Article ID: 1673-1719 (2007) Suppl.-0045-06

Trends of Extreme Precipitation over the Yangtze River Basin of China in 1960−2004

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Abstract: Recent trends of the rainfall, intensity and frequency of extreme precipitation (EP) over the Yangtze River Basin are analyzed in this paper. Since the mid-1980s the rainfall of EP in the basin has significantly increased, and the most significant increment occurred in the southeast mid-lower reaches, and southwest parts of the basin. Summer witnessed the most remarkable increase in EP amount. Both the intensity and frequency of EP events have contributed to the rising of EP amount, but increase in frequency contributed more to the increasing trend of EP than that in intensity. The average intervals between adjacent two EP events have been shortened. It is also interesting to note that the monthly distribution of EP events in the upper basin has changed, and the maximum frequency is more likely to occur in June rather than in July. The synchronization of the maximum frequency month between the upper and mid-lower reaches might have also increased the risk of heavy floods in the mid-lower reaches of the Yangtze River.

Key words: extreme precipitation event; spatial and temporal pattern; climate change; the Yangtze River Basin

Introduction

Extreme climate and weather events are one of the most deadly and costly natural disasters in the world. Shifting of the frequency and intensity of the extreme events has more far-reaching impact on the nature and human society than the changing of the mean value [1−3]. Possibility for increasing of extreme events under global warming background has drawn much attention from the governments and academic communities all over the world. Many studies revealed that the trends of extreme events depended on the spatial and temporal scales involved [2−3]. The Yangtze River Basin is a sensitive area to the climate change, where precipitation shows a sharp seasonal and interannual variabilities. With the acceleration of water-cycling induced by climate warming, unevenly distribution of precipitation over the Yangtze River Basin is more likely to be enhanced. Based on the daily observational data of 147 stations in the basin, spatial and temporal variations of extreme precipitation (EP) in the last 45 years are analysed in present study.

1 Spatial distribution of thresholds of extreme precipitation

It is stated in the regulations of China Meteorological Administration, torrential rain is an event with daily precipitation ⩾ 50 mm. If it is used as the threshold, there would be a large area of no torrential rain in the upper reaches of the Yangtze River. In order to compare the trends of intensive precipitation events in high rainfall regions with those in low rainfall regions, it is suitable to follow the regulation of World Meteorological Organization, i. e. events with possibility > the 90th percentile or < the 10th percentile are defined as extreme events. In present study, the daily precipitation at a station exceeding the 95th percentile in whole observational period (1960−2004) is defined as an EP event for the station. Therefore, all stations have the same EP frequency in the last 45 years, but with various temporal distributions.

Received: December 7, 2006; revised: February 28, 2007
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As shown in Fig.1, the geographical distribution of the threshold of EP, the value of the 95th percentile daily precipitation generally decreased from southeast to northwest, with the largest value in the Poyang Lake sub-catchment (⩾ 25 mm/d) and smallest values in the headstream regions (about 10 mm/d). In the mid-lower Yangtze reaches, except the Hanjiang River sub-catchment, the value was over 15 mm/d, while in most parts of the upper Yangtze reaches, except the southwestern region, the value was less than 15 mm/d.

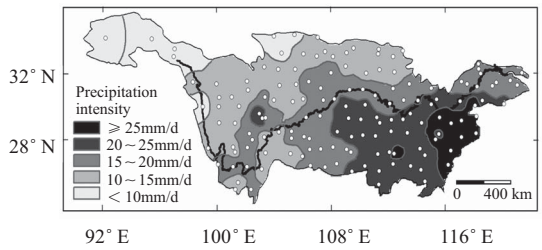

Fig. 1 Spatial distribution of the 95th percentile daily precipitation over the Yangtze River Basin

2 Trends of extreme precipitation

2.1 *Total rainfall*

Non parametric Mann-Kendall tests [4] are performed for 69 meteorological stations in the upper reaches, 78 meteorological stations in the mid-lower reaches to identify gradual monotonic trends and abrupt step changes of EP during the recent 45 years in the Yangtze River Basin. Results show that the yearly total rainfall of area averaged EP slightly declined over the upper reaches, without any sign of abrupt change in the whole period of l960−2004 (Fig. 2a), but it has significantly increased over the mid-lower reaches since 1986, when an abrupt change was detected (Fig. 2b).

