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Precipitation trends and their impact on the discharge of China's four largest rivers, 1951–1998

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Abstract This paper analyses the long-term trends of precipitation (amount, days and intensity) in China during the last 50 years, based on the long-term precipitation data from 678 meteorological stations. Using the annual observed data at the main hydrometric stations on China's four largest rivers, the response of river discharge to climate change is analysed using linear regression methodology. It was found that the annual precipitation in the past 50 years has had a noticeably regional dependence. A general rising trend for annual precipitation appears at most stations in the west of China (west of longitude 103°E); the same increasing trend occurs in southeast China (in the lower reaches of the Yangtze River, the Huaihe River watershed and Zhujiang River watershed) and in the western part of northeast China. However, a decreasing trend appears in the middle part of east China and its surrounding regions. The number of precipitation days display a marked decrease in east China, with positive trends in west China. An increasing trend in the daily-averaged precipitation intensity is found in most regions. Such climate change is probably a benefit, easing the drought situation in northwest China. It was found that the river discharge in these regions is increasing markedly. However, the increase of precipitation intensity may lead to a frequent occurrence of floods. The negative trend in precipitation in the semiarid middle part of east China and the positive trend in rainy southeast China bring adverse effects, causing more droughts in the middle of eastern China, and more floods in southeastern China. The serious cut-off of flow during the 1990s in the Yellow River and the frequent flood disasters of the Yangtze River during the last 10 years are the results of precipitation change.

Key words China; discharge changes; flood disasters; large river; precipitation variation

INTRODUCTION

China is a country that suffers from frequent flood and drought disasters. Serious floods and droughts have occurred for almost a third of the time during the past 1470-year period, greatly influencing the national economy and people's lives (Xie, 2001). Since the 1980s, global warming has led to a worldwide increase in the variation of precipitation. However, the variation in precipitation has marked regional patterns. The floods in southeast China and the droughts in the north are characteristic of the spatial distribution of disasters in China during the last 10 years. Typical examples are the big flood in the Yangtze River watershed in 1998, in the Huaihe River watershed in 2003, and increasingly serious flow cut-off in the lower reaches of the Yellow River in the middle and late 1990s.

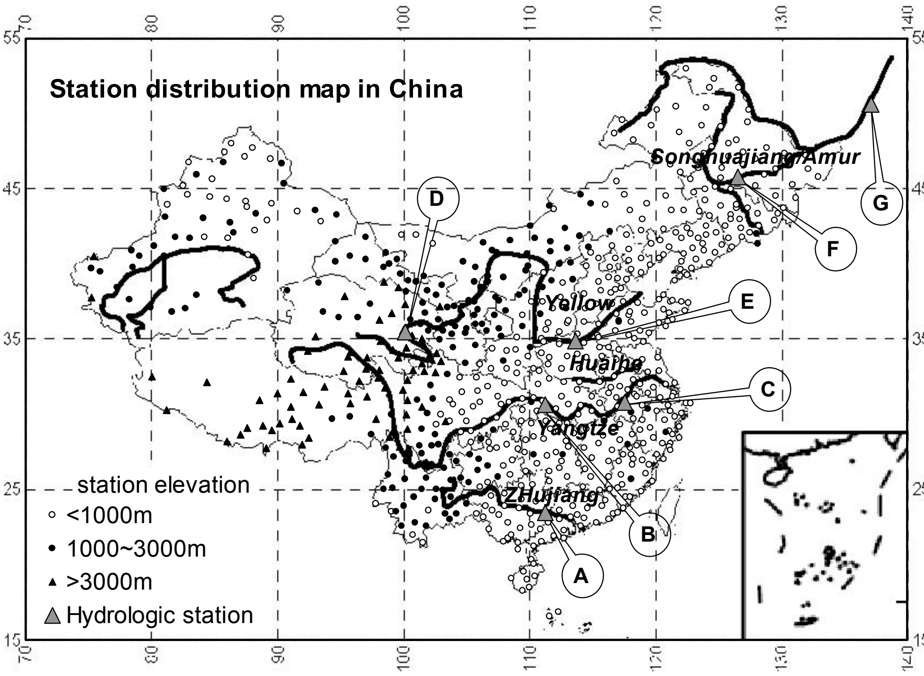

Fig. 1 The distribution of meteorological and hydrological stations.

