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Trends of summer dry spells in China during the late twentieth century

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With 6 Figures

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Summary

In the present study the trends in frequency and duration of dry spells in six sub-regions of China were analyzed for the summer-half-year season (April–September) in period 1956–2000. A dry spell was defined as a number of consecutive days without measurable precipitation. For the frequency of short dry spells (length $<$10 days), significant changes are observed in the North, Northeast and Southwest China. For the frequency of long dry spells (length $\geq$10 days) there are significant trends in North and Northeast China; while no remarkable trends in frequency are found in other regions. There are also significant lengthening trends in dry spell duration in North and Northeast China, resulting mainly from the long-term changes in short dry spells. No significant change is observed for the maximum length in all regions. It is found that the temporal distribution of precipitation within the rainy season would notably impact the features of dry spells. An increase in the precipitation amount does not necessarily mean a synchronous reduction in dry spell frequency and/or duration. Seasonal mean anomalies of 500 hPa heights in association with the long dry spells show similar spatial patterns over the middle to high latitudes for five of the six sub-regions (with exception of the case of Southwest China), resembling a west–east direction dipole in latitudes about 30° N northwards. For the case of Southwest China the dominant feature in 500 hPa heights is the negative anomalies over most middle to high latitude Asia. Among these cases there are recognizable differences, particularly, in the tropical regions in western Pacific. That would provide useful information of circulation background for understanding the climate extremes.

1. Introduction

Drought events are major disasters resulting in heavy losses to agriculture in China, which contributed more than half of the total losses due to the weather and climate relevant disasters (Huang et al, 1997; Wang et al, 2002). Of the climatological aspect, drought appears as a large negative precipitation anomaly on seasonal to annual time scales, associated with a remarkable deficient of soil moisture. On the synoptic time scale, the drought is directly caused and increasingly aggravated by a number of consecutive no-rain days. These no-rain days are usually known as the dry spells. The longer the dry spells are, the more severe the drought stress become. Most of the previous studies concerned with China's drought paid much attention to anomalously low monthly- to seasonal precipitation amount (Li et al, 1996; Gong and Wang, 2000). Some works analyzed the extreme precipitation events including the precipitation intensity, maximums etc (e.g., Zhai et al, 1999). The climatological aspects relating to precipitation and the atmospheric circulations are summarized in Zhang and Lin (1992), and Ding (1994). Changes in the precipitation amount and intensity would clearly result in changes in dry spell. Apparently, an evenly temporally distributed rainfall would be helpful for reducing occurrence of long dry spells and for mitigating drought stress, contrary to that, if the same amount precipitation fall in fewer days there would be longer dry spells and greater drought stress.

The aim of the present study is to identify the long-term changes in dry spells based on daily precipitation records of China during the late twentieth century. The seasons of concerning is summer-half-year (i.e., April–September). It is the time when most intensive agriculture activities occur. Dry spells in these months are of importance since the related dry spells and droughts would exert great influence on agriculture in China.

2. Data and method

2.1 Data

The daily precipitation data set used here are taken from the China Meteorological Administration (CMA) observation archives. Daily precipitation amount as well as the precipitation type is recorded. There are six kinds of readings, namely, (1) no precipitation, (2) zero-precipitation (daily precipitation reading less than 0.1 mm), (3) precipitation from fog, frost and dew, (4) precipitation from pure snow, (5) precipitation from snow and rain, and (6) precipitation from rainfall. Since the precipitation from fog and dew is considerably low, all days with this type of precipitation readings are regarded as non-precipitation days in our analysis. The dry spells are defined on the basis of types 1, 2 and 3.

The modern nation-wide networks of weather observing stations in main land China are operated beginning just in 1950s. Here the selected 164 stations are all with data available for at least 46 years. Among these 164 stations, there are 11 with missing data during the entire period of 1956–2000, including one two-missing-day station and 10 one-missing-day stations. Compared to the number of total records, the number of missing data is much low. Here we simply ignored the 11 missing data; all 11 days are regarded as no-rain days.

Climate data sets often suffer from discontinuities resulting from the station displacing, instrumental improvement, environmental change, and other factors. Among them a remarkable one is the urbanization occurring in major cities. That notably impacts the daily to monthly mean temperatures. Also reportedly tends to increase the monthly to annual precipitation amount compared to the non-urbanization cities. Given the fact that our object of the present study is to analyze the long-term changes in the dry spells (i.e., in the terms of no-rain days), and that there is no substantial results on the possible influence of these problem on the number of rainy days, here we do not detect and correct the discontinuity in the daily precipitation data sets. The detection and correcting are also very hard since the summer rainfall usually are of small spatial scales and occur in very short time period. We suppose that would have no significant influence on our analysis and conclusion.

