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Daily precipitation changes in the semi-arid region over northern China

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Abstract

The semi-arid area in northern China is an agro-pastoral transition zone. The environment there is sensitive to climate variation, particularly to precipitation change. Daily precipitation records of 30-gauge stations from May to September during 1956–2000 are analysed in this study. The precipitation amounts show only slightly decreasing trends; however, some aspects of the rainfall characteristics display significant changes. Compared to the 1950s, rainy days have been reduced by about 8 days in the 1990s. Significant change is observed in the number of days when there is light rain ($<10\,\mathrm{mm\,day^{-1}}$). The days with light rain also show a significant tendency toward a stronger intensity, whereas those days with moderate and above moderate rains do not. At the same time, the long duration precipitation ($\geqslant$3days) event is found to decrease remarkably with a linear trend of -5.6% per 10 years. In contrast, the frequency of long dry spells ($\geqslant$10 consecutive days without rainfall) is becoming more frequent at a rate of 7.2% per 10 years. Taking 30 stations as a whole the maximum daily rainfall displays no evident trend. But the median of the maximums shows a step-like drop beginning in 1979 and the low values are notable until the early 1990s. This is coincident with the large-scale climate regime shift over East Asia, probably suggesting a response of regional daily precipitation extremes due to the change of the East Asian summer monsoon system.
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Keywords: Semi-arid region; Northern China; Daily precipitation

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1. Introduction

The semi-arid area in northern China is a transition zone. To the south of this region is the semi-humid North Plain, which is an agriculturally intensive region. To the north is the nomadic region, and the deserts are farther north of that. In terms of climate, this is a marginal region where the East Asian summer monsoons are getting so weak that the monsoonal rainfall may be extremely low in some years. Isohyets extend in the northeast and southwest approximately spreading along the topography elevation. The annual precipitation decreases from the southeast to the northwest, with about 550 mm to the south and less than 200 mm to the north. This region receives most (more than 60%) of its annual rainfall in summer (Tao and Chen, 1987; Lau et al., 1988). Similar to the annual precipitation, summer rainfall also gradually decreases from the North Plain to the northern arid area. This transition zone is, to some degree, similar to the western African Sahel. Thus the environment is sensitive to the regional climate, particularly to the precipitation, and is also very vulnerable to the global climate change (Ye and Chen, 1992). Most of the precipitation there falls in the warm seasons in association with the arrival of the summer monsoon (Samel et al., 1999). Summer is also the time when vegetation activity is at its maximum, thus even small water deficiencies would likely put heavy drought stress on the plants, agriculture and environment. Due to the large variability of precipitation and the increasing human activity, this agro-pastoral transition zone is also known as one of the high-risk regions of desertification (FAO, 1977). Investigating the precipitation changes there is helpful for understanding the regional response to the East Asian summer monsoon variation and the global change, and for understanding the rapidly growing environmental problems such as desertification.

There are numerous studies analysing the precipitation over East Asia, including northern China (e.g. Yatagai and Yasunari, 1995; Gong and Wang, 2000). However, most of them were concerned with the monthly-seasonal mean condition. The change in daily extreme, which is a very important aspect of precipitation in a semi-arid region, has received much less discussion. Some studies investigated extreme precipitation using daily data (for example, Zhai et al., 1999a, b). But, they focused on a broad section of East Asia or entire China and paid less attention to the transition area in northern China. As is well known, the features and changes in precipitation usually differ vastly from region to region. A nation-wide mean condition would easily ignore the local to regional details.

In this study we examined the warm season precipitation changes in the semi-arid region over northern China. Instead of studying the seasonal rainfall amount, here we are concerned with daily extremes, emphasizing the number of rainy days, precipitation intensity, maximum daily rainfall, persistence of the daily rainfall and the dry spell duration. The analysis seasons are from May to September, which are the warmest months of the year and also the months with the most precipitation (contributing about 85% of the annual precipitation on average). These months are of great importance for agriculture and human activity.