Spatially, the yearly total rainfall of EP showed significant positive trends at 15 stations in the Jinsha River sub-catchment of the upper reaches, 23 stations in the Poyang Lake, Dongting Lake sub-catchment and main stream section of the mid-lower reaches, and significant negative trends at 12 stations in the central and northern upper reaches (Fig. 3a). Changes in yearly total EP over the Yangtze River Basin are quantitatively expressed in terms of differences of the mean values of 1987−2004 minus 1960−1986 (Fig. 3b). Increments of the yearly total, in most parts of the mid-lower reaches except Hanjiang River sub-catchment, lay between 50 mm and 100 mm, and in the Poyang Lake and Dongting Lake area exceeded

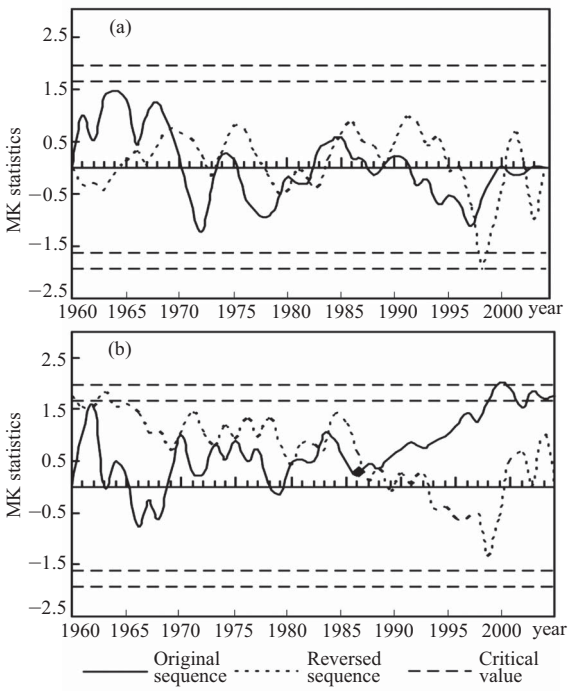

Fig. 2 Abrupt change of yearly area averaged EP for the Yangtze River Basin (dashed lines denote the 90% (inner) and 95% (outer) confidence level, respectively)
(a) the upper reaches, (b) the mid-lower reaches

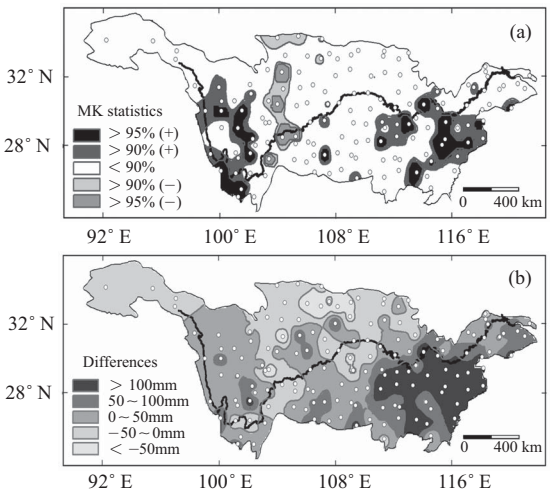

Fig. 3 Spatial patterns of average yearly EP over the Yangtze River Basin (a) long-term trends in 1960−2004, (b) differences of average yearly EP for 1987−2004 minus 1960−1986

100 mm. In the upper reaches, it reduced from 0 to 50 mm at the northern and northwestern regions, and increased from 0 to 50 mm at the other regions.