China is of large geographical extent, covering various climate zones (Zhang and Lin, 1992). Different regions may experience different temporal features in dry spells. Therefore it might be inappropriate to simply average over all station to make mean time series for the country. The means for sub-regions is likely to be good alternatives. For example, Wang and Gaffen (2001) divided China, nearly equally, into four sub-regions in their analysis of recent changes in precipitation, temperature and other meteorological

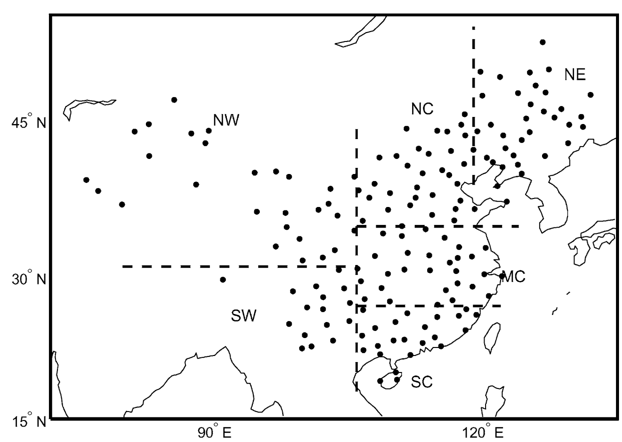

Fig. 1. Distribution of the stations and six sub-regions

Table 1. Climatology of dry spells in six regions. All statistics are mean annual values for April–September based on the entire period of 1956–2000

	Precipitation (mm)	Number of days without rain (days)	Dry spells		
			Frequency* (times)	Length (days)	Maximum length (days)
South China	1197.4	92.5	29.1 (1.3)	3.2	12.9
Middle China	870.4	106.8	30.1 (1.8)	3.6	13.9
North China	369.0	130.1	29.4 (3.0)	4.6	19.0
Northeast China	488.3	116.0	32.7 (1.9)	3.6	14.4
Northwest China	205.4	132.3	24.0 (3.5)	8.1	26.6
Southwest China	883.7	77.2	28.8 (0.9)	2.7	12.0
All-station	620.1	113.1	29.2 (2.2)	4.4	16.9

* Shown in parentheses are the frequencies of long dry spells ($L \geq 10$ days)

variables. It should be noted that this kind of simple dividing is also without appropriate concern of the climatological differences. Here we divided all stations into six sub-regions with regard of the climate regionalities. They are: (1) South China (SC), including 23 stations, (2) Middle China (MC), 29 stations in there, (3) North China (NC), 35 stations, (4) Northeast China (NE), 33 stations, (5) Northwest China (NW), 28 stations, and (6) Southwest China (SW) with 16 stations. The detail can be found in Fig. 1. These sub-regions can be verified by the results from empirical orthogonal function analysis of summer or annual precipitation anomalies, especially in the eastern portion of the domain (e.g., Nitta and Hu, 1996). This kind of dividing of sub-regions is similar to those used in Gong and Wang (2000) and Zhai et al (1999) in their analysis of regional precipitation amount, as well as the precipitation extremes in China. The climatological precipitations for each sub-region are shown in Table 1. For more information refer to Zhang and Lin (1992), and Ding (1994).

2.2 Dry spell

A dry spell is usually defined as a number of consecutive days without precipitation. Sometimes a very small amount precipitation amount is also considered as dry and to be included in a dry spell (e.g., Gregory et al, 1997; Huth et al, 2000). In the present study a dry spell is defined as a number of consecutive days during which no measurable precipitation is recorded. The number of days for each dry spell defines the length (L). To reveal the long-term changes in the dry spells, we counted the frequency of the dry spells during the hottest six months (1 April–30 September) for each year. And then the ordinary least-squares method was applied to the time series of the frequency to check the linear trends. The confidence level of the trend is estimated using F statistic. Prior to analysis, the dry spells were classified into seven ranges according to their length. They are ranges (1) $L < 5$ days, (2) $5 \leq L < 10$ days, (3) $10 \leq L < 15$ days, (4) $15 \leq L < 20$ days, (5) $20 \leq L < 25$ days, (6) $25 \leq L < 30$ days, and (7) $L \geq 30$ days. Many previous studies emphasized on the long dry spells because of their strong influence on agriculture and drought, and the threshold of 10 days are widely used by various authors (e.g., Sivakumar, 1992; Bonsal and Lawford, 1999; Huth et al, 2000; Anagnostopoulou et al, 2003). Thus, in addition to the above ranges, two simple ranges of short and long dry spells were also considered. The short dry spells are defined as those events with length shorter than 10 days (i.e., $L < 10$ days), while the long dry spells refer to the others (i.e., $L \geq 10$ days).

3. Results

3.1 Mean conditions

To gain basic information on the dry spells, we calculated the climatological means for the six regions as the first step. Table 1 shows the results. All statistics are made with respect to the entire period 1956–2000. Generally speaking, there are notable differences among those regions in precipitation as well as in the statistics of dry spells. The precipitation is highest in the South (1197.4 mm), and lowest in the Northwest (nearly one fifth of the amount of the South). The tendency of decreasing from the south to the north is clear, except for the Northeast where precipitation is a little higher than the nearby regions. The statistics for dry spells demonstrate the similar spatial features for those regions. The number of days without rain increases evidently from the South to the North. In South China the number is 92.5 days, while in the North and Northwest China there is 130.1 and 132.3 days without rain, respectively. It is interesting to note that the mean frequency of dry spells does not monotonously increase with the increasing number of no-rain days. Instead, the frequency decreases as the number of dry days gets more. The highest frequency (32.7 times/year) appears in the Northeast. But in the Northwest, where the lowest precipitation amount and most number of dry days are observed, there is just 24.0 times of dry spells per year. This is the lowest number in all six regions. That would be due to the higher occurrence of long dry spells. For example, the long dry spell (longer than 10 days) is of highest occurrence in the Northwest (3.5 times/year).