2. Material

The precipitation data sets used in our research were derived from the China Meteorological Administration (CMA) observation archives. The daily precipitation amount and the corresponding type are recorded. There are six kinds of readings: (1) no precipitation, (2) zero-precipitation (trace precipitation, daily precipitation reading less than 0.1 mm), (3) precipitation from frost, fog and dew, (4) precipitation from pure snow, (5) precipitation from snow and rain, and (6) precipitation from rainfall. Since the precipitation from frost, fog and dew is considerably low, all days with this type of precipitation are regarded as non-precipitation days in our analysis. We chose 30-gauge stations from the data sets. These stations are fairly evenly spread over the entire study region. The modern nation-wide networks of weather observing stations in main land China began operation in the 1950s so the 30 selected stations all have data available for at least 46 years. Among these stations, seven stations began in 1951, eight in 1952, two in 1953, eight in 1954 and five in 1955. Two stations began in the autumn of 1955. Thus, for simplicity, we only analysed the period from 1956 to 2000. In total there are eight missing records. But only one occurs in the summertime. We see this as a minor problem, and just ignore this

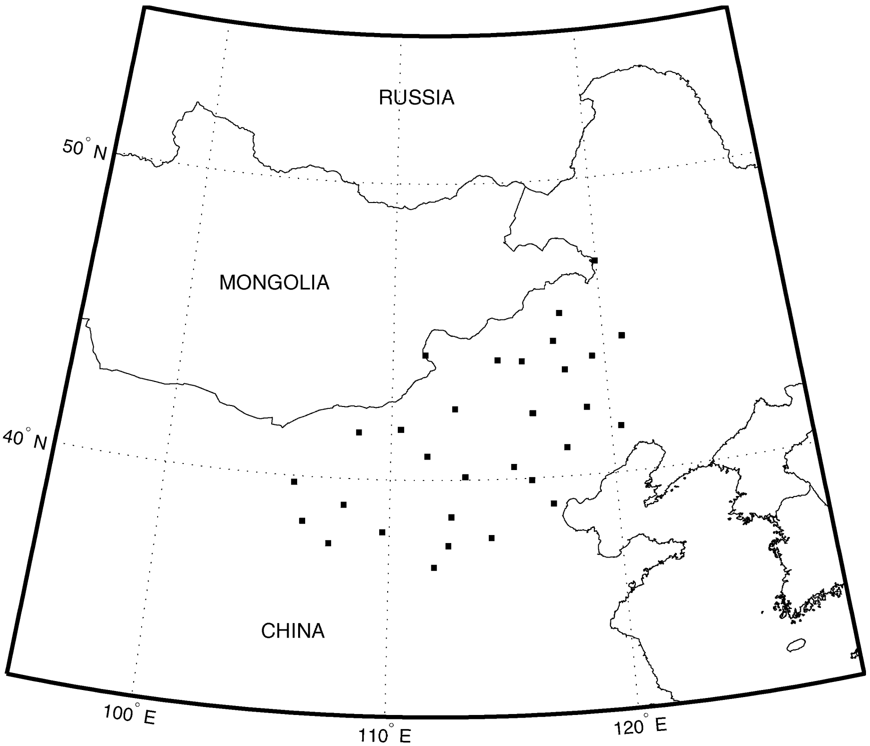

Fig. 1. Geographical distribution of the 30 stations. See Table 1 for the names and detailed statistics of the precipitation.

missing day. Fig. 1 shows the geographical positions of these 30 stations. Detailed information including the climatological rainfall is shown in Table 1. Climates for annual and summer precipitation amounts are both based on the reference period of 1961–1990.

The CMA categorized daily precipitation (P) into five intensity groups. They are, $P<10$ mm, $10\leqslant P<25$ mm, $25\leqslant P<50$ mm, $50\leqslant P<100$ mm and $P\geqslant 100$ mm day^{-1}. This classification has proven to be one of the important climatological features in the study of precipitation in China (Zhang and Lin, 1992). It is convenient to use the

