

Characteristics of consecutive dry days variations in China

Yawen Duan^{1,2} · Zhuguo Ma¹ · Qing Yang¹

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Abstract Consecutive dry days (CDDs) can serve as an effective measure of extreme precipitation and seasonal droughts. Using daily rain gauge data from 718 stations in China for the years 1961–2012, this paper documents the spatial and temporal characteristics of CDDs in the cold season (November to March) and the warm season (April to October). The results show that the long-term linear trends in CDDs have significant regional and seasonal differences. In the cold season, 57 % of the stations record decreases in CDDs, whereas in the warm season, 67 % of the stations record increasing trends. Applying the Ensemble Empirical Mode Decomposition (EEMD) to CDDs in selected regions, we found that 3-year oscillations account for most of the variance in CDDs, and this interannual variability is more pronounced in the cold season than in the warm season. Particularly in South China, CDDs in the cold season are most affected by oscillation of about a 3.3-year period. The decadal oscillations in CDDs over North China and the middle-lower reaches of the Yangtze River show larger variance than do other regions. Over North China, decadal variations in CDDs in both seasons are similar, with high phases during the 1990s and greater amplitude during the last 20 years,

whereas over middle-lower reaches of Yangtze River, the amplitudes of decadal oscillations in CDDs decreased since the 1990s in both seasons. In terms of secular trends, significant increases in CDDs over Southwest China in the cold season and South China in the warm season are noteworthy as they contribute largely to CDD variance and experience sharper slopes in recent years.

1 Introduction

The changing characteristics of precipitation under global warming has attracted the interest of many climate scientists (Trenberth et al. 2003; Dai 2006; Sun et al. 2007; Evans 2010; Durack et al. 2012; Huang et al. 2013; Kharin et al. 2013). Among all the aspects it involves, the relationship between the distribution of annual precipitation and extreme precipitation events is an important one. For example, for the same amount of annual precipitation, an inhomogeneous distribution of precipitation may lead to extreme precipitation events. Even within an increase or decrease in total precipitation, disproportional changes could occur in the upper end of the precipitation frequency distribution (Groisman and Knight 2008).

Inhomogeneity of annual precipitation may appear as two kinds of extreme events and either of them could lead to natural disasters, i.e., frequent heavy precipitation (flood) and long-term absence of precipitation (drought). Different from extreme heavy precipitation, drought caused by the deficiency in precipitation tends to occur in larger spatial scale and lasts longer. In average, the global damages caused by droughts reaches 6–8 billion dollars annually (Wilhite 2000; Hao et al. 2014). Particularly in China, an agricultural country with the largest population in the world, drought imposes high risk to agriculture and people's lives (Huang et al. 2012; Zhang and Zhou 2015).

The original version of this article was revised: In the Abstract section, “Particularly in South China, CDDs in the cold season are most affected by oscillation of about a 3.3-year period” should read “Particularly in South China, CDDs in the cold season are most affected by oscillation of about a 3.3-year period”.

✉ Zhuguo Ma
mazg@tea.ac.cn

¹ Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

² University of Chinese Academy of Sciences, Beijing 100049, China

Maximum consecutive dry days (CDD) is used as an index for assessing extreme precipitation event and seasonal drought. Frich et al. (2002) first defined the maximum number of consecutive days with precipitation less than 1 mm as CDD. Their study showed a general reduction in CDDs with notable exceptions in parts of South Africa, Canada, and eastern Asia. This index was then adopted by Expert Team on Climate Change Detection and Indices (ETCCDI) as one of the 27 climate change indices that are widely used in detecting and studying of extreme climate events, especially droughts (Alexander et al. 2006; Vincent and Mekis 2006; Oikonomou et al. 2010; Zhang et al. 2011; Field et al. 2012).

To better understand the variations of extreme precipitation and dry spells in China, several attempts have been made to analyze the spatial and temporal characteristics of CDDs (Gong et al. 2004; Gong et al. 2005; Wang et al. 2010; Lei and Duan 2011). During the second half of the twentieth century, the frequency of long dry spells (≥ 10 consecutive days without rainfall) in the summer over northern China increased significantly, whereas short dry spells were less frequent (Gong et al. 2004). Moreover, the duration of maximum CDDs over northern China also increased (Liu et al. 2008). All these suggest a dry tendency over the Northern China. In addition, the regional differences in CDDs over China are significant. For example, in contrast to the drier conditions over North China, the middle-lower reaches of Yangtze River becomes wetter owing to the shortening of the extreme dry spells (Wang et al. 2010).