The mean duration of dry spells also varies notably from region to region. The mean length in the South is 3.2 days; the length extends to 8.1 days in the dry regions over the Northwest. On average, the mean length of dry spells averaged over all 164 stations is 4.4 days. Clearly, most of dry spell events end within one week. Those short periods of no-precipitation days are of less importance with regard of the drought stress. The droughts are often directly related to the long duration dry spells. We calculated the maximum length for each station each year; then averaged over the region and the entire period. The mean maximum length in South China is 12.9 days, and increases to 19 and 26.6 days in North and Northwest China, respectively. Longer duration appear in the northern regions. More details are listed in the Table 1.

3.2 Trends in the frequency of dry spells

In order to reveal the long-term changes, we calculated the linear trends in the frequency of dry spells for each dry spell range. All trends are estimated for whole time period of 1956–2000 using ordinary least squares technique and presented in the terms of times per decade as well as in percent per decade. Results are shown in Fig. 2.

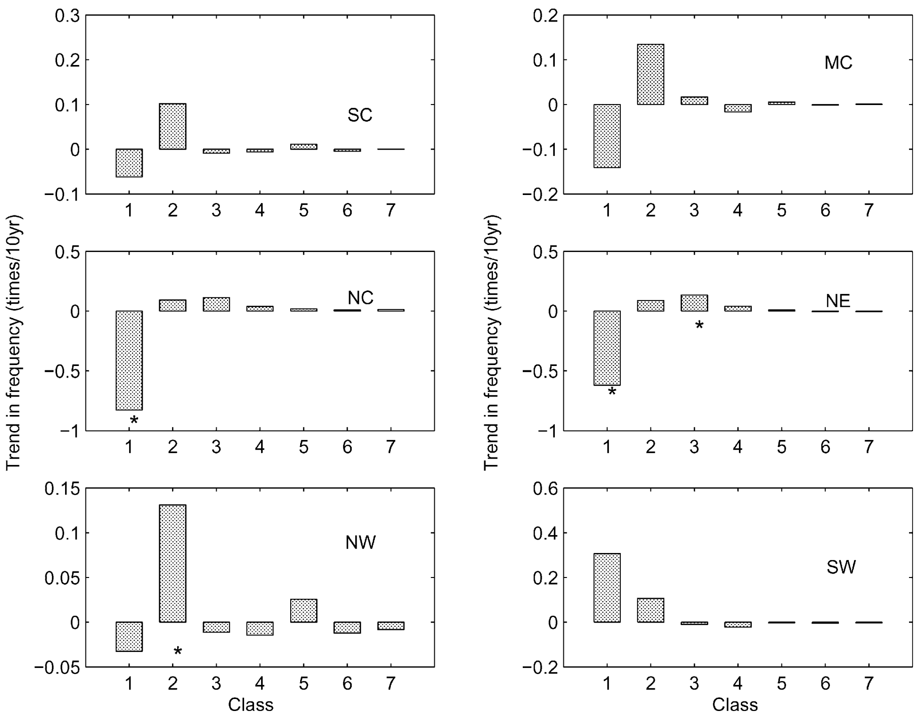

Fig. 2. Trends in dry spell events categorized within 5-day-wide bins for six regions. Class "1" refers to $L<5$ day(s) dry spells and, "2" to "7" refers to $5 \leq L < 10$, $10 \leq L < 15$, $15 \leq L < 20$, $20 \leq L < 25$, $25 \leq L < 30$, and $L \geq 30$ days dry spells, respectively. Asterisks indicate those significant at the 0.05 level. Unit is times/10 yr

Among all seven ranges, larger trends are clearly evident for the short duration dry spells, i.e., those events shorter than 10 days. The changes in frequency of short dry spells in three northern regions (i.e., North, Northwest and Northeast China) are particularly remarkable. All significant trends in short dry spells are observed in these three regions. The changes in the longer length ranges are apparently smaller in terms of absolute values; that might be partly due to their low occurrence. Among all cases, only four ranges in three regions are statistically significant. However, it should be mentioned that the small number of station and the relatively low occurrence in the longer dry spell ranges would give rise to larger uncertainty in estimating their linear trends and reduce the reliability of the results. To overcome this flaw, we additionally analyzed two simple ranges, namely, the short ($L < 10$ days) and the long ($L \geq 10$ days) dry spell by combining the corresponding ranges.