The recent studies of precipitation variation in China show that the variations in precipitation frequency (number of precipitation days per year) and of precipitation amount had regional patterns in the period 1953–1997. Bordered by longitude 103°E, to the west the precipitation increased by over 5–10% (10 years)$^{-1}$. To the east, the precipitation increased significantly on the middle and lower reaches of the Yangtze River and in the southeast coastal areas, but showed a decreasing trend in most of the middle part of east China, the middle Yangtze River watershed, and eastern part of northeast China. These studies also detail the features of seasonal variation in precipitation (Wang *et al.*, 2002; Zhai *et al.*, 1999) and consider the causes of variation.

The variation in river runoff and the response of river runoff to climate change are serious concerns worldwide. The 2001 IPCC report summarizes the achievement in this field thoroughly (Arnell *et al.*, 2001). Recently, more and more studies have paid attention to the influence of climate change on annual runoff (Yang *et al.*, 2002, 2003; Grabs *et al.*, 2002), the variation of monthly distribution in runoff, and of runoff in snowmelt periods.

This paper analyses the regional features in precipitation variation, based on the precipitation data at 678 meteorological stations located all over China, from 1951 to 1998. The Yangtze and Zhujiang rivers are used to represent the southeast of China (in the lower reaches of the Yangtze River, Huaihe River and Zhujiang River watersheds) (Fig. 1), where precipitation shows an increasing trend; the Yellow River is used to represent the middle part of eastern China where precipitation shows a decreasing trend; and the Songhuajiang/Amur River is used to represent northeast China where the precipitation change is varied. Lastly, the impact of the regional variation in precipitation on the runoff and flood disasters is analysed in order to improve our understanding of the influence of climate change on water resources and provide some scientific basis for dealing with these changes.

RESEARCH METHOD AND DATA

Research method

In this paper, the linear regression method is used to determine the long-term trend and regional features of precipitation in China in the last 50 years. The *t*-test method is then used to determine the significance level of the trend. The analysed annual precipitation variables include the annual precipitation amount, precipitation days and mean daily precipitation intensity, in which the variation in the precipitation amount determines changes of water resources, while precipitation day and intensity are linked to flood and drought disasters. Based on the trends in precipitation and runoff, the response of runoff to the precipitation changes of the four largest rivers in China: the Yangtze, the Yellow, the Songhuajiang/Amur and the Zhujiang rivers, is analysed. The relationship between the flood or drought disaster and the changes of precipitation day and intensity are studied according to the changes in the disaster areas in the Yangtze River watershed.

Meteorological data

The daily precipitation data for the period 1951–1998 used in this study is from 670 stations, all with more than 30 years of records, and from eight stations distributed in the high mountains of west China (with an altitude of above 1000 m a.m.s.l.) with records of longer than 20 years, due to there being fewer stations in high mountains (Fig. 1). The annual precipitation amount, precipitation days and mean daily precipitation intensity are quantified statistically. Precipitation days is defined as the number of days with measurable precipitation, i.e. the precipitation amount is more than or equal to 0.1 mm. The mean daily precipitation intensity is obtained by dividing the annual precipitation amount by the corresponding precipitation days.

Hydrological data

The annual discharge data for the last 50 years are from the seven stations along the four rivers. The main characteristics of the selected stations are listed in Table 1 and they are shown in Fig. 1. Both the Yangtze River and the Yellow River originate in the Tibetan Plateau. In the source areas of the two rivers, where human activities are relatively infrequent, the runoff change has natural features. However, on the middle and lower reaches of the two rivers and the watershed of the Songhuajiang and Zhujiang rivers (dominant industrial and agricultural regions in China), the influence of human activities on runoff are very marked (Chen *et al*, 2001; Ren *et al*., 2002). The water resource of the Yellow River watershed is severely deficient, although flood events have occurred frequently in history.

TRENDS OF PRECIPITATION AND DISCHARGE

After showing the variation trends of the annual precipitation amount and runoff as well as the correlation of precipitation frequency (precipitation day) and intensity changes *versus*

Table 1 The characteristics of the hydrometric stations on the four biggest rivers.