The CDD is an useful indicator for short-term drought (Frich et al. 2002). However, most of the previous studies only focused on the long-term trends. Using daily rain gauge data from 718 stations in China for the years 1961–2012, this paper documents the spatial and temporal characteristics of CDDs over China and the regional differences between the selected regions. Particularly, by using Ensemble Empirical Mode Decomposition (EEMD), the characteristics of CDDs at various timescales are examined. Data and methods are described in Sect. 2; analyses of the climatology, linear trend, and time-scale characteristics of CDDs in typical regions are presented in Sect. 3; and conclusion and discussion in Sect. 4.

2 Data and method

2.1 Data and division of regions

Daily precipitation data from 824 stations were taken from the China ground climate dataset (version 3.0), provided by China Meteorological Administration (CMA). The study period was 1961–2012, and stations missing more than 6 months of data were excluded. For the remaining stations, absent data were replaced by the mean values of the study period. After the

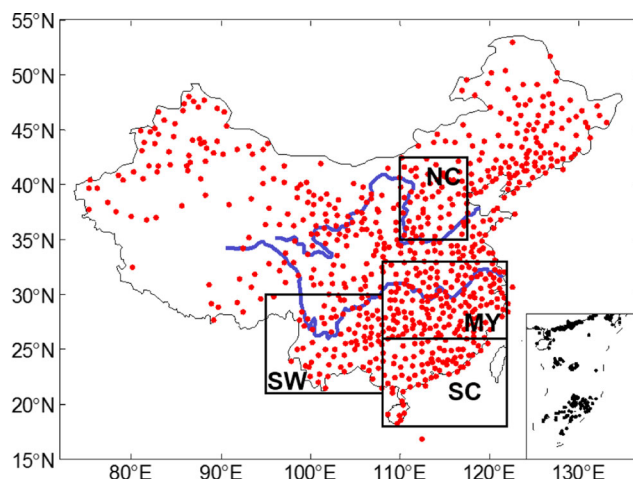


Fig. 1 Location of the rain gauge stations and the regions considered in this study. SW, SC, NC, and MY denote Southwest China, South China, North China, and the middle-lower reaches of the Yangtze River, respectively

strict quality control process, only 718 stations were used. The locations of the stations are shown in Fig. 1.

Precipitation-related extreme events in China have very different regional characteristics (Ding et al. 2006). Therefore, four typical regions in China were selected to further investigate the multi-timescale characteristics of CDDs. As shown in Fig. 1, these regions are (1) North China (NC), (2) Southwest China (SW), (3) middle-lower reaches of the Yangtze River (MY), and (4) South China (SC). The division of the regions is the same as that of Wang et al. (2004), Ma and Shao (2006), and Huang et al. (2012).

2.2 Definitions of indices

CDD means the maximum number of consecutive days with precipitation less than a certain threshold which varies (Frich et al. 2002; Nastos and Zerefos 2009; Zolina et al. 2013). Considering the vast regional climate differences in China, we adopt the low threshold of 0.1 mm/day for better regional comparisons rather than 1 mm/day. Due to the strong seasonality of the behaviors and influences of CDDs, we calculated the CDDs in the cold season (November to March of the next year) and the warm season (April to October), respectively. This division of cold/warm season was based on the multiyear mean monthly mean temperatures of China during 1961–1990, with months during warm season having mean temperature above 12 °C and cold season under 7 °C.

In addition to CDDs, the total no-precipitation days and frequency of no-precipitation periods in both seasons were also examined. Specifically, a day with precipitation less than 0.1 mm is defined as a no-precipitation (no-pre.) day, and a no-precipitation period is the time length between two adjacent precipitation days.

2.3 EEMD method

The EEMD method (Huang and Wu 2008; Wu and Huang 2009) is adopted here to extract the signals of various timescales from area-averaged CDDs. It is a self-adaptive method that is widely used in non-linear and non-stationary time series analysis (Qian et al. 2009).

The EEMD takes full advantage of the statistical characteristics of white noise to overcome the drawbacks of mode mixing problem in empirical mode decomposition (EMD) method (Huang et al. 1998). Therefore, it is well capable of extract physically meaningful components from the raw data (Wu and Huang 2009).

This method decomposes a time series into several oscillatory components at various timescales called intrinsic mode functions (IMFs) and a non-linear secular trend (ST) (Wu and Huang 2009). In this study, an ensemble size of 1000 and a white noise with amplitude of 0.2 times the standard deviation of CDDs were used. For the 52-year CDDs, four IMFs denoted as IMF_n ($n = 1, 2, 3, 4$) and an ST component were obtained.

Moreover, the Student *t* test was applied to examine the significance of linear regression. And, the Kriging method was used as the spatial interpolation method.