Figures 3 and 4 display the temporal changes in the short and long dry spells. Since the absolute values of mean and variance of dry spells are vastly different among regions, in order to make the trends comparable easily, we calculated their relative trends (divided by the means and multiplied by 100%) for each region. There are differently temporal features among regions. Of the frequency of short dry spells, larger trends are observed in three northern regions, as well as in the Southwest. Largest trends appear in the North (−2.79%/10 yr), the Northeast (−1.72%/10 yr) and the Southwest (+1.48%/10 yr). In the other three regions the long-term changes are considerably smaller. Compared to the short dry spells, the trends in long events are much greater. The greatest trend of +9.19%/10 yr in Northeast China is as strong as 5.3 times the trend of short dry spell. The same case is true in North China, where the trend in long dry spell events is about 2.3 times that of short dry spell. In the Southwest, the negative trend of long dry spells is about 3.2 times that of the short event. It is of interest to note that the trends in frequency of short and long dry spells are in opposite directions. In all regions where the short dry spells show negative trends there is tendency towards higher positive values in the long dry spell events, and vice versa (Table 2).

Our results show that the highly significant trends occur in North and Northeast China. This is consistent with the simultaneous changes in other meteorological variables such as the cloud amount and humidity. During the last five decades there are decreasing cloudiness trends in much of

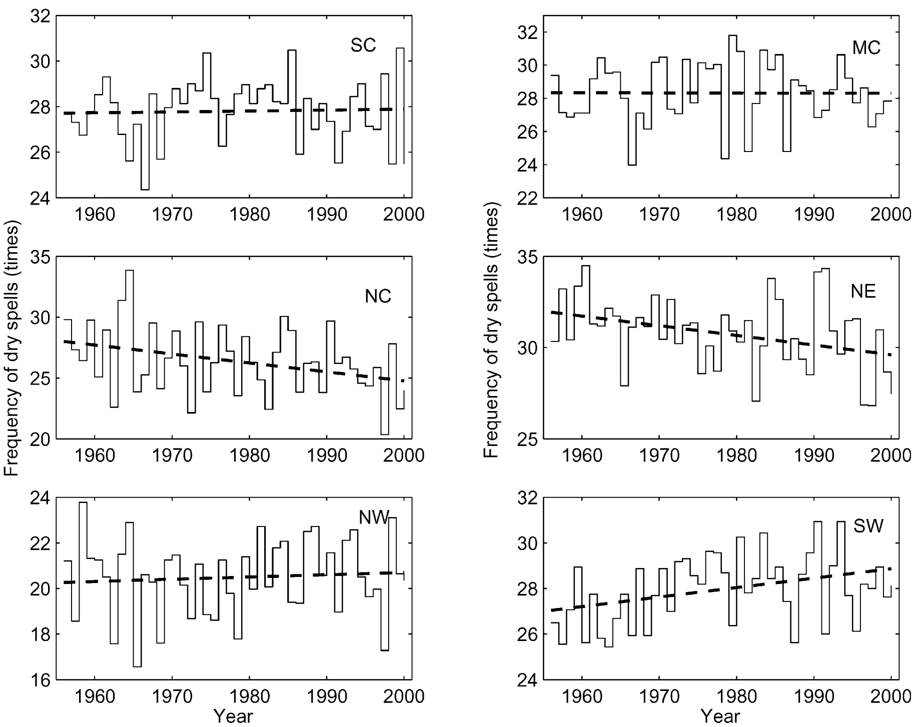

Fig. 3. Time series of regional mean frequency of short dry spells ($L < 10$) for six regions. Dashed lines are linear trends estimated using ordinary least-squares technique

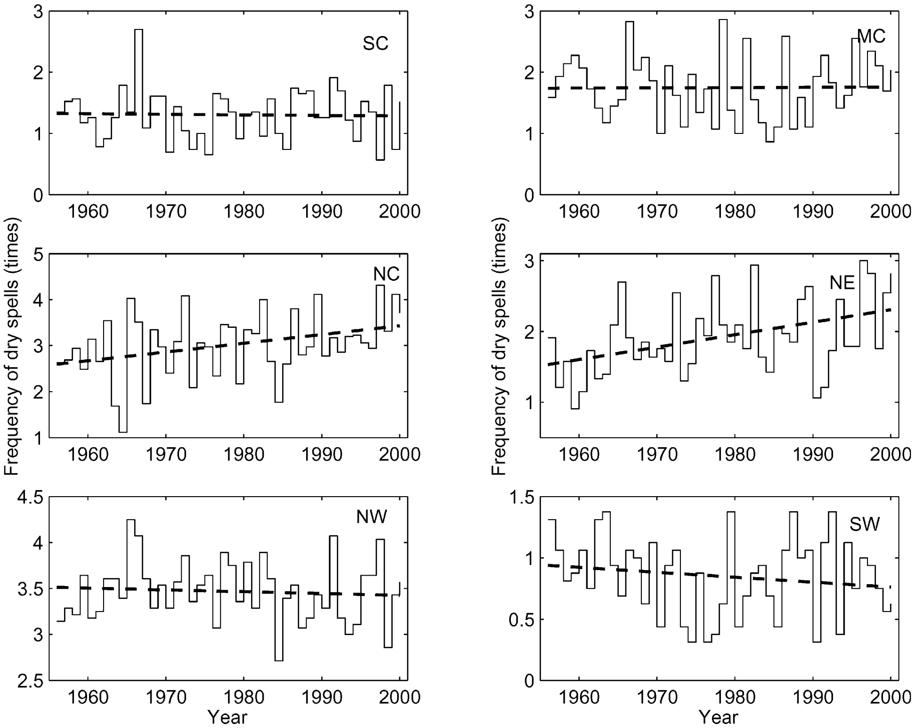

Fig. 4. Time series of regional mean frequency of long dry spells ($L \geq 10$) for six regions. Dashed lines are linear trends estimated using ordinary least-squares technique

