Chinese Science Bulletin 2006 Vol. 51 No. 5 594—600

DOI: 10.1007/s11434-006-0594-6

River discharge changes in the Qinghai-Tibet Plateau

CAO Jianting[1, 2], QIN Dahe[3], KANG Ersi[4]
& LI Yuanyuan[2]

1. Laboratory for Climatic Studies, China Meteorological Administration, Beijing 100081, China;
2. General Institute for Water Resources and Hydropower Planning and Design, Ministry of Water Resources, Beijing 100011, China;
3. China Meteorological Administration, Beijing 100081, China;
4. Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

Correspondence should be addressed to Cao Jianting (email: caojianting@giwp.org.cn)

Abstract Annual mean discharge data of the five large rivers in the exorheic region of the Qinghai-Tibet Plateau from 1956 to 2000 are analyzed for trends with the Mann-Kendall nonparametric trend test. The results reveal that though in general no increasing trends exist in the total river discharges, significant regional differences of river discharge exist, reflecting the decreasing trends of discharge in the Yellow River and the Tongtian River (upper Changjiang River), an increasing trend in Yalong River, and inverted change in the Lancang River and Yarlung Zangbo River. Based on analyses of the seasonal discharge, it is found that climatic change had a significant effect on the seasonal variation of river discharge in the Qinghai-Tibet Plateau. In spring (from March to May) the discharge increased significantly, especially in the source area of the Yellow River. Together with the analyses on data of the mean temperature in the Northern Hemisphere and climatic data within the river basins, the relationship between discharges and mean temperature of the Northern Hemisphere is explored, which indicates that there is no increase in the stream discharge in the Qinghai-Tibet Plateau with global warming. It is probably the increasing evaporation, caused by rising temperature that offsets the hydrological effect of increasing precipitation.

Keywords: global warming, variation of river discharge, Mann-Kendall test, hydrological cycle, Qinghai-Tibet Plateau.

The Qinghai-Tibet Plateau is sensitive to global climate changes, and its mean warming amplitude during the past 50 years is greater than that of the Northern Hemisphere and other regions in the same latitude[1,2]. Due to its specific geomorphic conditions, the Qinghai-Tibet Plateau, in turn, exerts strong feedback on the global climate[3]. Many of the linkages between the Qinghai-Tibet Plateau and global climate involve the hydrologic cycle, including atmospheric moisture transport from lower to higher elevation region. The transport of moisture is predicted to increase with warming; both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature[4−6]. Under global warming, mainly in the middle and west region of northwest China, precipitation increases significantly. Some researchers even advanced the issues of climatic shift from warm-dry to warm-wet in northwest China[7]. Wang[8] revealed that the annual mean temperature in east China reached the peak in the past century, and precipitation also had a weakly increased trend. The mean annual precipitation during 1990s increased by 5 percent as compared with that during 1970s to 1990s.

Are the effects of global warming on the precipitation in the Qinghai-Tibet Plateau, which is located in middle-lower latitude, similar to the higher latitude or to other regions such as the northwest China? Global surface air temperature had increased by 0.6°±0.2℃ over the past century[4]. Based on analysis of the instrument-measured climatic data of the Qinghai-Tibet Plateau, it was found that the surface air temperature generally rose from 1950s to 1990s except for a decreasing trend in the east edge of the plateau; the 1980s was a warming period and the mean annual temperature in the main part of the plateau, especially in Tibet and Qinghai, was higher than that of the 1950s, and the increasing extent was 0.1－0.3℃ per decade. During 1990s, most part of the Qinghai-Tibet Plateau was continually warming and the mean temperature increasing trend was accelerated[9,10]. Recent research indicated that the climate change in the Qinghai-Tibet Plateau was basically characterized by the rising temperature and increasing precipitation[11].

Under the background of global warming, do the effects of the mean global surface air temperature rise on the hydrological cycle detectable by hydrological data sets? River discharge is particularly useful for addressing this issue, because it provides an integrative measure of the continental water cycle (precipitation, evaporation, etc.). Research on discharge change in different places has been paid much attention to also for its importance in detecting the effect of climate change on water resources. Much research progress has been made in this field[12−17].

Together with the climate data within the basins of the large rivers in the Qinghai-Tibet Plateau, the analysis of the discharge change of large rivers is significant in revealing the effect of global warming on the hydrological cycle of the Qinghai-Tibet Plateau. As for China, many large rivers originate from the Qinghai-Tibet Plateau, the analysis of the change of the large rivers discharge in the plateau is also useful for the projection of water resource variation.

1 Data and methodology

The exorheic drainage in the Qinghai-Tibet Plateau covers 124.32×10^4 km^2, being about 50.3% of the whole plateau[1]. Five large rivers, namely the Tongtian River, the Yellow River, the Lancang River, the Yalong River and the Yarlung Zangbo River, were selected in the exorheic region for data reasons. Hydrological stations were chosen as near the source as possible, and at the same time the scale of river discharge was considered. The total control drainage area of the selected five stations is 483215 km^2, occupying 44.73% of the exorheic region area in the Qinghai-Tibet Plateau. The locations of rivers and hydrological stations are shown in Fig. 1, and the basic characteristics of hydrological stations are shown in Table 1.