3 Results

3.1 The climatology and trends of CDDs

The spatial characteristics of CDD climatology during 1961–1990 show great differences between the cold and the warm seasons. As shown in Fig. 2, in the cold season, the minimum value of the multiyear mean CDDs is below 10 days, occurring mainly in Sichuan Basin and increasing both southward and northward. In the warm season, the minimum value of CDDs is around 5 days and it is mainly distributed in the area adjacent to the eastern Tibet Plateau. The multiyear mean CDDs in the warm season shows a meridional pattern, gradually increasing eastward

and westward from 102° E. However, high values of CDDs in the warm and cold seasons are both seen in southern Xinjiang and the northern Tibet Plateau, approaching 114 days in the cold season and 77 days in the warm season.

The changes in the length of CDDs provide useful information regarding drought tendencies (Orlowsky and Seneviratne 2012) because increasing CDDs may indicate enhanced dryness and high risk for seasonal droughts. Figure 3 shows the spatial distribution of linear trends in CDDs during 1961–2012. Of the total 718 stations, 57 % record negative trends in CDDs in the cold season, whereas 67 % of them show increased CDDs in the warm season. Over the west of 100° E, CDDs in both seasons decrease, particularly in northern Xinjiang during the cold season, indicating a wetter climate. However, the spatial characteristics of trends in CDDs over south of 35° N has distinct seasonal and regional differences. In the cold season, CDDs increase over Southwest China and decrease over the middle-lower reaches of the Yangtze River in a NE–SW pattern. In the warm season, a triple pattern emerges. CDDs significantly increase at maximum rate of 3 days/10 years over the coastal regions of South China and the zone between the Yangtze and Yellow rivers but decrease over the middle-lower reaches of the Yangtze River.

Furthermore, considering the changes in precipitation, the total no-precipitation days and the frequency of the no-precipitation periods during the study period that are shown in Fig. 4, a better understanding of the seasonal wet and dry tendencies were obtained.

In the cold season, over the West and Northeast China, with significant increments in precipitation and frequency of no-precipitation periods (Fig. 4a, e), the total no-precipitation days (Fig. 4c) and CDDs (Fig. 3a) decrease. These changes indicate that the precipitation events in these areas are more frequent and the dry spells become shorter. In contrast to the abovementioned changes, over Southwest and North China, the precipitation amount (Fig. 4a) and frequency of no-precipitation periods (Fig. 4e) in the cold season decrease, whereas the total no-precipitation days (Fig. 4c) and CDDs (Fig. 3a) increase, pointing to increasing risk of short-term droughts.

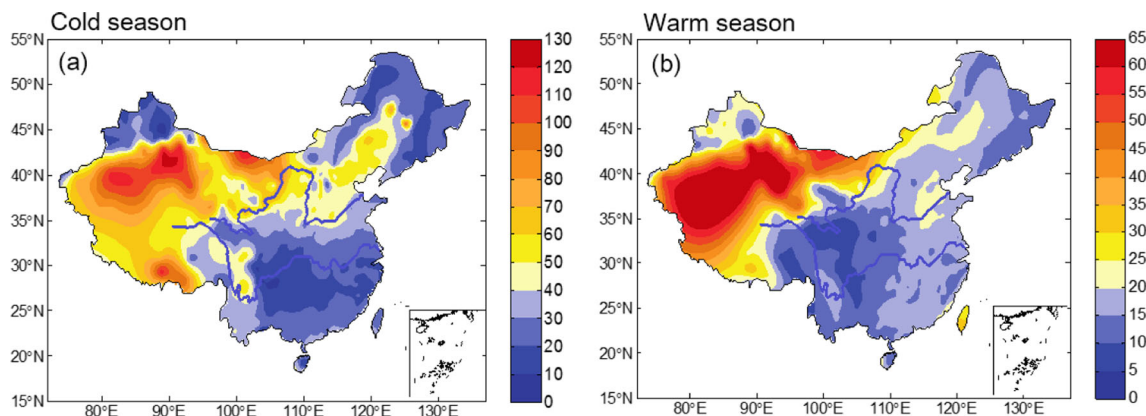


Fig. 2 Spatial distribution of climatology of consecutive dry days (CDDs) during the years 1961–1990 over China in **a** cold season and **b** warm season. Units: days