Table 2. Statistics for trends in dry spells and precipitation amount. Last two columns show the correlations between the precipitation amount (*P*) and the average frequencies for short dry spells (*SL*) and long dry spells (*LL*)

	Trends in frequency of dry spells[1]		Trend in precipitation[2]	Correlation (*SL*, *P*)	Correlation (*LL*, *P*)
	SL events	*LL* events			
South China	+0.14 (+0.04)	−0.71 (−0.01)	+0.48 (+57.54)	+0.30*	−0.49**
Middle China	−0.02 (−0.01)	+0.24 (+0.00)	+0.96 (+83.28)	+0.63**	−0.63**
North China	−2.79 (−0.74)*	+6.31 (+0.19)*	−3.65 (−134.49)	+0.80**	−0.77**
Northeast China	−1.72 (−0.53)*	+9.19 (+0.18)**	−1.64 (−79.87)	+0.64**	−0.61**
Northwest China	+0.48 (+0.10)	−0.57 (−0.02)	+1.07 (+22.07)	+0.74**	−0.60**
Southwest China	+1.48 (+0.41)*	−4.75 (−0.04)	−0.06 (−5.49)	−0.21	−0.44**
All-station	−0.75 (−0.20)	+3.10 (+0.07)*	−0.30 (−18.75)	+0.58**	−0.63**

* Significant at the 0.05 level; ** At 0.01. *SL*: $L < 10$ days; *LL*: $L \geq 10$ days. [1] Trend units are %/10 yr, in parentheses are times/10 yr; [2] Units are %/10 yr, and in parentheses are mm/10 yr

China. The largest decreases are observed in North and Northeast China. From early 1950s to middle 1990s, the annual mean total cloud amount over this region is as strong as −3% per 10 years in excess of 95% confidence level for many stations. The surface relative humidity is found to decrease simultaneously, with a rate of −1.0–−1.5% per 10 years (Kaiser, 1998; 2000). Simultaneously, the number of light rain (daily precipitation amount less than 10 mm) events in northern China has been decreasing since 1950s, with a significant linear trend of −3.2% per 10 years (Han and Gong, 2003). These all agree well with the reduction of the frequency of short dry spells and the increasing frequency of long dry spells, and also suggest that the temporal distribution of precipitation within the rainy season plays important role in changing temporal features of dry spells.

3.3 Changes in the length of dry spells

In addition to frequency, the length of dry spells is of high importance too. We calculated the mean length of the dry spells. When all dry spells are taken as a whole, the positive trends (i.e., the lengthening tendency) are dominant. In five of

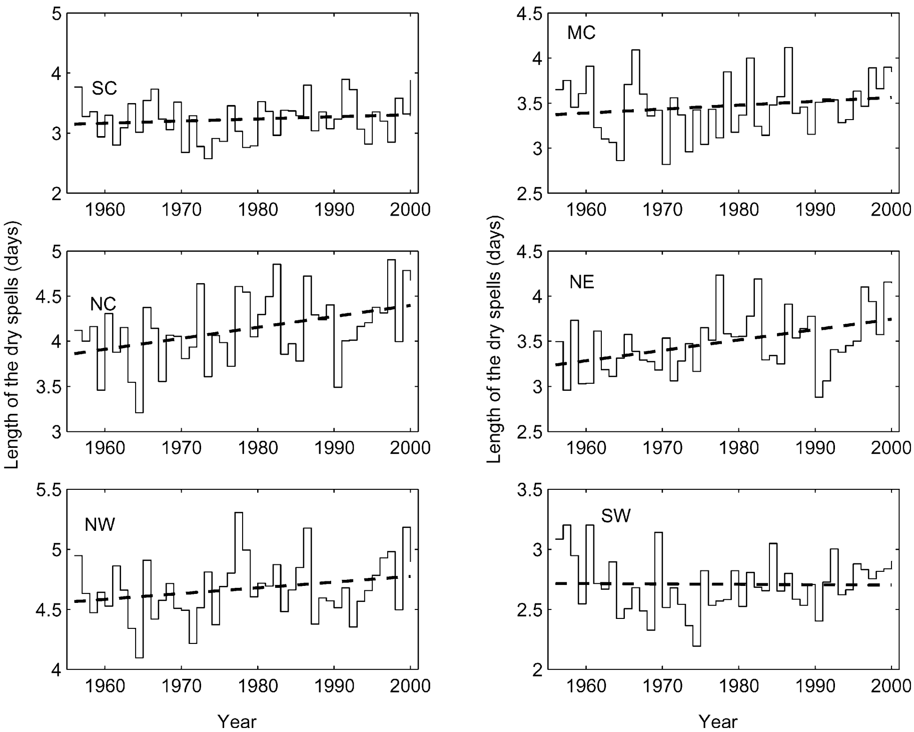

Fig. 5. Time series of the regional mean length of the dry spells for six regions. Mean length is averaged for all dry spell events. Dashed lines are the linear trends