2.2 *Intensity and frequency*

Intensity and frequency are the two factors determining

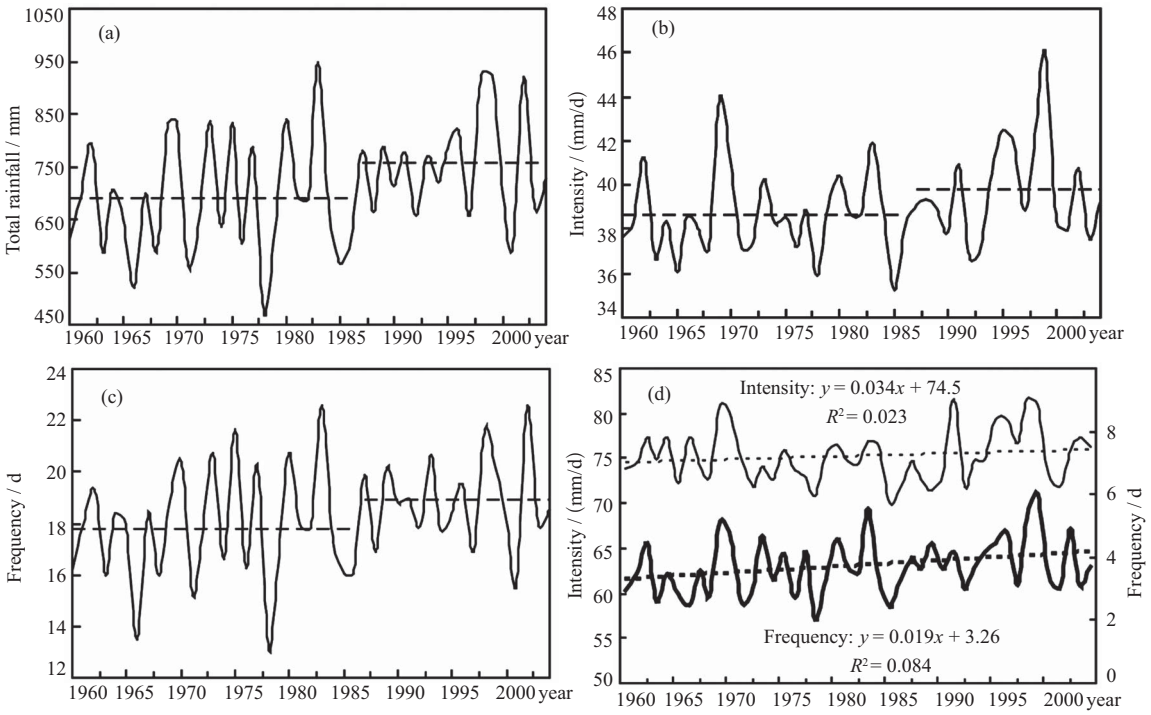

Fig. 4 Time series of EP over the mid-lower reaches (a) total amount, (b) intensity, (c) frequency (dashed lines in a, b, and c indicate average values for 1960−1986 and 1987−2004, respectively), (d) linear trends (dot lines) of the intensity (the upper panel) and frequency (the lower panel) of torrential rain

precipitation amount. Analyses of long term trends for the annual average intensity and frequency of EP in different regions in the Yangtze River Basin reveal that the average intensity of EP has weakly increased and the frequency slightly declined over the upper reaches in the last 45 year, and both the two observed trends are not significant. Whereas, the intensity and frequency rainfall of EP over the mid-lower reaches show a significant positive trend at the 95% and 90% confidence level, respectively. Similar with the yearly total rainfall of EP (Fig. 2), abrupt change points detected for the intensity and frequency of EP over the mid-lower reaches are both at the year 1986. In comparison with 1960−1986, the yearly total, intensity and frequency of EP in 1987−2004 have increased by 65 mm, 1.2 mm/d and 1.2 d, respectively (Figs. 4a−c). Since the yearly frequency of EP $>$ 95th percentile is 18.3 d, the increment of average intensity of about 1.2 mm/d only contributes 22 mm (about one third) to the rising of total amount, which means that the rising of the yearly total of EP over the mid-lower reaches are largely due to the increment of frequency of EP events. Especially for torrential rain events $\geqslant$ 50 mm/d (Figs. 4d), the total amount of torrential rain have showed a positive trend significant at the 95% confidence level in the last 45 years, and increased by 44 mm in 1987−2004 compared with 1960−1986. But significance of the positive trend is higher for torrential rain frequency (at the 95% confidence level) than for torrential rain intensity (not significant) .