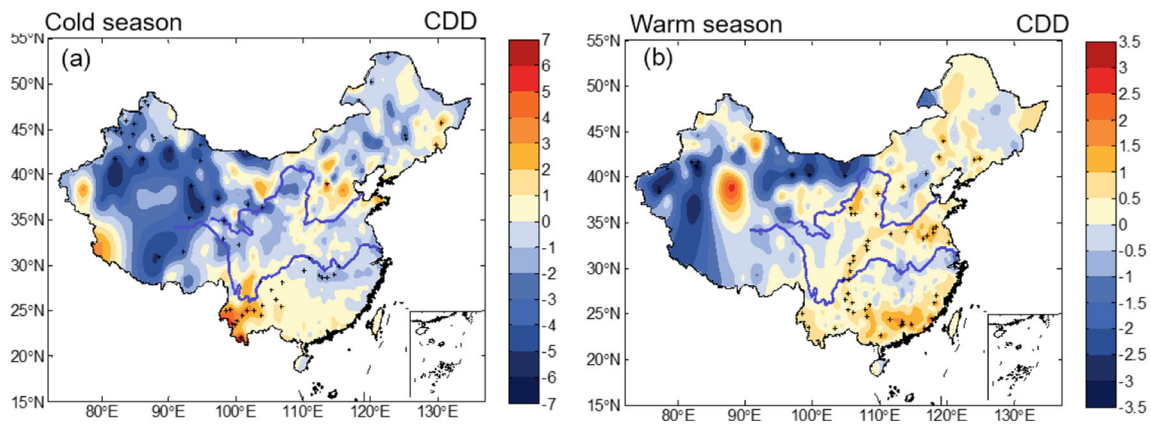


Fig. 3 Linear trends of consecutive dry days during the years 1961–2012 over China in **a** cold season and **b** warm season. Units: day/10 years. Dots indicate trends significant at the 5 % level

In the warm season, the most noteworthy feature is the consistent increase in the total no-precipitation days (Fig. 4d) over east of 100° E during 1961–2012 which are statistically significant at the 5 % level. However, as shown in the right column of Fig. 4, over the Northeast and North China, the increase in no-precipitation days mainly embodies in less but longer no-precipitation periods, because more stations experience decrements in precipitation amounts and frequency of no-precipitation days along with increments in CDDs. While over Southwest China and the meridional area adjacent to the eastern Tibet Plateau, all indices increase significantly except for the precipitation amount. These observations suggest that over this area, the no-precipitation periods not only last longer but also happen more frequently.

3.2 Timescale characteristics of CDDs in the typical regions

To better understand the trends seen in the above section, time series of selected regions are further analyzed. These regions are with obvious linear trends according to the above results, and some of them experienced serious seasonal drought during the study period (Huang et al. 2012). Figure 5 shows the area-averaged CDDs and precipitation in four typical regions (Sect. 2.1). Among the four regions, the increase in CDDs over Southwest China (SW) in the cold season is the most significant (1.25 day/10 years). The increment started in the 1990s, and the precipitation also decreased noticeably. During 2007–2009, extreme CDDs greater than 32 days occurred consecutively and reached the maximum of 35 days during the entire study period in 2012. The reduced precipitation and prolonged dry spells manifest the serious seasonal drought condition in the early twenty-first century in this area. Different from the cold season, the increase of CDD in the warm season began in the late 1970s in the SW region and maintained high values during the 1990s and 2000s.

In terms of annual precipitation, South China (SC) is the most humid of the four regions. Previous studies showed that the recent increases in precipitation over South China were mainly manifested as higher precipitation intensity (Zhai et al. 2007, Ren et al. 2010). This kind of change suggests the increasing temporal inhomogeneity in annual precipitation, which might be accompanied by prolonged dry spells. As shown in Fig. 5c, d, CDDs in both seasons in South China increased, especially in the warm season, by 0.8 days/10 years. Another noticeable feature of CDD in this region is the frequent high values of CDDs. During the cold seasons of 1973, 1983, 2003, and 2007, CDDs were longer than 35 days and in some stations longer than 45 days. And during the warm seasons of 1979 and 2004, CDDs exceeded 30 days. Such extended periods with no precipitation increase the risk to humid regions like South China.

The precipitation over North China (NC) show great seasonal differences between the cold season and warm season as well as the CDDs. The mean value of CDDs during 1961–2012 in the warm season is 18.9 days, fluctuating between 15 and 25 days, whereas the mean duration of CDDs in the cold season is two times longer, i.e., 46.3 days, and changes between 30 and 60 days. Despite the difference in the multiyear mean value, CDDs in both seasons have similar temporal variations. Especially during the 1990s, CDDs in both seasons were high, with mean value of 51.8 days in the cold season and 20.4 days in the warm season. And during this period, distinct extreme values of CDDs were observed. Particularly in the cold season, CDD lasted for 98.5 days in 1997 and in some stations exceeded 130 days, causing devastating drought.