Table 3. Trends in length of dry spells. Unit is days/10 yr

	Short dry spells	Long dry spells	All dry spells	Maximum length
South China	+0.018	−0.007	+0.036	−0.010
Middle China	+0.021	−0.065	+0.043	−0.083
North China	+0.057*	+0.132	+0.122**	+0.549
Northeast China	+0.043*	−0.130	+0.115**	+0.127
Northwest China	+0.023	−0.246	+0.048	−0.374
Southwest China	+0.012	−0.175	−0.003	−0.335
All-station	+0.032**	−0.527	+0.070**	+0.030

* Significant at the 0.05 level; ** At 0.01

the six regions, there are tendency towards longer dry spells. However, only the largest trends in North and Northeast China (with values of +0.122 and +0.115 days/10 yr, respectively) are significant, with the confidence level of 99% (Fig. 5). In the other four regions, the trends are much smaller, and none of them is statistically significant. In order to reveal more detail, we did an additional investigation considering just short and long dry spells. In all regions there are same positive trends in the length of short dry spells. The largest values of +0.057 and +0.043 days/10 yr occur in North and Northeast China, respectively. Both are above the 95% confidence level. For the long dry spells, all regions (except for North China) show tendency toward shortening length. However, none of these trends is statistically significant (Table 3). This means that the remarkable trends in the mean length in North and Northeast China result mainly from the lengthening in short dry spell events.

3.4 Trends in the maximum length

We investigated the temporal features in the longest dry spells for all regions. The longest dry spell for each year and each station is identified, and then all values are averaged to get the annual regional means. There are slight negative trends in regions of South, Middle, Northwest and Southwest China. Positive trends show up in regions of North and Northeast China. The largest trend appears in the North with a value of +0.55 days/10 yr. However, none of those trends is statistically significant. That implies that there are no remarkable long-term changes in the longest dry spells even the frequency of long dry spells changes significantly.

3.5 Correlation between precipitation amount and frequency of dry spells

A lot of authors found that the monthly-to-annual precipitation amount experienced non-random changes. For example, Huang et al (1999), Gong and Ho (2002), and Hu (1997) indicated there are significant changes at interannual to interdecadal variations in northern and southern China. Over the northern regions (NC, NE and NW) most of precipitation occurs as the strong convective rainfall, falling in a short time associated with the thunderstorms. Differing from that, most precipitation in the southern regions arises from the large-scale East Asia summer monsoon system. Thus there might be differences with regarding of the precipitation amount-dry spell relationship. The relationship between mean rainfall and the average frequency for dry spell ranges shows distinct relations. The high frequency of short dry spells tends to occur in seasons with high precipitation. One exception occurs in Southwest China where the frequency decreases as the precipitation amount increases. For the long duration dry spells ($L \geq 10$ days), frequency decrease remarkably as rainfall amount increases. As shown in the last two columns in Table 2, this kind of in-phase relationship for short duration dry spells and out-phase relationship for the long duration events are most significant in the arid and semi-arid northern portion of China (NC, NE and NW). It is interesting to note that similar relationships are also observed in semi-arid West Africa (Sivakumar, 1992). These relationships will be helpful in predicting and assessing the frequency of different range dry spells. Here the confidence levels of the correlation coefficients are estimated by using t statistic.

Furthermore, it is important to examine whether there is any particular trend in dry spells in association with the rainfall amount in these regions, particularly for the northern regions which are experiencing significant long-term changes in dry spell events. Results show that the precipitation amount displays only slight long-term trends, none statistically significant in any of the six regions. However, as revealed above there are significant trends in dry spells (in frequency and length) over North, Northeast and Southwest China (Table 2). This implies that the temporal distribution of rainfall in growing season can greatly change even though the total rainfall amount does not. A weaker variation in the precipitation amount does not guarantee a near average frequency of dry spells and drought stress. In some instances, even a notable increase in the precipitation amount does not necessarily mean there is a simultaneously consistent reduction of drought stress, particularly in the northern regions. The caveat should be borne in mind that the frequency of dry spells is directly related to the temporal characteristics of the daily precipitation within the rainy seasons, not to the precipitation amount itself. An increase in the precipitation amount does not necessarily mean a synchronous reduction in dry spell frequency and/or duration. The risk of drought may be underestimated if based only on month-annual precipitation amount.

4. Circulation

Variability in the atmospheric circulation (both the high and low frequency components), as well as the weather type is usually analyzed for understanding the extreme events including the dry spells (e.g., Huth et al, 2000; Kutiel et al, 1998). Local and regional dry spells would be influenced by large-scale atmosphere circulation and by such factors as the surface temperature teleconnections (e.g., Pena and Douglas, 2002; Bonsal and Lawford, 1999). As mentioned above, long dry spells are much important for environment and agriculture, thus, we focused just on the long dry spells in this section. We investigated which circulation conditions are associated with the occurrence of long-lasting dry spell events. Each dry day is apparently related to a favorable synoptic condition. But the continuous dry days would, to large degree, be associated with the low frequency variability in the large-scale atmospheric circulation. We did not apply band or low pass filter to isolate these frequencies in atmospheric circulations. Alternatively, the simple monthly to seasonal averaging is served to suppress the synoptic frequencies and retain the lower frequency components in the present study.