River	Code see Fig. 1	Station	*S* (km^2)	Lat. °N	Long. °E	RP	*R* ($\times 10^8 m^3$)
Zhujiang	A	Wuzhou	329700	23.48	111.30	1951–2000	2064
Yellow	B	Tannaihai	121900	35.50	100.15	1956–1997	204
	C	Huayuankou	730000	34.92	113.65	1951–2000	409
Yangtze	D	Yichan	1010000	30.66	111.23	1951–2000	4315
	E	Datong	1705300	30.77	117.62	1951–2000	8958
Songhuajiang/ Amur	F	Haerbin	391000	126.58	45.77	1951–1999	437
	G	Komsomolsk	1730000	50.63	137.12	1951–1990	3194

S: drainage area; *R*: runoff; RP: discharge record period.

flood disasters, the effects of climatic change on runoff are analysed. For convenience, the territory of China is divided into west and east parts bounded by longitude 103°E.

Variation trends of annual precipitation and runoff

A main feature of the precipitation distribution is that the mean annual precipitation increases gradually from the northeast of China, from an amount of less than 400 mm (only 15 mm at individual stations), towards the southeast of China where it reaches more than 1500 mm. Based on the analysis of the precipitation data from the 678 meteorological stations during 1951–1998, it was found that the various trends of annual precipitation have clear regional characteristics (Fig. 2). The increase of annual precipitation occurs mainly in the southeast of China, corresponding to the middle and lower reaches of the Yangtze River, Huaihe watershed and Zhujiang watershed, respectively, and the western parts of the northeast and the west of China. Among these areas with positive trends, the south of eastern China has the greatest increase with the 5–40 mm (10 years)$^{-1}$, and even 120 mm (10 years)$^{-1}$ at some stations. The western part of northeast China follows with an increasing trend of 5–15 mm (10 years)$^{-1}$ in most areas; in western China precipitation shows a generally positive trend of 5–10 mm (10 years)$^{-1}$. However, a negative trend of precipitation occurs in the middle part of eastern China, that is generally larger than 5 mm (10 years)$^{-1}$, and above 30 mm (10 years)$^{-1}$ in some regions. As for the relative trend of precipitation, the maximum, with a trend of more than 5% (10 years)$^{-1}$ in most regions and even more than 15% (10 years)$^{-1}$ in some areas, occurs in the northwest of China, with less precipitation. But in the southeast and the northeast of China with relatively high precipitation, the relative positive trend is below 2% (10 years)$^{-1}$ in most areas. In the middle part of east China where the precipitation shows a decreasing trend, the relative trend is below 15% (10 years)$^{-1}$. The relative trend of precipitation is consistent with the analysis results of Wang *et al.* (2002) from 2.5° × 2.5° grid precipitation data.

Corresponding to the increasing precipitation, the runoff increases and brings about a rise in lake water levels in the northwest of China (Lan Yongchao *et al.*, 2003; Shi Yafeng *et al.*, 2003; Zhang Guowei *et al.*, 2003). In order to study the runoff changes in the region located in the central part of eastern China with its decreased precipitation, and in the region spanning the Yangtze and Zhujiang watersheds with its