The middle-lower reaches of the Yangtze River (MY) experiences relatively homogenous temporal distribution of annual precipitation. The mean value of CDDs during 1961–2012 is 20.2 days in the cold season and 15.8 days in the warm season, a difference of 4.4 days. In contrast to other regions, CDD in the cold season over this region decreased during the study period (−0.4 days/10 years). In addition, CDD values greater than 25 days were more frequent in the cold season

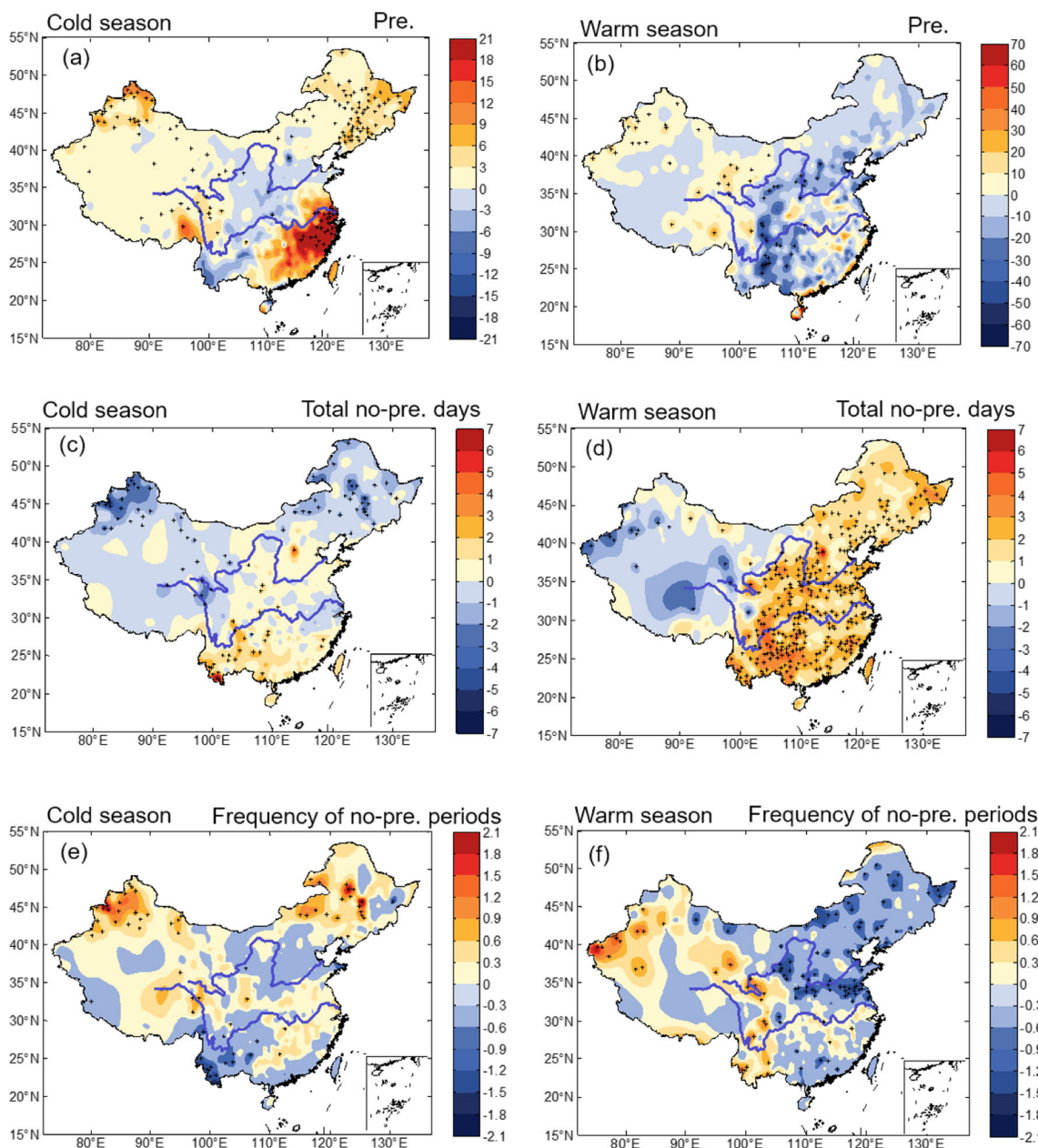


Fig. 4 Linear trends of **a, b** precipitation, **c, d** total no-precipitation days, and **e, f** frequency of no-precipitation periods in the cold season (*left column*) and warm season (*right column*) during 1961–2012. Units:

mm/10 years (precipitation), days/10 years (total no-precipitation days) and times/10 years (frequency of no-precipitation periods). *Dots* indicate trends significant at the 5 % level

before the 1990s than afterward. In the warm season, however, CDDs of this area were high during the middle 2000s.