Here we checked the relationship between lower to middle troposphere circulation (in terms of 850 hPa velocity and 500 hPa height) anomalies and long dry spell frequency, using composite method. Here both 500 hPa height and 850 hPa wind data are taken from the National Centers for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR) reanalysis data sets (Kalnay et al, 1996). For each region, the five years of highest frequency of long dry spells are identified first. Then the composites of 850 hPa wind vectors and 500 hPa heights are obtained by subtracting climate mean (with respect to the entire period) from the average values of the five years. The composites are the dominant circulation patterns in association with the long dry spells. Due to the regional differences, the five years of high frequency vary from region to region. These years for all six regions are listed as follows.

For South China: 1964, 1966, 1986, 1991, 1998.
For Middle China: 1966, 1978, 1981, 1986, 1995.
For North China: 1965, 1972, 1989, 1997, 1999.

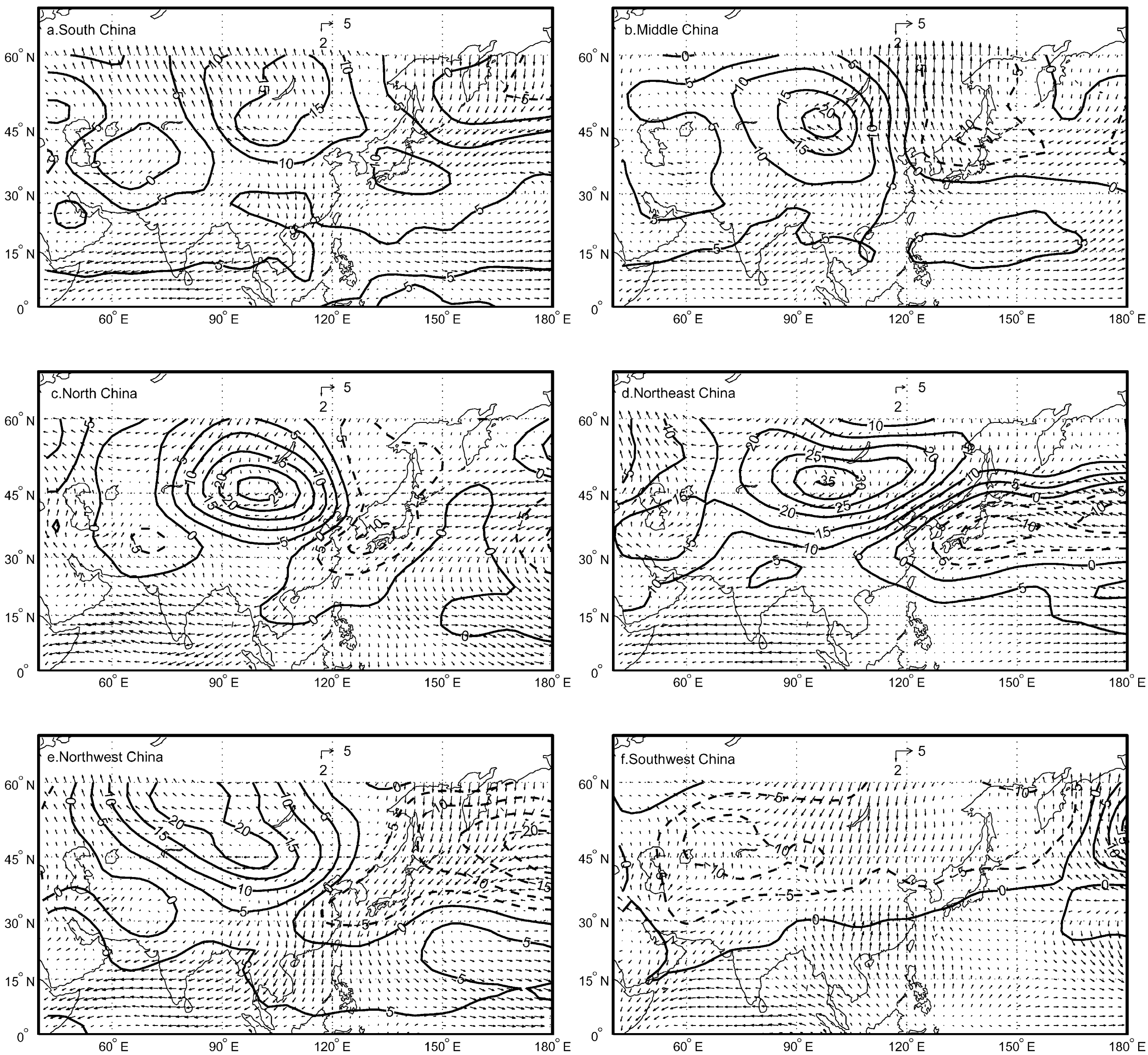

Fig. 6. Shown in contours are anomalies of 500 hPa height in association with long dry spells for April–September. Negative contours are shown as dashed lines. Contour interval is 5 gpm. Wind anomalies at 850 hPa are shown as vectors. Unit is ms^{-1}

For Northeast China: 1977, 1982, 1996, 1997, 2000.
For Northwest China: 1965, 1966, 1982, 1991, 1997.
For Southwest China: 1962, 1963, 1979, 1987, 1992.