Table 1
Statistics for the precipitation at the 30 stations

Station name	WMO code	λ (°E)	φ (°N)	H (m)	Year (from)	D (days)	P_a (mm)	P_s (mm)	P_s/P_a (%)
Erenhot	53068	111.5	44.2	965	1955	0	139.5	119.3	85.6
Jurh	53276	112.9	42.4	1152	1952	1	210.5	180.9	86.0
Haliut	53336	108.5	41.6	1290	1954	0	201.6	175.3	87.0
Darhan	53352	110.4	41.7	1376	1953	0	256.3	218.3	85.2
Huhehaote	53463	111.6	40.8	1063	1951	0	401.6	337.6	84.0
Datong	53487	113.3	40.1	1069	1955	0	376.9	313.8	83.3
Jartai	53502	105.8	39.8	1033	1955	0	103.1	87.3	84.7
Otog Qi	53529	108.0	39.1	1381	1954	0	277.2	235.3	84.9
Yinchuan	53614	106.2	38.5	1112	1951	0	193.8	153.4	79.2
Yulin	53646	109.7	38.2	1058	1951	0	400.1	326.9	81.7
Yuanping	53673	112.7	38.8	838	1954	1	425.7	358.3	84.2
Yanchi	53723	107.4	37.8	1349	1954	0	287.5	227.8	79.2
Taiyuan	53772	112.6	37.8	779	1951	2	456.8	368.8	80.7
Jiexiu	53863	111.9	37.1	750	1954	0	495.6	393.3	79.3
Arxan	50727	119.9	47.2	1028	1952	0	445.3	367.9	82.6
Uliastai	50915	118.0	45.5	839	1955	0	247.6	216.1	87.3
Abag Qi	53192	114.9	44.0	1128	1952	0	242.0	210.6	87.0
Shijiazhuang	53698	114.4	38.0	81	1955	0	527.6	432.4	82.0
Xi Ujimqin Qi	54012	117.6	44.6	997	1954	1	329.7	284.7	86.4
Jarud Qi	54026	120.9	44.6	266	1952	0	380.4	344.0	90.4
Lindong	54027	119.4	44.0	485	1953	0	373.9	339.3	90.8
Xilin Hot	54102	116.1	43.9	991	1952	1	276.3	243.9	88.3
Linxi	54115	118.1	43.6	800	1952	0	370.6	334.0	90.1
Duolun	54208	116.5	42.2	1247	1952	2	370.0	319.1	86.2
Chifeng	54218	119.0	42.3	572	1951	0	354.8	311.0	87.7
Chaoyang	54324	120.5	41.6	176	1952	0	476.4	419.2	88.0
Huailai	54405	115.5	40.4	538	1954	0	383.0	331.7	86.6
Chengde	54423	117.9	41.0	374	1951	0	521.7	458.3	87.8
Beijing	54511	116.3	39.9	55	1951	0	577.0	505.9	87.7
Tianjin	54527	117.2	39.1	5	1954	0	559.5	483.3	86.4
Average							355.4	303.2	85.3

The second column is the World Meteorological Organization (WMO) coding number of each station. λ is the longitude, φ the latitude, H the elevation, D the missing day(s) in data sets, P_a the annual precipitation, P_s the May–September precipitation amount, the percentage of May–September precipitation in relation to the annual amount is also shown in the last column. The first year of the data is shown in the sixth column. Statistics are with respect to the base period of 1961–1990.

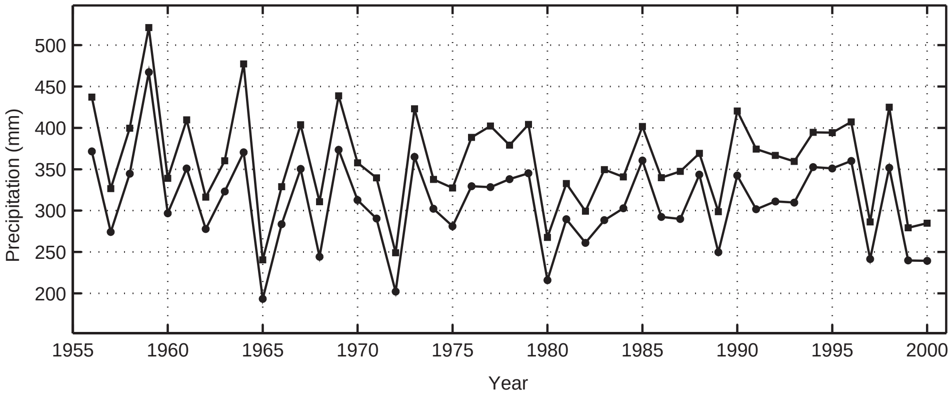

Fig. 2. Annual (the upper line) and May–September (the lower line) precipitation amounts averaged from 30 stations.

same groups in order to compare our results with those of the previous research. However, when analysing the changes in the precipitation intensity, we combined the last two groups since the last group of precipitation is infrequent in occurrence in the northern China.

The mean precipitation over all 30 stations in both May–September and whole year show slight decreasing linear trends, but neither is statistically significant (cf. Fig. 2). In contrast to the rainfall amount, however, we will show in the next section that there are profound and significant changes in some aspects of the daily rainfall characteristics. This can provide additional information for a better understanding of the local and regional environment problems.