In order to extract the characteristics of the CDD variations at different timescales, the EEMD was applied to the area-averaged CDD time series. Table 1 gives the variance contributions and cycles of CDD components obtained by the EEMD.

In general, 3-year oscillations contribute most for CDD variations (larger than 40 %) except for the warm seasons in South China (32.4 %). And, this interannual variation is more significant in the cold season than in the warm season. The variance contributions of IMF1 are all above 60 % in the cold season in

North China, South China, and the middle-lower reaches of Yangtze River and warm season in Southwest China, which means that the CDDs in those regions/seasons are dominated mostly by interannual variances. Especially in South China, CDD in cold season is influenced mostly (73.1 %) by the oscillation of about a 3.3-year period, with high values occurring frequently.

As for decadal oscillations of CDDs, which are represented by IMF3s and IMF4s in Fig. 6, North China and middle-lower reaches of Yangtze River have relatively larger variance contribution than do other regions (Table 1). Though the variance

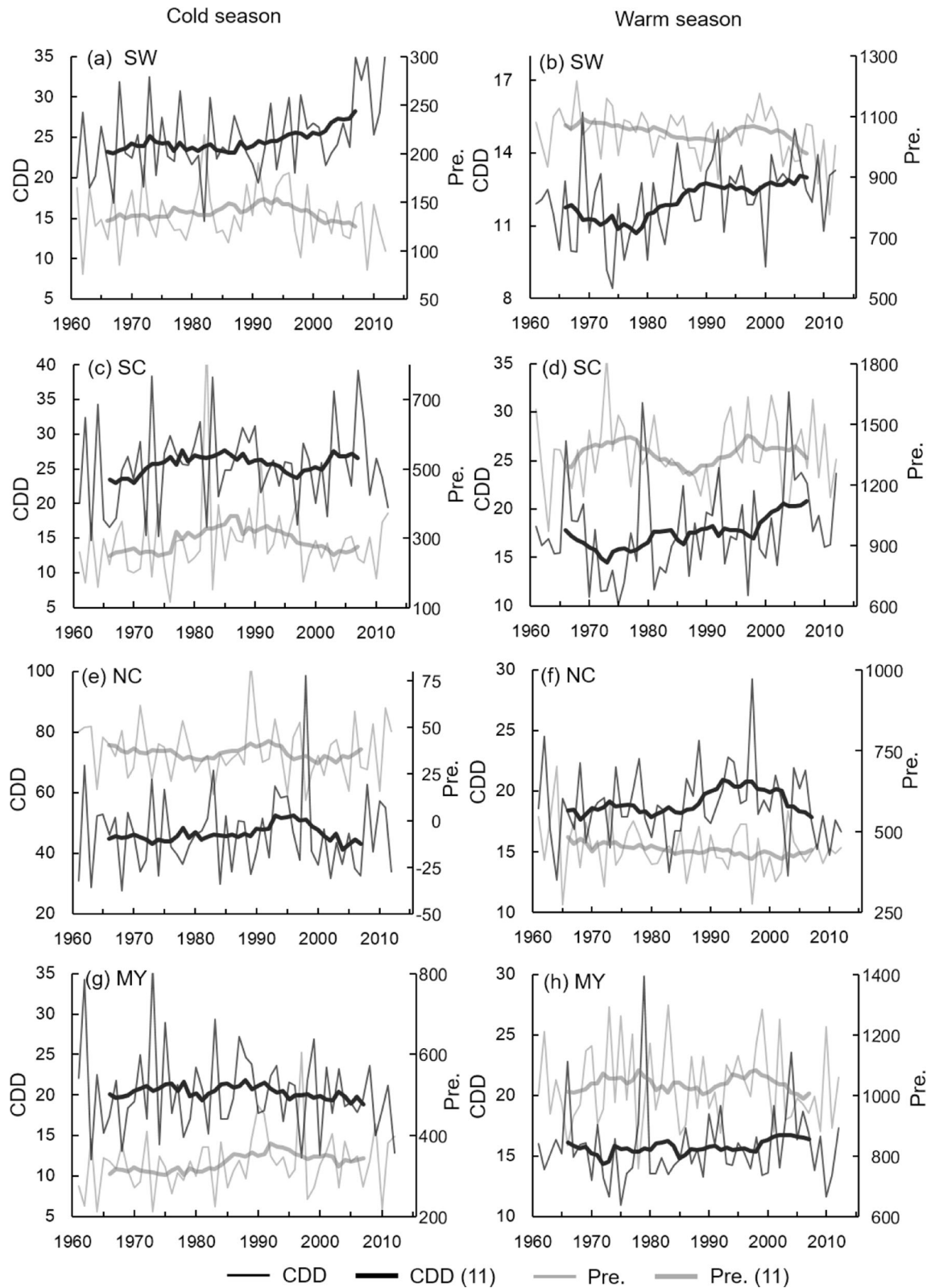


Fig. 5 Time series of area-averaged consecutive dry days and precipitation in the four regions during the cold season (left column) and warm season (right column). The thin black lines represent CDD, and the thin gray lines represent precipitation. Bold lines are the

