of TNND varies from -12 to 4 days/52 years. A total of 65.3 % of stations show decreasing

trends, and 14.9 % of these decreasing trends are significant at the 5 % level and mainly located in the northern part.

For the PDED in the wet season, the change is from -8 to 28 days/52 years. Increasing trends are detected at 94.4 % of the stations, and 26.5 % of these increasing trends are significant. In the dry season, the change of PDED varies from -90 to 30 days/52 years. A total of 77.8 % of the stations show decreasing trends, and 32.1 % of these decreasing trends are significant and mainly located in the northern part of Northeast China. According to Fig. 4, the regional means of the TNND and PDED also show increasing and decreasing trends in the wet and dry seasons, respectively. However, the trends of TNND are not significant. The trend test results of the PDED are consistent with the findings of Gong et al. (2005) who reported a significant increasing frequency of long dry spells (length >10 days) and also significant lengthening trends of dry spell duration over Northeast China in the summer-half-year (April to September) during the period 1956–2000.

According to these analyses, the trends of both TNND and PDED show a marked seasonal difference. The wet season is becoming drier and the dry season is becoming wetter, which is consistent with that obtained by other authors, who revealed a wet tendency in winter and a dry tendency in summer over Northeast China (Zhang et al. 2011; Zhang et al. 2009b).

Fig. 2 Climatologies of the **a, b** DP90th (days), **c, d** TNND (days), and **e, f** PDED (days) in the (*top*) wet and (*bottom*) dry season during the period 1961–2012

Similar trends have also been reported over the middle and lower Yellow River (Zhang et al. 2011) and Pearl River basin (Zhang et al. 2009a). However, the dry tendency of wet season

Table 1 Numbers of series with increasing, decreasing, or stationary trends, and percentages of series with significant trends at the 5% level for the TNND and PDED in the wet and dry season during the period 1961–2012

Index	Increasing trend		Decreasing trend		Stationary trend
	Total	SS (%)	Total	SS (%)	
Wet season					
TNND	60	15.0	11	0.0	1
PDED	68	26.5	4	0.0	0
Dry season					
TNND	23	0.0	47	14.9	2
PDED	15	0.0	56	32.1	1

SS statistical significance: $\alpha=0.05$

and wet tendency of dry season detected by the PDED are more predominant than those detected by the TNND. Yu et al. (2014a, b) studied trends in the SPI during the crop-growing season (May to September) over Northeast China from 1960 to 2009 and found only 12 stations showing significant decreasing trends. In comparison, the drought trend in the wet season revealed in this paper using the PDED index is more prominent. This indicates that the shift of dry spell durations is important for the drought variation over Northeast China over the past decades, and the PDED index focusing on extremely long dry spells can better detect drought trends in this case than indices from the total level.

A significant positive correlation (at the 1 % level in the wet season and at the 5 % level in the dry season) between the regional means of the PDED and TNND was detected Fig. 4g, h. We also calculated the ratio between the regional means of the PDED and TNND (RPT) as shown in Fig. 4e, f and computed its linear trends. In the wet season, the RPT

Fig. 3 Trend test results of the **a, b** TNND and **c, d** PDED in the (left) wet season and (right) dry season during the period 1961–2012. Sizes of triangles represent magnitudes of trend estimates (days/52 years). Filled triangles denote statistically significant series at the 5% level

Fig. 4 Inter-annual variation of regional means of **a, b** TNND, **c, d** PDED, and **e, f** RPT in the (left) wet season and (right) dry season during the period 1961–2012. The thin solid line denotes the original value, the thick solid line represents the 11-year moving average, and the

dashed line denotes the linear trends. Linear correlation between regional means of the TNND and PDED in the **g** wet season and **h** dry season during the period 1961–2012

exhibits a significant increase (at the 5 % level) of 8.3%/52 years. In the dry season, the RPT shows a significant decrease (at the 5 % level) of nearly 11%/52 years. The increasing RPT in the wet season indicates a growth of the contribution from the prolonged dry episode duration to the

total number of no-rain days in the wet season, which further implies a concentration trend of dry or wet days. This trend will lead to greater drought pressure which, however, cannot be fully detected by indices focusing on the reduction of total precipitation.

3.3 Inter-annual variation of the TNND, PDED, and RPT

Figure 4a–f presents the inter-annual variation of the regional means of the TNND, PDED, and RPT. In the wet season, the variation characteristics of these three indices are similar to each other, showing a slight increase before about 1980, then a decrease during the 1980s and a relatively rapid increase since the beginning of the 1990s. In the dry season, except for a slight increase around the 1990s, the TNND, PDED, and RPT exhibit an overall wavelike decrease.