3. Results

3.1. Number of rainy days

We counted the number of rainy days in May–September for each year station by station. If an amount of precipitation $\geqslant 0.1\,\mathrm{mm\,day^{-1}}$ is observed, this day is regarded as a rainy day. On average, there are 48.1 rainy days from May to September. Then we calculated the changes in the regional mean number of the rainy days. Averaging all 30 stations, there is a negative trend of -1.56 days per 10 years. This trend is statistically significant at the 99% confidence level. In the late 1950s, on average there were around 53 rainy days, in the 1990s this was reduced to about 45 days. This is a total decrease of about 8 days. Our analysis also shows that the long-term change in the number of rainy days is mainly caused by the significant reduction of days with light rain. As Fig. 3 shows, the number of days with a daily precipitation amount less than 10 mm has been decreasing since the 1950s. This significant (above the 99% level) linear trend is -1.42 days per 10 years. At the same time, however, the rainy days with moderate and above moderate rains do

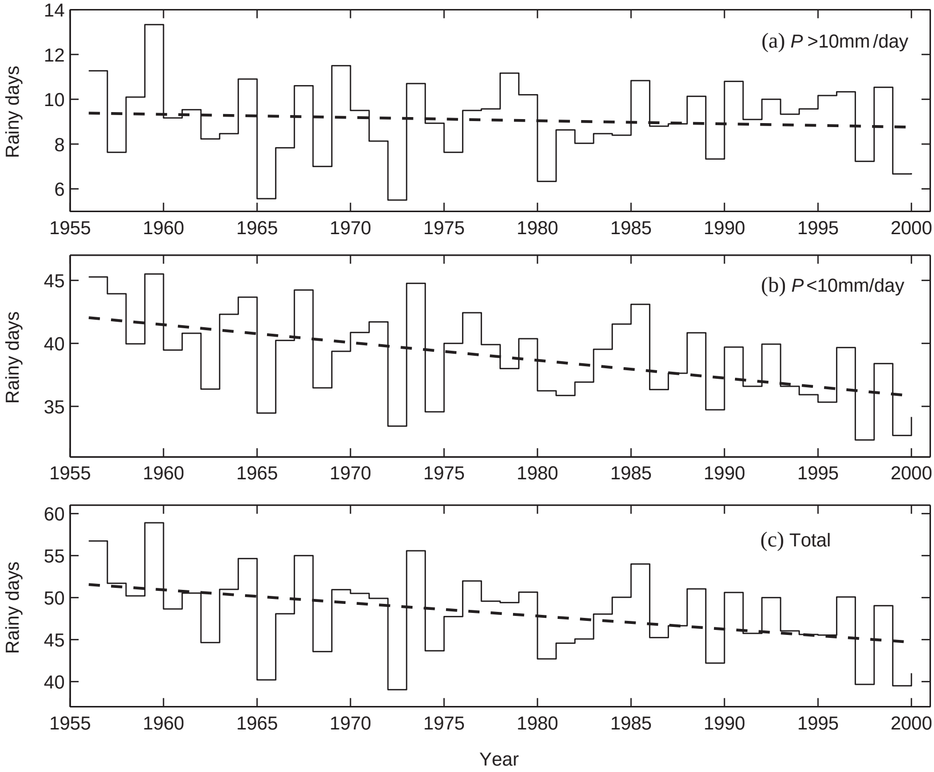

Fig. 3. Number of days with different daily rainfall. (a) Daily rainfall greater than 10 mm, (b) daily rainfall less than 10 mm, and (c) total rainy days per station. Dashed lines are linear trends.

not show evident changes. This implies that about 90% of the long-term changes in the number of rainy days is due to the reduction of the number of light rain days.

The decreasing number of rainy days is consistent with the observed reduction in cloudiness and humidity in northern China. Kaiser (1998, 2000) analysed the cloud cover over China, and found there were decreasing cloudiness trends in much of the country. The largest decreases were observed in northern and north-eastern China. From the early 1950s to the middle 1990s, the trend of annual mean total cloud cover over this region was as strong as -3% per 10 years in excess of a 95% confidence level for many stations. The surface relative humidity was found to decrease simultaneously, with rates of -1.0% to -1.5% per 10 years. The changes in cloud cover and relative humidity fit well with the reduction of the number of rainy days. If the linear trend of the number of rainy days is represented in the form of percentage, yielding -3.2% per 10 years, this number is comparable to the trend of decreasing cloud cover.

3.2. Precipitation intensity

Generally speaking, almost all of the stations in this region experienced typical semi-arid rainfall, i.e. much of the precipitation was produced in the form of convective rainfall occurring in limited days in summer. The number of light rain days accounts for 80.9% of the total number of rainy days, but this contributes only 31.8% of the total May–September precipitation amount. Contrary to that, the number of days with moderate to extreme rains accounts for only 19.1% of the total number of rainy days. However, they contribute 68.2% of the precipitation amount. Among the four groups, the moderate rain accounts for the greatest percentage of the total amount, nearly one-third (see Table 2 for details).