corresponding 11-year moving averaged time series. The four regions are **a, b** Southwest China, **c, d** South China, **e, f** North China, **g, h** middle-lower reaches of the Yangtze River. Units: days (CDD), mm (precipitation)

Table 1 Variance contributions and mean cycles of area-averaged CDD components at various timescales obtained by ensemble empirical mode decomposition (EEMD)

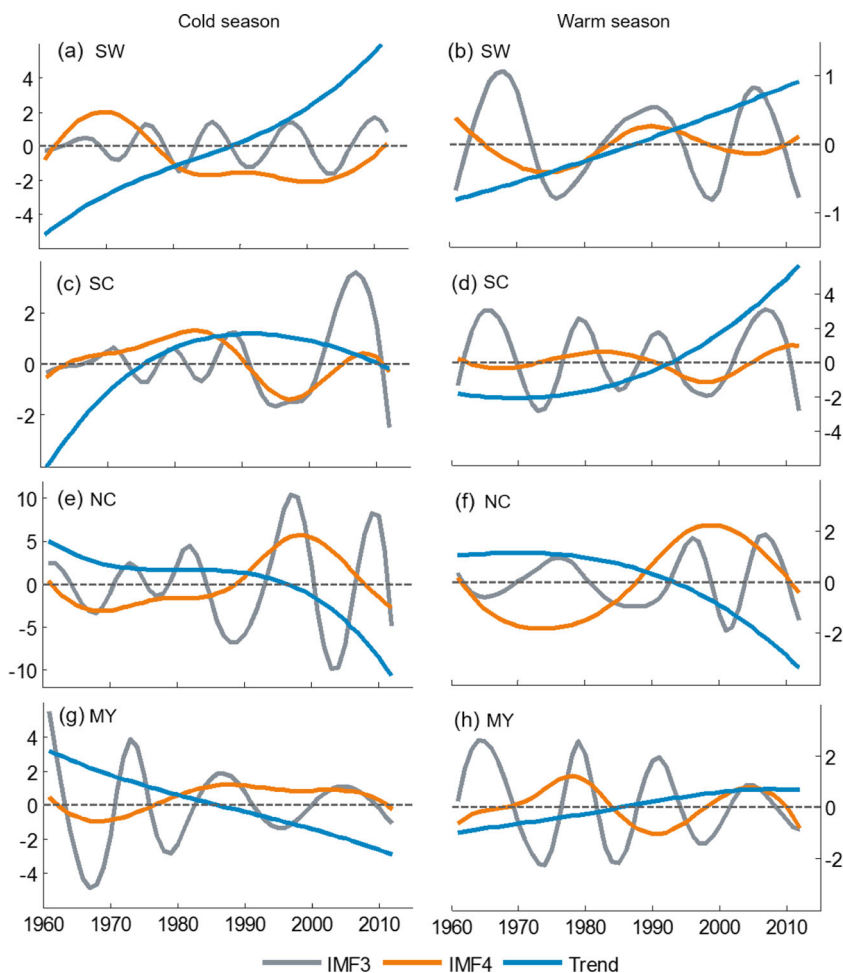
Cycle(variance contribution)		IMF1	IMF2	IMF3	IMF4	Trend
SW	Cold season	3.0(40.2)	6.1(18.1)	11.2(3.1)	40.3(6.8)	-(31.8)
	Warm season	3.3(61.6)	8.0(13.0)	18.4(12.8)	27.1(1.9)	-(10.6)
SC	Cold season	3.3 (73.1)	5.8(16.6)	13.6(4.3)	29.0(1.4)	-(4.6)
	Warm season	2.7(32.4)	7.0(34.6)	13.7(12.1)	25.2(1.2)	-(19.8)
NC	Cold season	3.2(68.6)	8.6(5.8)	11.6(12.1)	40.4(4.2)	-(6.6)
	Warm season	3.0(46.1)	7.4(20.8)	15.4(6.2)	48.3(14.5)	-(12.4)
MY	Cold season	2.9(69.0)	5.5(6.3)	15.1(14.1)	36.3(1.6)	-(9.1)
	Warm season	2.9(49.2)	7.4(26.4)	14.0(17.8)	28.4(3.8)	-(2.8)