There have been obvious spatial changes in trends of the intensity and frequency of EP over the Yangtze River Basin since 1986. The intensity of EP showed a positive trend at 12 stations in the upper reaches and also 12 stations in the mid-lower reaches, and a negative trend at 6 and 3 stations in the above-mentioned reaches, respectively (Fig. 5a). In comparison with 1960−1986, the average intensity of EP in 1987−2004 in most parts of the Yangtze River Basin has increased except the northern and northwestern region, with increments < 1 mm/d in the great majority of stations in the upper and mid-lower reaches, and those from 2 to 4 mm/d mainly in the lower Mintuo River sub-catchment and Wujiang River sub-catchment of the upper reaches and the Dongting Lake area and mainstream section of the mid-lower reaches (Fig. 5b). The spatial distributions of trends for the annual frequency of EP events (Fig. 5c) are similar to those for the annual total (Fig. 3a), and significant positive trends located in the southeastern and

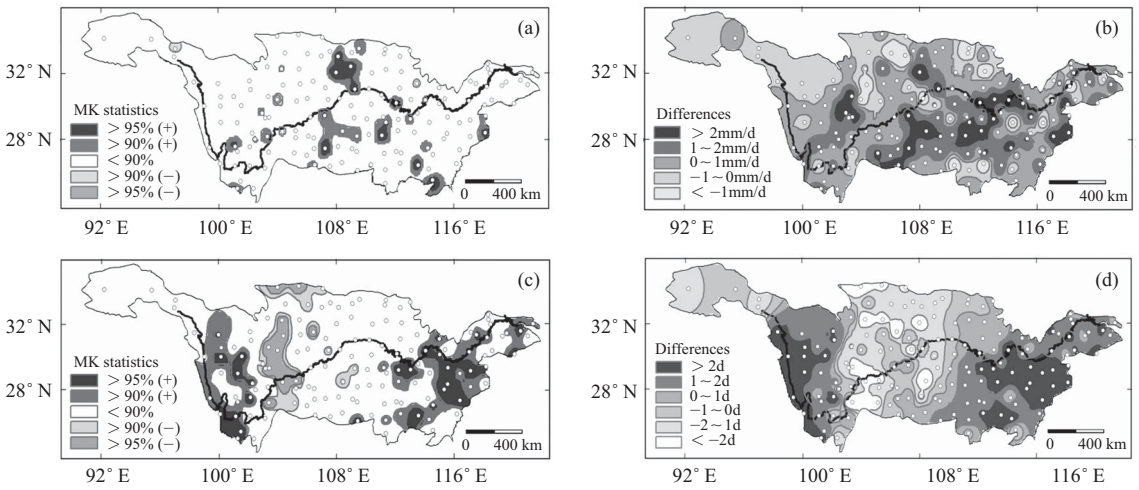

Fig. 5 Spatial patterns of trends for the intensity and frequency of EP over the Yangtze River Basin (a) MK trends of intensity in 1960−2004, (b) differences of average intensity for 1987−2004 minus 1960−1986, (c) MK trends of frequency in 1960−2004, (d) differences of annual frequency for 1987−2004 minus 1960−1986

southwestern parts of the Yangtze River Basin, however, in the central region of the upper reaches, there were 18 stations showing significant negative trends. The annual frequency of EP in 1987−2004 has increased relative to 1960−1986, in the eastern and western (except the headstream) regions, and reduced in the central part of the Yangtze River Basin. The differences of the annual frequency for most stations ranged between 1−2 d, and only at stations showing a significant trend, the differences exceeded 2 d. Especially for stations in the Jinsha River sub-catchment in the upper reaches and the Dongting and Poyang Lakes sub-catchment in the mid-lower reaches, the differences reached up to 3.2 d and 3.1 d, respectively (Fig. 5 d).