An interesting question is whether the precipitation intensity is changing or not. We calculated the trends in precipitation intensity for different rain types. Here the precipitation intensities are classified into four kinds, namely, the light rain ($<10\,\mathrm{mm\,day^{-1}}$), the moderate rain ($10$–$25\,\mathrm{mm\,day^{-1}}$), the heavy rain ($25$–$50\,\mathrm{mm\,day^{-1}}$) and the extreme rain ($\geqslant 50\,\mathrm{mm\,day^{-1}}$). Results are shown as follows.

(1) Light rains: $+0.04\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$, significant at the 95% confidence level.
(2) Moderate rains: $+0.01\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$.
(3) Heavy rains: $-0.16\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$.
(4) Extreme rains: $-0.37\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$.
(5) Moderate and above rains: $-0.09\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$.

Obviously, there are no identically dominant trends in these intensities. The light rains are getting more intensive (with a positive trend), while the heavy and extreme rains display negative linear trends. The tendency for the moderate rains is so small that it is nearly indiscernible. All types on average show a slight trend of $+0.08\,\mathrm{mm\,day^{-1}}\,10\,\mathrm{year^{-1}}$. This value is not statistically significant. However, the tendency for light rains toward stronger intensity is significant at the 95% confidence level. This trend has been very steady since the middle of the 1960s (see Fig. 4). The above analysis shows that the number of light rain days is decreasing while at the same time the precipitation intensity is getting more intensive. This implies the

Table 2
Frequency of daily rainfall

	Light rain ($<10\,\mathrm{mm\,day^{-1}}$)	Moderate rain (10–$25\,\mathrm{mm\,day^{-1}}$)	Heavy rain (25–$50\,\mathrm{mm\,day^{-1}}$)	Extreme rain ($\geqslant 50\,\mathrm{mm\,day^{-1}}$)
Rainy days (%)	79.0	14.5	5.0	1.5
Amount (%)	28.6	32.1	24.0	15.3
Mean intensity ($\mathrm{mm\,day^{-1}}$)	2.6	15.6	34.2	72.5

The number of rainy days and their amounts are shown in the form of percentage to the total number of rainy days and the total amount, respectively.

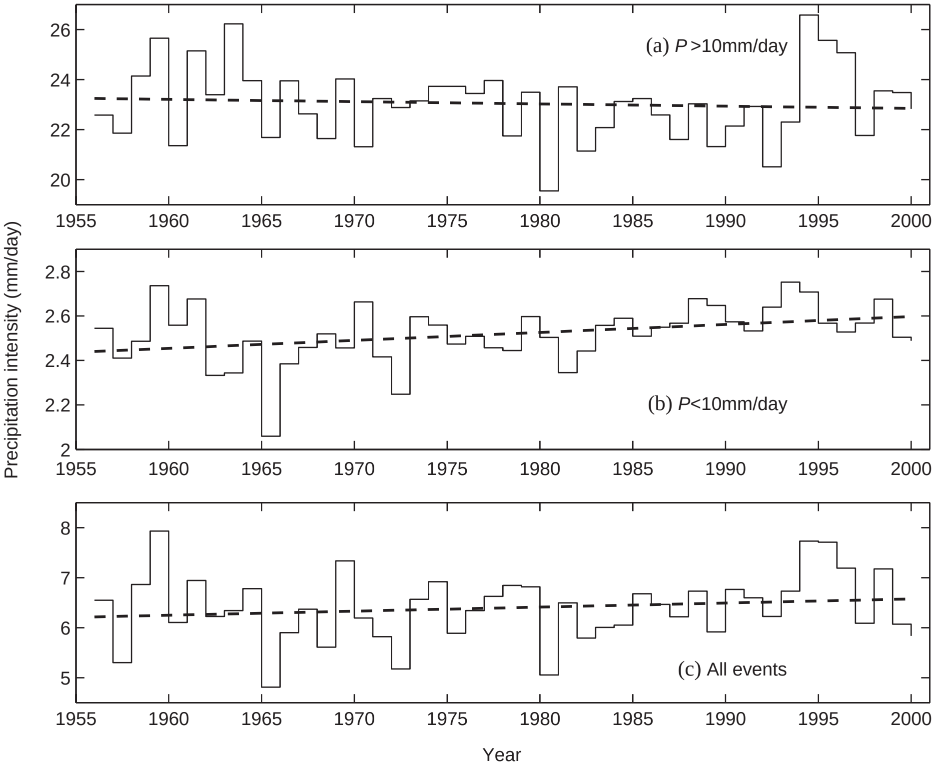

Fig. 4. Changes in the precipitation intensity. (a) Mean intensity for moderate and above rains, (b) mean intensity for light rains, and (c) mean intensity for all types of rains. Dashed lines are the linear trends.

convective processes, which produce light precipitation, would be getting more active and more intensive.