Units: years (cycle). SW, SC, NC, MY denote Southwest China, South China, North China, and the middle-lower reaches of the Yangtze River, respectively

contributions of them are not as large as the interannual variations, they provide climate backgrounds for extreme events and the useful information for long-term climate forecast. Over North China, cycles of IMF3 and IMF4 in cold and warm season have similar phase change, all staying at a high phase during the 1990s. Moreover, most of the decadal components, especially IMF3, experienced greater amplitudes during the last 20 years.

Over the middle-lower reaches of the Yangtze River, the decadal variations of CDDs manifest most in its IMF3s, which show greatest variance contributions (14.1 % in the cold season and 17.8 % in the warm season) among the four regions. This 14- or 15-year oscillations show lower amplitude in recent years, which may indicate that, under this background, extreme events of CDDs might be less frequent in this area.

Fig. 6 The IMF3 (gray lines), IMF4 (yellow lines), and secular trends (blue lines) of CDDs obtained by the EEMD in the four regions during the cold season (left column) and warm season (right column). The four regions are the same as in Fig. 5



In terms of secular trends, the increasing tendencies of CDDs in Southwest China in the cold season and South China in the warm season are noteworthy. These non-linear trends showed noticeable variance contributions of 31.8 % and 19.8 %, respectively. And, both of them experienced sharper slopes in recent years, suggesting increasing risk in seasonal droughts over the next several years.

4 Conclusion and discussion

Consecutive dry days (CDDs), defined as the maximum number of days with precipitation less than 0.1 mm, can serve as an effective measure of extreme precipitation and seasonal droughts. Using daily rain gauge data from 718 stations in China for the period of 1961–2012 and ensemble empirical mode decomposition (EEMD), this paper documents the spatial and temporal characteristics of CDDs in the cold season (November to next March) and the warm season (April to October). The major findings are summarized below:

1. In terms of linear trends, changes in CDDs during the years 1961–2012 have significant regional and seasonal differences. In the cold season, 57 % of the stations record decreased CDDs, whereas in the warm season, 67 % of the stations record increased CDDs. In the cold season, West China and Northeast China are wetter with decrements in CDDs and noticeably increments in both precipitation amount and frequency. Whereas, Southwest and North China are drier with longer CDDs and more dry days. In the warm season, the total no-precipitation days increase significantly and consistently in the east of 100° E. Over the coastal regions of South China and the zone area between the Yangtze and Yellow river, there are less no-precipitation periods but extended CDDs. And over Southwest China, the dry spells not only last longer but also happen more frequently.
2. As for timescale characteristics of CDDs, which examined by EEMD, the 3-year oscillations contribute most to CDD variances, and this interannual variability is more significant in the cold season than in the warm season. Especially in the cold season in South China, the 3.3-year oscillation account for 73.1 % of the change in CDD, with high values occurring frequently. Decadal oscillations in North China and the middle-lower reaches of the Yangtze River are more profound than in the other regions. In North China, CDDs in both seasons have similar decadal changes, all staying at high phases during the 1990s and most of them have greater amplitude during the last 20 years, whereas in the middle-lower reaches of the Yangtze River, the amplitudes of decadal oscillations of CDDs reduce during the last 20 years in both seasons. As for non-linear secular trend, increases in CDDs over Southwest in the cold season

and South China in the warm season are noteworthy because they contribute a lot to the CDD variances and have sharper slopes in recent years.

In this paper, the spatial and temporal characteristics of CDDs over China are documented. However, the mechanisms responsible for these changes are still not clear. Some of the previous studies investigated the mechanisms by directly looking at the atmospheric circulation in typical CDD durations (Lei and Duan 2011, Gong et al. 2005). However, our results suggest that the characteristics of CDDs at various timescales vary seasonally and regionally, which implies that different mechanisms are dominating in different regions and timescales. Thus, identifying the dominating mechanisms for variation of CDDs in different regions and timescales is a challenge to our further studies.

Furthermore, CDDs and droughts are closely correlated (Frich et al. 2002; Groisman and Knight 2008), and this is also seen in this study. It must be pointed out that CDDs are only based on the duration of precipitation absence and do not directly include the impact of enhanced evapotranspiration as driver for droughts (Orlowsky and Seneviratne 2012). So, how the behavior of CDD compares with other drought indices for the regions in China is another open question that needs to be addressed in further studies.

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