2.3 *Time interval between EP events*

Besides intensity and frequency, time interval between the EP events is another main character of intensive precipitation. In the case that extreme heavy precipitation concentrates in a certain region, it is apt to bring about regional flood events; and when EP events in the upper reaches and in the mid-lower reaches happened at he same time, there would be a basin-wide floods. Calculations of the time interval between the adjacent EP events reveal that the probability distribution of EP over the Yangtze River Basin is composed of 60% of events with 1−10 d time interval, 18% of events with 11−20 d time interval, 8% of events with 21−30 d time interval and so on. Along with the extension of time interval, the frequency of corresponding EP events reduced evidently (Table 1). Previous study showed that torrential rain lasting for a long time period and covering a large area of the basin frequently resulted in the Yangtze River floods, and EP events with short time intervals played an important role in the producing of flood disasters in the Yangtze River Basin [5]. Therefore, the EP events with 1−5 d time interval play an important role in producing the basin-scale floods. The MK trends for the frequency of the EP events with 1−5 d time interval over the basin are similar to those for the annual frequency of all EP events in 1960−2004.The MK trends showed a slightly decreasing trend over the upper reaches, but a significantly increasing trend over the mid-lower reaches with an abrupt change at the year 1986. In

Table 1 Probability distribution of EP events with different time intervals over the Yangtze River Basin during 1960−2004 (%)

Region	Time interval between adjacent EP events					
	1−5 d	6−10 d	11−15 d	16−20 d	21−25 d	26−30 d
Upper reaches	43.88	19.80	11.36	7.02	4.30	2.57
Mid-lower reaches	37.10	17.43	10.98	8.12	5.12	4.04
Whole basin	40.26	18.55	11.16	7.61	4.78	3.35

Table 2 Monthly frequency of EP events over the Yangtze River Basin during 1960−2004 (%)

Region	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Upper reaches	0.16	0.23	1.06	4.65	10.9	18.6	22.4	19.7	14.9	5.77	1.45	0.19
Mid-lower reaches	1.60	2.72	6.38	11.6	14.6	17.2	14.5	11.9	8.33	6.15	3.84	1.14
Whole basin	0.93	1.56	3.89	8.35	12.9	17.9	18.2	15.6	11.4	5.97	2.72	0.69

comparison with 1960−1986, the annual frequency of the EP events with 1−5 d time interval in 1987−2004 over the mid-lower reaches has increased by 0.61d on the average, which accounts for 50% of the increment of all EP events. Spatial patterns of the MK trends for the annual frequency of the EP events with 1−5 d time interval (Figure omitted) are also similar to those for all EP events, but there are less station showing significant positive or negative trends. At stations showing significant positive trends, the average annual frequency of the EP events with 1−5 d time interval increased nearly 2 d in 1987−2004 than that in 1960−1986, accounts for 60% of the increment of all EP events, which means that the increase in the annual total of all EP events over the Yangtze River Basin mainly came from increase in EP events with shorter time interval.

As for monthly distributions, EP events over the Yangtze River Basin concentrated mostly in the flood season from April to October. EP events in May to September accounted for 86% of annual total over the upper reaches and those in April to August accounted for 70% of annual total over the mid-lower reaches. In general, the peak period of EP events of the upper reaches lagged behind that of the mid-lower reaches (Table 2), favourable for avoiding the occurrence of basin-scale floods. However, the monthly distribution of EP events over the Yangtze River Basin has changed in the last 45 years. In the upper reaches, stations with EP events have significantly increased in June but reduced in September, meanwhile in the mid-lower reaches, those with EP events have significantly increased in summer season (June, July and August) but reduced in September (Fig. 6 a). Therefore, EP events of the upper reaches and ones of the mid-lower reaches have concentrated in summer, especially in June, this resulted in not only the gradual approach of the peak periods of EP events of the upper reaches and the mid-lower reaches with each other, but also increase in the kurtosis of peak period. The distribution of the pentad frequency of EP events during the flood season is plotted in Figs. 6 b−c. It is shown that the timing of the peak of EP events over the mid-lower reaches was about