3.3. Maximum daily rainfall

Extremely heavy daily rains are frequently reported in the semi-arid regions. As Table 1 demonstrates, heavy and extreme rains contribute about 35.0% of the precipitation amount even though they occur occasionally (accounts for only 5.3% of the total number of rainy days). To examine the long-term changes in these extremely heavy daily rains, we compared the maximum values among all 30 stations for each year. Results are shown in Fig. 5. Since the median can provide an alternative measurement of these maximum events, we also computed the medians among these maximums for each year, and plotted the time-series in Fig. 5 for comparison. No evident linear trends are found in both time-series; instead, for the median of the maximums there is a step-like change in 1979/80. The medians in period 1980–1993 are evidently lower than the previous period. We checked the significance of the change using a t-test, the average for period 1956–1979 is

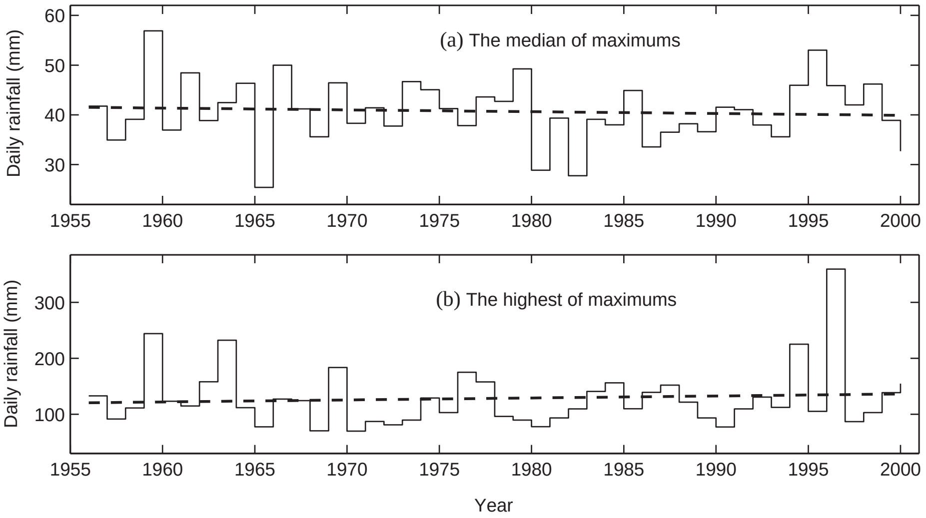

Fig. 5. Changes in the daily precipitation maximums. (a) The median of the maximums of 30 stations in May–September for each year; (b) the highest value of the maximums among all 30 stations. Dashed lines are the linear trends.

42.0 mm day^{-1}, for period 1980–1993 is 37.1 mm day^{-1}. The *t*-value is 2.6, which is statistically significant at the 95% confidence level. A lower median of maximums means there is a weaker intensity in the extreme rains for a majority of stations. This implies that even the highest values do not change significantly, many stations experienced a reduction in the maximum daily rainfall from 1980s to the early 1990s. It is interesting to note that there is a similar step-like change in the annual and May–September precipitation amount around 1979/80 (cf. Fig. 2). The 1979/80 changes might be physically associated with the large-scale regime shift in precipitation over the entire East Asia, relating to the summer monsoon circulation system (Gong and Ho, 2002).

3.4. Persistence of daily precipitation

Most precipitation falls as occasional showers, but there are some rainfalls occurring in successive days. To examine the persistence of these rainfalls, we counted their duration and frequency, i.e. counted the number of 1-day rainfalls, 2-day rainfalls and so on. Fig. 6 plots the numbers of these cases for both short duration and long duration. Here short duration is defined as the 1- and 2-day rainfalls, the long durations are those that last for at least 3 days. As Fig. 6 shows, the 1- and 2-day cases do not show evident trends. But the long duration precipitation events display remarkable reduction in the occurrences. The linear trend is −0.29 per 10 years, this change, in magnitude, is equal to −5.6% per 10 years and significant at the 99% confidence level. Since the large-scale and long-duration precipitation usually results from the large-scale weather systems, the