Considering the great impacts of precipitation in the wet season on agriculture and the dry tendency of wet season revealed in Section 3.2, we further investigated the inter-annual variation of the PDED and RPT in the wet season for every single station, finding four major variation patterns (Fig. 5). The most predominant (Fig. 5a, b) pattern is similar to the regional mean condition but with larger amplitude. Stations showing this pattern are generally located in the northern part of Northeast China. The second pattern (Fig. 5c, d) is characterized by a decrease before about the middle of the 1980s and an increase afterwards and is associated with eight stations mainly located in

the southwestern part. The third pattern (Fig. 5e, f) is similar to the second one, except that the turning points are shifted to an earlier time of around the middle of the 1970s. Six stations of this pattern also concentrate over the southwestern part. The fourth pattern reveals a slight increase before the late 1970s, then a decrease until the middle of the 1980s and a rapid increase afterwards. Five stations showing this pattern are located in the southeast. Overall, the PDED and RPT have gone through a rapid increase in the wet season since the beginning of the 1990s for all patterns, indicating increasing drought pressure in the wet season during the last two decades over Northeast China.

Yu et al. (2014a, b) studied the time series of regional average precipitation during the crop-growing season (May to September) over Northeast China from 1960 to 2009 and detected two abrupt changes in 1984 and 1996, with significantly (at the 5 % level) decreasing trends during the period 1965–1983 and 1996–2009, and increasing trends from 1984 to 1995. These findings are similar to the results in this paper in terms of the overall dry, wet, and dry tendency. However, in our study, the first dry tendency ended around 1980, then the wet tendency continued to about 1990, and the latest dry

Fig. 5 Four variation patterns of the PDED (left) and RPT (right) in the wet season and the associated stations (middle). The value shown is the 11-year moving average, black rectangles denote the means of the

stations of a particular pattern, and the upper and lower limits represent the maximum and minimum values, respectively

tendency started since entering the 1990s. This difference indicates that indices focusing on extremely long dry spells are able to reveal different drought signals compared with indices based on the total precipitation.

4 Conclusions

Using daily precipitation datasets during the period 1961–2012 over Northeast China, this study focuses on the spatial and temporal changes of the prolonged dry episode duration and also explores the relationship between the prolonged dry episode duration and total number of no-rain days. The major conclusions are as follows:

- 1) Increasing and decreasing trends are dominant in the wet and dry seasons respectively for both the TNND and PDED, indicating that the dry season is becoming wetter and wet season becoming drier. Furthermore, the dry tendency of wet season and wet tendency of dry season detected by the PDED are more prominent than that detected by the TNND. The drought trend in the wet season revealed in this paper is also more significant than that observed by Yu et al. (2014a, b) using the SPI. Therefore, changes in the duration of dry spells are crucial for the drought variations over Northeast China over the past several decades, and the PDED index focusing on extremely long dry spells has greater power in drought monitoring and analysis than indices from the total level in this case.
- 2) There exists a significant positive correlation (at the 1 % level in the wet season and the 5 % level in the dry season) between the regional means of the PDED and TNND. The RPT exhibits a significant (at the 5 % level) increase of 8.3%/52 years in the wet season and a significant decrease (at the 5 % level) of nearly 11%/52 years. The increasing RPT in the wet season indicates the concentration trend of dry or wet days, which will result in greater drought pressure. However, this increasing drought pressure cannot be fully detected by indices from the total level.
- 3) An overall dry (before about 1980), wet (during the 1990s), and dry (after 1990) tendency in the wet season was detected over Northeast China from the regional mean level. Inter-annual variations of the PDED and RPT at the individual stations show four major variation forms. The most predominant form is similar to the regional mean condition but with larger amplitude. For all the variation forms, the PDED and RPT have undergone a rapid increase in the wet season since entering the 1990s, which is different with that observed by Yu et al. (2014a, b) who identified 1996 as the change

point from increasing to decreasing regional precipitation. This difference implies that the PDED index is able to reveal different drought signals compared with indices based on total precipitation.

Northeast China is an important agricultural zone in China, being highly sensitive to droughts. The increasing prolonged dry episode duration in the wet season is suggestive of a greater risk of droughts over Northeast China. Thus, effective measures are urgently needed to improve the management of water resources.

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