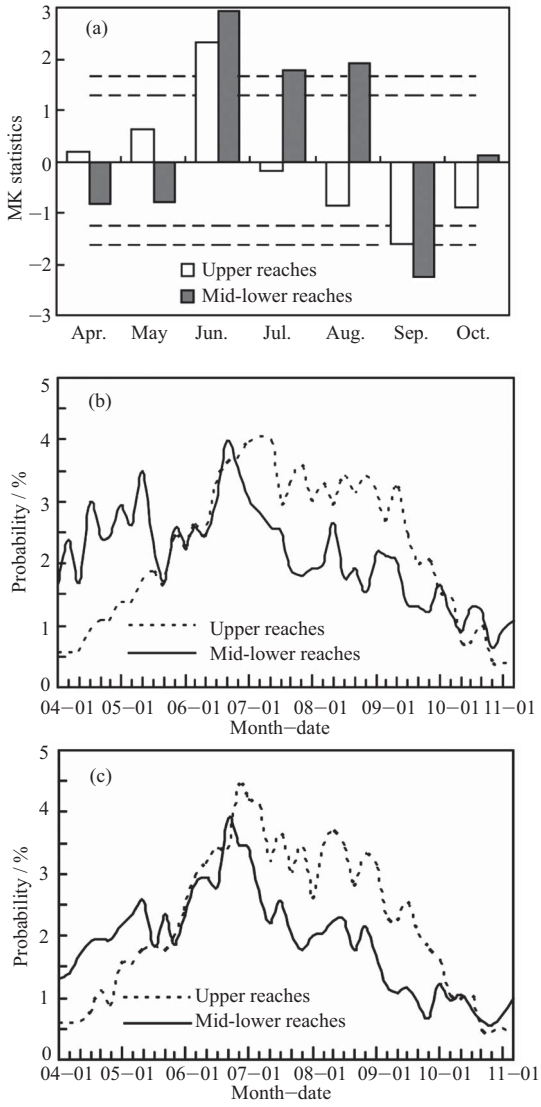

Fig. 6 Monthly variations of the number of stations with EP events in the flood season (a) MK trends, (b) frequency distribution of EP events in 1960−1986, (c) frequency distribution of EP events in 1987−2004

half month proceeded that over the upper reaches in 1960−1986 (Fig. 6b), but the interval between two peaks have shortened obviously in 1987−2004 (Fig. 6c). During 1960−

1986, EP events in June accounted for 18% and 17% of annual total over the upper reaches and the mid-lower reaches, respectively, but they have both increased by 2% in 1987−2004.

3 Conclusions

From the above analyses of the changes in the rainfall, intensity, and frequency of EP events over the upper and mid-lower reaches of the Yangtze River in 1960−2004, the following results are noted:

(1) Total rainfall, intensity and frequency of EP events over the mid-lower reaches of the Yangtze River showed significant positive trend with a abrupt change in the year 1986. In 1987−2004, the total amount, intensity and frequency of EP have increased by 65 mm, 1.2 mm/d, and 1.2 d, respectively, relative to 1960−1986.

(2) The EP over the Yangtze River Basin has shown obvious spatial changes. The annual total rainfall of EP has exhibited significant positive trends in the southeastern and southwestern parts of the basin, especially in the Poyang Lake and Dongting Lake sub-catchment in the mid-lower reaches and the Jinsha River sub-catchment in the upper reaches, and significant negative trends around the Sichuan Basin region in the upper reaches. No large area of significant trend was detected for the intensity of EP, while the spatial changes of trends for the frequency of EP are similar to the distribution of total amount.

(3) Since the mid-1980s, EP has shown a temporal concentration tendency. Not only the frequency of EP events with 1−5d time interval has significantly increased over the mid-lower reaches, but also the interval of peaks of EP events between the upper reaches and the mid-lower reaches has shortened obviously as well.

In the last 45 years, annual air temperature has increased significantly over the Yangtze River Basin [6]. It is urgently needed to further study on the trends of spatial and temporal variations of EP and its influence on the Yangtze River floods under the global warming background.

Acknowledgements

We would like to thank the National Climate Center for providing the valuable climate data.

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