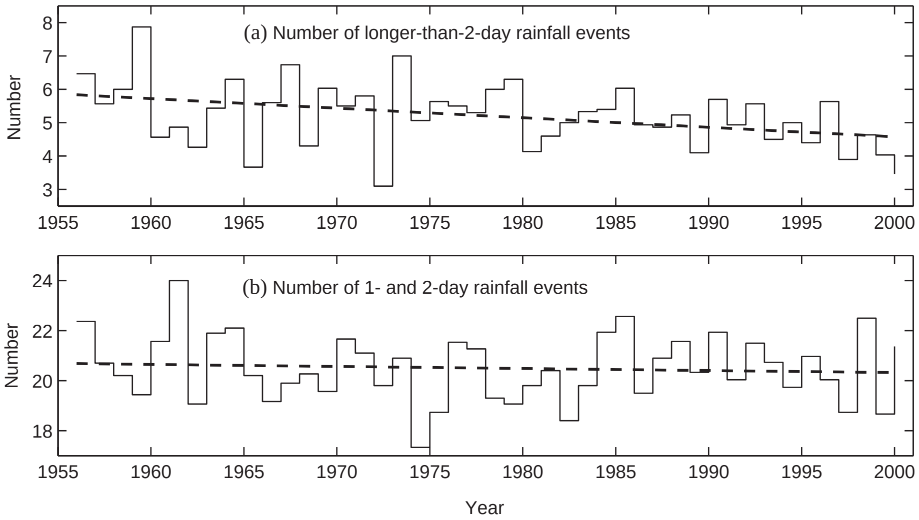

Fig. 6. Changes in the daily precipitation persistence. (a) The number of long duration rainfall events, (b) the number of short duration rainfall events. Averaged over the 30 stations for each year. Dashed lines are the linear trends.

reduction in frequency of long duration rainfall might suggest there is a tendency for large-scale atmospheric circulation systems toward fewer favorable conditions for long duration precipitation. This kind of change might be systematic with a very large spatial scale.

3.5. *Dry spell duration*

Consecutive days without rainfall can cause and enhance drought stress. The longer the no-rain periods, the higher the drought stress. In order to examine the changes in the dry spells during the summer, we computed their frequencies with respect to the duration (i.e. the 1-day dry spells, 2-day dry spells and so on). Fig. 7 displays the results. Here only two classes of dry spell durations are shown: one is a less than 10-day case (short dry spell) and the other is a dry spell equal to or longer than 10 days (long dry spell). The frequency of short dry spells is found to decrease slightly with a linear trend of −14.7 times per 10 years (i.e. −2.0% per 10 years). The frequency of long dry spells shows a remarkable positive trend, 4.4 times per 10 years (i.e. 7.2% per 10 years). Both are statistically significant at the 95% confidence level. Obviously, the long dry spells are substantially increasing in frequency. Therefore, it can be inferred from these analyses that drought stress is generally increasing despite the precipitation amount not changing significantly during the same time period. It can also be seen that there are very high frequencies of long dry spells in 1999, 1991 and 1982, but the precipitation amount in these years are not so low (see also Fig. 2). The temporal distribution of rainfall in a growing season can greatly change even though the total amount does not. Clearly, a weaker variation in the precipitation

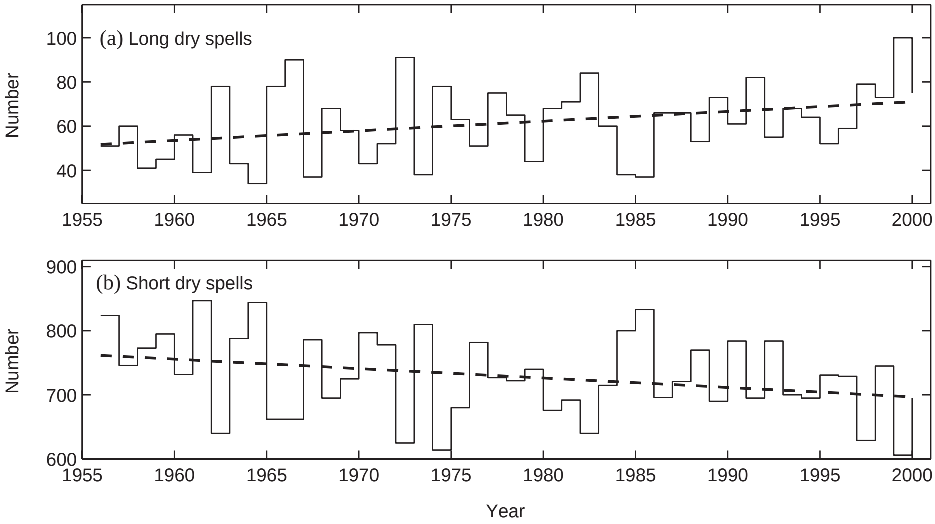

Fig. 7. Changes in the frequency of dry spells. (a) The number of long dry spells (longer than 10 days), (b) the number of short dry spells (shorter than 10 days). From all 30 stations in each year. Dashed lines are the linear trends.

amount does not guarantee a usual risk of drought; furthermore, even a notable increase in the precipitation amount does not necessarily mean there is a consistent reduction of drought stress.