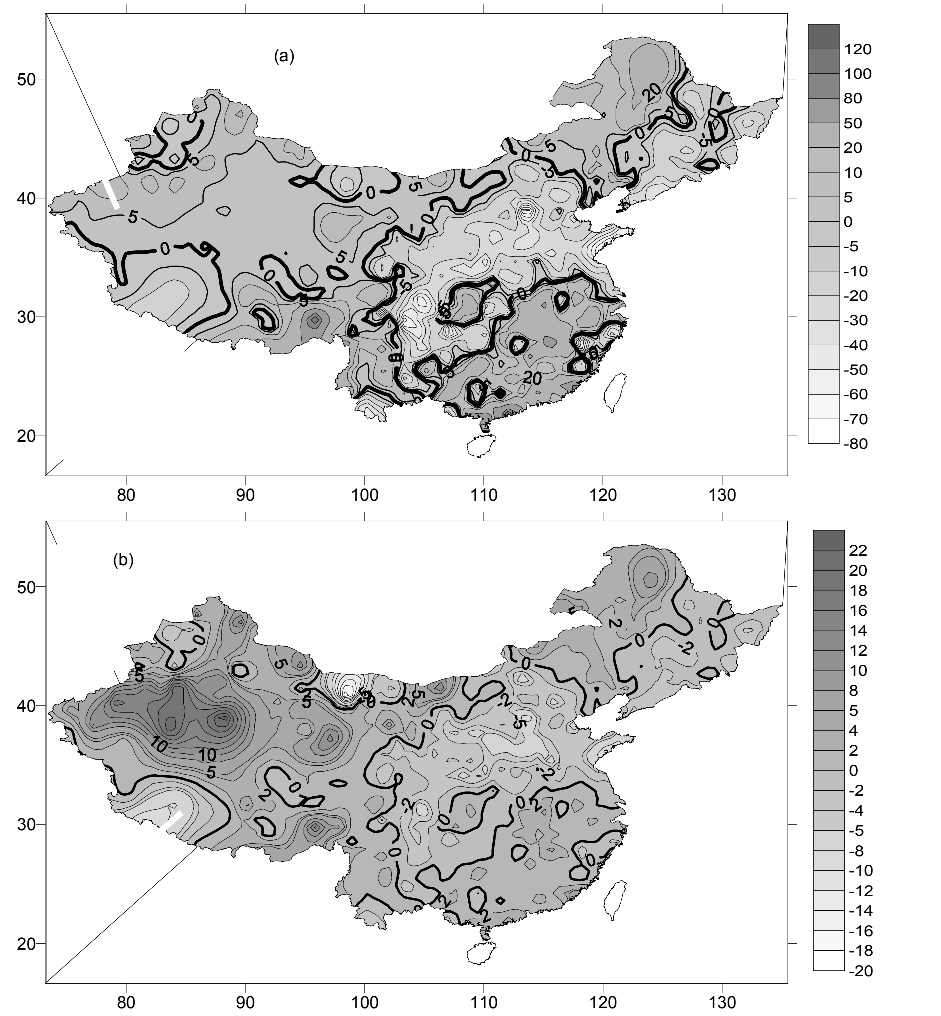

Fig. 2 Contour maps of (a) absolute and (b) relative trends of annual precipitation over China.

increased precipitation, the representative rivers (the Yellow and the Yangtze rivers), respectively, are considered. Figure 3 shows the variations of annual runoff at the main hydrometric stations on the four rivers.

The measured discharge at Wuzhou station on the Zhujiang River shows a negative trend of –43.2 $m^3 s^{-1}$ (10 years)$^{-1}$ or –0.7% (10 years)$^{-1}$ during 1951–2000 due to the precipitation decrease in the upper Zhujiang River (Fig. 3(a)). At Yichang station on the middle reaches of the Yangtze River, the discharge demonstrates a weak, insignificant decrease with a trend of 153 $m^3 s^{-1}$ (10 years)$^{-1}$ (1.4% (10 years)$^{-1}$) for 1951–2000 due to the reduced precipitation on the middle reaches. However, at Datong station on the lower Yangtze River, the discharge, after compensating for the discharge reduction at Yichang, shows a weak increase with a trend of 266 $m^3 s^{-1}$ (10 years)$^{-1}$ (0.8% (10 years)$^{-1}$) because of the increased precipitation in the lower reaches of the Yangtze. At Tangnaihe station in the upper reaches of the Yellow River, the measured discharge shows no change during 1951–2000, owing to its being located just inside the transition belt between the areas of increasing and decreasing precipitation. At Huayuankou station on