Results are shown in Fig. 6. For cases of SC, MC, NC, NE and NW, there are similar spatial structures in the middle to high latitude in East Asia. Over the latitudes about 30° N northwards, a remarkable anticyclonic center is situated at the inland about west of 120° E, while a cyclonic cell situated in the east. This kind of spatial pattern, to much extent, resembles a west–east direction dipole. The similarity among northern cases (i.e., NC, NE and NW) is much large. However, detailed checks suggest that there are recognizable differences. For the case of NC, the negative center is situated over Korea and the southern Japan, while for the case of NE, the center moves notably to the east. For the case of NW, the anomalous cyclonic center is situated over the high latitude North Pacific. Among three northern cases, the differences in anomalous anticyclonic centers are also discernable, although the changes are slight. Compared to the case of NC, the center shifts to east and to west in cases of NE and NW, respectively. The changes in 850 hPa wind field are generally consistent with the 500 hPa heights over the middle latitude East Asia for the three north cases, suggesting an equivalent barotropic structure in relation to the frequent long dry spell events. In general, the dominant aspect of the 500 hPa geopotential height for three north cases is the positive anomaly cell over the landmass, which might play much important roles in the variations of long dry spells in North, Northeast and Norwest China.

Of more importance, remarkable differences appear over the lower latitudes for the cases of SC and MC. For the case of SC, a notable positive anomaly center covers the southern China, and an anticyclonic system is also evident at the 850 hPa wind field in there. For the case of MC, an isolated anomalously positive center appears over the western Pacific (to east of Philippines). The circulation changes in the middle troposphere over East Asia are strongly influenced by the large-scale Northwestern Pacific Subtropical High, particularly by its extent and location (Gong and Ho, 2002). The 500 hPa anomalies for cases SC and MC clearly provide clues of connection to activity of the Subtropical High. The case of SC suggests that when there are frequent long dry spells in South China the Subtropical High tends to extend westward, compared to its climate position of about 120–130° E. While the long dry spells in Middle China is usually associated with a southward shift of the Subtropical High. These display that in addition to the well known notion of strong relationship between summer precipitation in east China and the Subtropical High (Zhao, 1999; Chen and Zhao, 2000), the long dry spells there are also related to its location and strength.

For the case of SW, the dominant feature in 500 hPa height is the negative anomalies over most middle to high latitude Asia. The center of the huge cyclonic system is situated at the Central Asia. This pattern is totally different from the situations for other cases. In the wind field at 850 hPa, no large-scale circulation pattern consistent with 500 hPa height anomaly is found over the whole Asian continent, nor is there any evident regional circulation system over the target region and the vicinities. That might suggest that the circulation mechanism(s) causing long dry spells in Southwest China are much different from that for other regions. Precipitation in Southwest China is influenced by Indian monsoon as well as East Asian summer monsoon. That would make the situation complicated. The continental-scale anomalous circulation pattern displayed here might be related to both monsoons. The details is not well understood yet, a further study is needed.

5. Conclusion

There is no overall trend in the frequency of dry spells in six sub-regions of China. In three regions, namely, the North, Northeast and Southwest China, there are statistically significant linear trends in the frequency of short dry spells, with values of -2.19, -1.72, and $+1.48\%/10$ yr, respectively. Significant trends in the long dry spells are observed only for North and Northeast China with the rates of $+6.31$ and $+9.19\%/10$ yr. In other regions no significant trend is found in frequency of long and short dry spells. Generally, the long and short periods have opposite trends in most regions.

There are also notable lengthening trends in dry spell duration in North and Northeast China at rates of $+0.122$ and $+0.115$ days/10 yr, respectively, both with the confidence level of 99%. Much of the trends result from the long-term changes in short dry spells. There is no significant change in the maximum length in all regions.

It is found that the precipitation amount changes slightly and not significantly in North, Northeast and Southwest China. However, the dry spells have changed remarkably in these regions. The temporal distribution of the rainfall within rainy season would play important role for the long-term changes of dry spells. Same amount precipitation does not necessarily mean a same feature in dry spell and drought stress.

Seasonal mean anomalies of 850 hPa velocities and 500 hPa heights in association with the long dry spells show similar spatial patterns over the middle to high latitudes for five of the six sub-regions (with exception of the case of Southwest China). Over the latitudes about 30° N northwards, a remarkable anticyclonic center is situated at the inland about west of 120° E, while a cyclonic cell situated in the east, resembling a west–east direction dipole in latitudes. For the case of Southwest China the dominant feature in 500 hPa heights is the negative anomalies over most middle to high latitude Asia. Among these cases there are recognizable differences, particularly, in the tropical regions in western Pacific. That would provide useful information of circulation background for understanding the climate extremes.

Our results show that the most significant changes in dry spells occur in North and Northeast China. These are also vulnerable regions facing growing environmental and eco-societal problems. The increasing frequency of (and the lengthening of) the long dry spells would put more drought stresses in there.

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