4. Discussion

The immediate causes for daily rains are synoptic conditions. The long-term changes in the weather situations can result in the corresponding variations in rainfall distribution and frequency. In addition to the climate change in the atmospheric circulation itself, two external factors (namely, global warming and human-induced land cover change) have recently been emphasized and related, at least partly, to the changes in both the amount and distribution of precipitation.

Hulme (1996) investigated the possible influence of climatic warming on the global arid to semi-arid region precipitation and temperature for the last one hundred years. Although there are general tendencies toward dry conditions, there are no identical features in precipitation among these regions even though temperature increasing is broadly observed. Some authors tried to find the links between the regional precipitation fluctuations over East Asia to global climate change (Hulme et al., 1994; Gong and Wang, 2000). But as is well known, the regional precipitation response to global climate change may greatly vary from region to region (Houghton et al., 2001), particularly over the semi-arid regions where the climatically marginal regions are often located. Many studies applied climate models to resolve this problem (Gao et al., 2002). Usually the precipitation simulation in humid regions has a relatively higher level of reliability. For example, research found in some regions and specific seasons (such as Europe in autumn) the magnitude of response increases with the intensity of the precipitation events (Frei et al., 1998). Wilby and Wigley (2002) indicated that the proportion of total precipitation derived from the extreme and heavy events would continue to increase in a warming future over North America. But it must be pointed out that for the arid to semi-arid regions it is very hard to estimate the changes of intensity. This is because the summer rainfall amount is contributed mostly by the convective precipitation, which is of a small spatial scale and with a short lifetime that cannot be reasonably simulated by present climate models. In the future more detailed modeling studies are in need for this transition zone, and more reliable downscaling techniques suitable to this region also should be developed.

As a vulnerable region, the semi-arid transition zone in northern China is facing desertification (FAO, 1977; UNEP, 1992). The land cover change, in turn, will also exert influence on the local and regional climate. In some regions around the globe, widespread desertification is producing additional significant warming trends in the surface temperature. This might enhance the drought stress (Balling, 1991), although some other studies showed that it would not be a global phenomenon (Jones and Reid, 2001). In their general circulation model experiments, Zhao and Pitman (2002) claimed that land cover change and global warming could cause similar changes in rainfall intensity in China. Land cover change (current land cover compared to the ‘natural’ land cover) could lead to reduced precipitation intensity over China. It should be mentioned that the coarse spatial resolution would miss many physical processes in the regional scale and nation-wide average would also ignore the regional differences. This problem needs further research using high-resolution regional models and in situ observations as well.

5. Summary

Our results show that there are significant secular trends in some aspects of the daily rains in the semi-arid area of northern China in May–September, though the seasonal rainfall amount has not changed evidently for the period 1956–2000. Given the fact that the potential evaporation (annual values vary from about 1500–2000 mm) is much higher than the actual moisture supply in this semi-arid region (Zhang and Lin, 1992), even a moderate increase in the precipitation amount cannot mitigate the drought stress significantly. On the other hand, the changes in temporal distribution of precipitation in warm seasons would cause notable consequence for the local environments.

During the last four decades or so, the number of rainy days is decreasing significantly at a rate of -1.56 days per 10 years. Compared to the 1950s, the number of rainy days reduced by about 8 days in the 1990s. The number of light rains accounts for about 90% of the long-term changes in the total number of rainy days. At the same time, the light rains show significant trends toward stronger intensity.

The highest maximum of daily rainfall among all 30 stations each year does not display evident trend, instead, the median of the maximums shows a step-like change in 1979/80. A smaller median of maximums means there is weaker intensity in the extreme daily rains from 1980s to the early 1990s.

The frequency of long duration rainfall ($\geqslant 3$ days) shows remarkable reduction with a linear trend of -5.6% per 10 years. While, the occurrence of long dry spells (equal to and more than 10 consecutive days without rainfall) is increasing at a rate of 7.2% per 10 years, implying an increasing drought stress.

Global warming and human-induced land cover changes are supposed to be frequently related, at least partly, to the changes in precipitation. However, mechanisms need further study in the future.

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