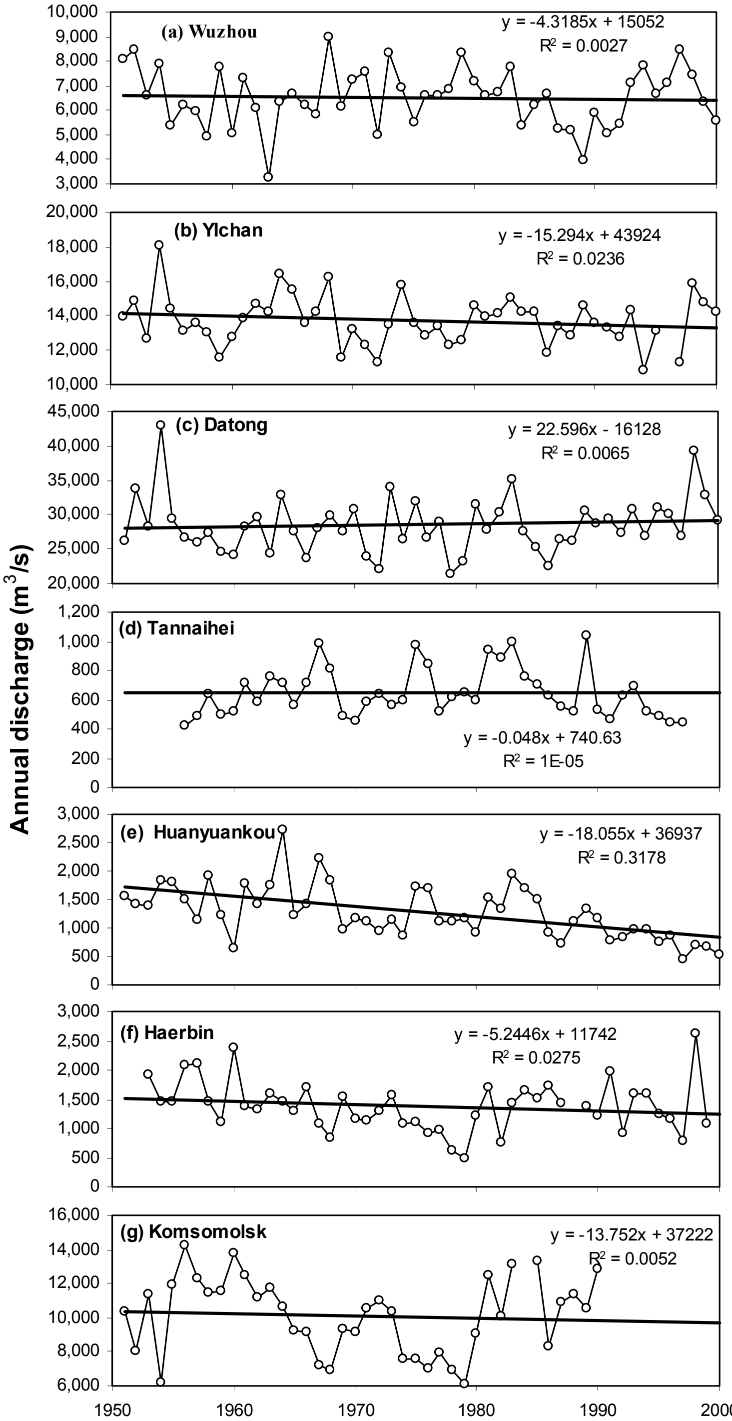

Fig. 3 The annual discharge and its trend at seven stations on four rivers: 1951–2000.

the lower reaches of the Yellow River, there is an obvious decrease in discharge with the decreasing trend of 182 $m^3 s^{-1} (10 \text{ years})^{-1}$ (14.4% $(10 \text{ years})^{-1}$). The decrease in discharge at the station is attributed to the effects both of climatic change and increased water consumption by industry and agriculture (Yang *et al.*, 2003). For the middle and lower reaches of the Yellow River, located in the drought- or semi-drought-prone regions of

China, the decrease of precipitation will lead directly to a decrease in discharge, and cause an increase in water consumption by industry and agriculture, especially in irrigation water use. Thus the decreased degree of discharge is strengthened on the middle and lower reaches of the Yellow River. The annual discharges at both Haerbin and Komsomolsk stations on the Songhuajiang/Amur River show negative trends of –52 and 138 $m^3 s^{-1}$ (10 years)$^{-1}$ (–3.8 and –1.4% (10 years)$^{-1}$), respectively, for 1951–1999.

Relationship of changes of annual precipitation day (precipitation frequency) and mean daily precipitation amount (averaged precipitation intensity) with flood disasters

The changes of the precipitation frequency and intensity directly influence the frequency and intensity of flood disasters. The changes of the annual precipitation day and mean daily precipitation intensity have different regional features from that of the annual precipitation amount. As a climate element, the annual number of precipitation days decreases very markedly (at a highly significant level) in east China with a negative trend of 10 days (10 years)$^{-1}$, even above 25 days (10 years)-1 in some stations, and with a negative relative trend of 5% (10 years)$^{-1}$, in most areas, but as high as 10% (10 years)$^{-1}$ in some areas like the circular area in the Bohai Gulf during 1951–1998 (Fig. 4). An increasing trend in the daily-averaged precipitation intensity is found in most regions except for a slight decrease over a zone in the southwest of China (Fig. 5).

Precipitation intensity and the probability of heavy rainstorms were strengthened, thus the flood probability at the regional and basin-scale increased. Extreme flood probability increased in the arid northwest of China, where usually droughts dominate. On the other hand, drought disaster also threatens the south of China, the lower Yangtze River where floods are a problem. Flood and drought records over the past 50 years show that flood or drought areas have increased since the 1950s (Li, 2001), especially in the 1990s (Fig.6).

DISCUSSION AND CONCLUSIONS

The paper analyses the trends of precipitation amount, frequency and intensity in China, based on the daily precipitation data from 1951 to 1998 at 678 meteorological stations in China, the response of river runoff to climate change and the problems for water resources, based on the annual runoff data of four representative rivers, the Yangtze, the Yellow, the Zhujiang and Songhuajiang rivers, by using the linear regression methodology and significance tests. The results show that the annual precipitation has obvious regional patterns. A general rising trend of annual precipitation of 5–10 mm (10 years)$^{-1}$ appears at most stations in the west of China (bordered by longitude 103°E). The same increasing trend occurs in the southeast of China (on the lower reaches of the Yangtze River, Huaihe and Zhujiang river watersheds), 5–40 mm (10 years)$^{-1}$ (in some areas even as high as 120 mm (10 years)$^{-1}$), and in the west of northeast China, 5–10 mm (10 years)$^{-1}$. However, a decreasing trend appears in the middle part of eastern China of more than 5 mm (10 years)$^{-1}$ (in some areas, above 30 mm (10 years)$^{-1}$). The frequency (number

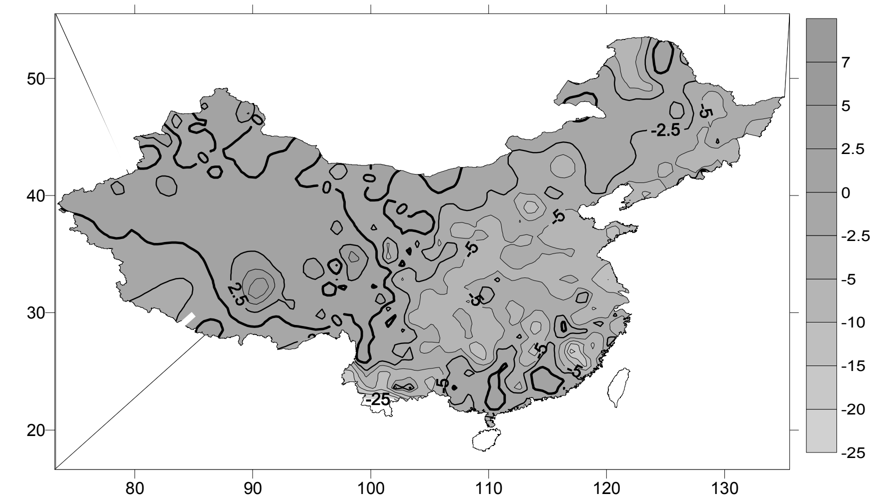

Fig. 4 Long-term trend of annual number of (measurable) precipitation days 1951–1998 (day (10 years)$^{-1}$).

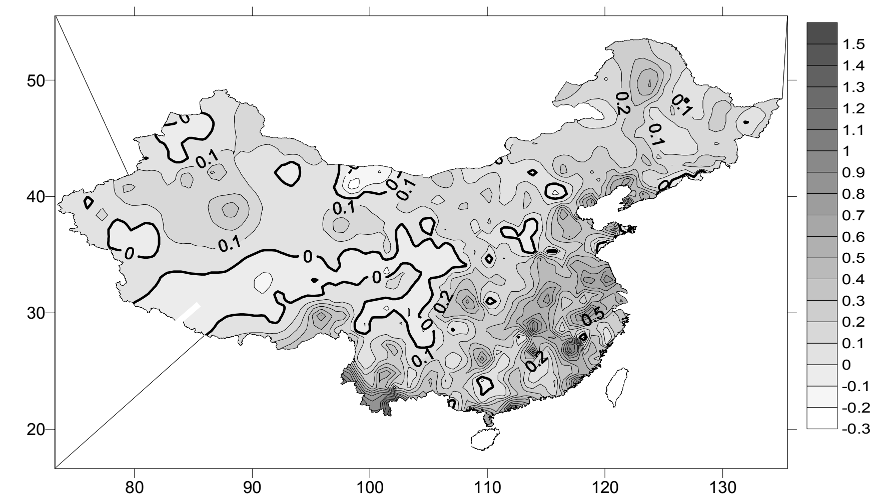

Fig. 5 Long-term trend of mean daily precipitation rate 1951–98 (mm day^{-1} (10 years)$^{-1}$).

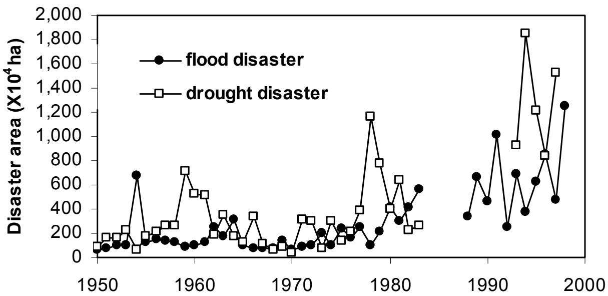

Fig. 6 The change of areas affected by flood and drought disaster 1950–1998.

of precipitation days) displays a marked decrease, 10 days (10 years)$^{-1}$ and particularly in the east. It was found that the relative trend of precipitation is usually less than 5% (10 years)$^{-1}$ in most areas, but reaches 15% (10 years)$^{-1}$ in the circular area along Bohai

Gulf. In most areas of western China the precipitation day is characterized by a positive trend of less than 7 days (10 years)$^{-1}$.

In addition to a slight decrease over a zonal area in the southwest of China, there is an increasing trend in the daily-averaged precipitation intensity, usually by less than 0.5 mm day^{-1} (10 years)$^{-1}$. A relative increase of less than 10% (10 years)$^{-1}$ is found in most regions.

On the one hand, such a climate change in China is probably a benefit as it eases the drought situation in northwestern China. It was found that river runoff in this region shows a marked increase. However, the increase in precipitation intensity may lead to a frequent occurrence of floods. On the other hand, the negative trend in precipitation brings disadvantageous effects to the semiarid middle part of eastern China and the rainy southeast of China, causing more droughts and more floods, respectively. The serious cut-off of flow during the 1990s in the Yellow River and the frequent big flood disasters during the recent 10 years in the Yangtze River and the Huaihe River watersheds are typical examples.

The spatial variation features of precipitation and discharge can be summarized as "more waterlogging in waterlogged areas and more droughts in drought areas". In the rainy areas, i.e. the middle and lower reaches of the Yangtze River and the Huaihe River watershed, the precipitation increased but the corresponding precipitation days decreased constantly over the last 50 years. This shows that the precipitation intensity and the probability of heavy rainstorms have been strengthened increasing the threat of heavy flooding of both the regional and the whole watershed. The big floods in the Yangtze River in 1998, and the Huaihe River watershed in 2003 are notable. However, the precipitation has decreased constantly over the past 50 years on the Yellow River, particularly in the amount, and there have been no floods since the last big flood in 1981. Furthermore, the cut-off on the middle and lower reaches in the 1990s caused by the continuous decrease in flow has become a serious ecological problem and aggravates the tensions caused by shortage of water resources.

The areas of both flood and drought disaster have increased in the Yangtze River watershed. With the decrease in the number of precipitation days in eastern China, the increase in precipitation intensity and thus the frequency of flood and drought disaster are strengthened. Flood and drought disasters may occur alternately in the same area.

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