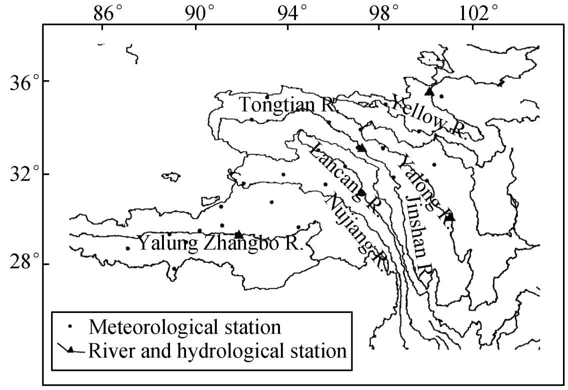

Fig. 1. Locations of the large rivers and concerned hydrometeorological stations in the Qinghai-Tibet Plateau.

Table 1 Characteristics of the hydrological station

Hydrological station	Location		River	Drainage (km^2)
	Long.	Lat.		
Zhimeida	97°14′	33°01′	Tontian	137704
Changdu	97°10′	31°08′	Lancang	50608
Tangneihei	100°09′	35°30′	Yellow	121972
Nugesha	91°52′	19°16′	Yarlung Zangbo	106060
Yajiang	101°01′	30°02′	Yalong	66871

As the hydrological stations are located in the source areas of the rivers, and water use by humans within every river basin is in relatively small quantity compared to the total discharge, the monitoring hydrological data reflect approximately the natural condition. The annual and seasonal discharge data and the meteorological data from 28 meteorological stations within or near the basins are used in this paper. The locations of the meteorological stations are also shown in Fig. 1.

The Mann- Kendall test, a nonparametric test, is an effective tool for analyzing change trend, and has been widely used to test trends in hydrology and climatology[18−20]. Chen and Xu[16] gave a reference of Mann-Kendall test in detail. The significance of trends has been analyzed on annual and seasonal bases with the nonparametric Mann-Kendall test for river discharge and for meteorological data in this paper.

2 The trends in discharge

2.1 The annual mean discharge

The trends of the total discharge of the five rivers and every river discharge over two periods were analyzed with the Mann-Kendall test. Z_c reflecting change trend was calculated, a positive value of Z_c indicates an ascending trend and a negative value indicates a descendant trend. The analysis results are shown in Table 2.

Table 2 Trends in mean annual discharge with the Mann-Kendall test

Discharge series	First year	Last year	Series length	Test Z_c	Significance
Total	1968	2000	33	0.11	
Lancang	1968	2000	33	0.79	
Tongtian	1956	2000	45	−0.01	
Yarlung Zangbo	1956	2000	45	−0.77	
Yellow	1956	2000	45	−0.30	
Yalong	1956	2000	45	0.47	
Total	1980	2000	21	−1.24	
Lancang	1980	2000	21	−0.45	
Tongtian	1980	2000	21	−1.84	a)
Yarlung Zangbo	1980	2000	21	1.24	
Yellow	1980	2000	21	−2.69	b)
Yalong	1980	2000	21	0.54	

a) Indicates 0.1 level of significance; b) indicates 0.05 level of significance; the blank indicates the significance level greater than 0.1.

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[1] Qinghai-Tibet Plateau Data Center, http://www.wdcd.ac.cn/.

It can be seen in Table 2 that the values of Z_c for total discharge series in either 1968—2000 or 1980—2000 are negative, which indicates a decreasing trend. The decrease of the Tongtian River and Yellow River discharge during 1980—2000 is a significant trend at 0.1 and 0.05 level respectively. The change trends of 33 years series and 21 years series for the Lancang River are different; the change trend of longer series from 1968 to 2000 is positive; and the trend of shorter series from 1980 to 2000 is negative. The discharge of the Yarlung Zangbo River has an increasing trend in shorter series and decreasing trend in longer series, which is opposite to that of the Lancang River which is located in the eastern part of the Qinghai-Tibet Plateau. The discharge series of the Yalong River in the far eastern part has an increasing trend over either 1968—2000 or 1980—2000 period.

Annual mean discharge change processes of the five rivers in the Qinghai-Tibet Plateau are also shown in Fig. 2. The series length of the Yellow River, the Tongtian River, the Yarlung Zangbo River and the Yalong River is from 1956 to 2000, while the series of the Lancang River from 1968 to 2000. The discharge trends of the Yalong River, the Lancang River and the Yarlung Zangbo River in southeast or south of the Qinghai-Tibet Plateau are observed in Fig. 2 with an increasing trend. The annual mean discharge of the Yalong River are observed with increasing trends, with the annual mean discharge increasing from 196.7×10^8 m^3 during 1970s to 214.1×10^8 m^3 during the 1990s, equaling 9%.

Generally the annual discharge of the Nugesha Hydrological Station in the Yarlung Zangbo River is observed with decreasing trend during the period from 1956 to 2000; the discharge anomaly is negatively 14% during the 1980s, but during the last 1990s, especially in 1998, 1999 and 2000, the discharge sharply increased and the anomaly is 50.7%.

In the Changdu Station of the Lancang River, the annual discharges fluctuate slightly. The discharge anomaly is 4% during 1980s compared with the mean discharge from 1968 to 2000. But the discharge increased in 1997, 1998 and 2000 respectively, and the three-year mean discharge anomaly reaches 15%. The discharge of the Zhimenda Station in the Tongtian River has no significant change trend. The mean discharges are observed at high stages during the 1960s and 1980s, and their anomalies are 9.5% and 18% respectively, but discharge decreased in 1990s with the anomaly −6%.

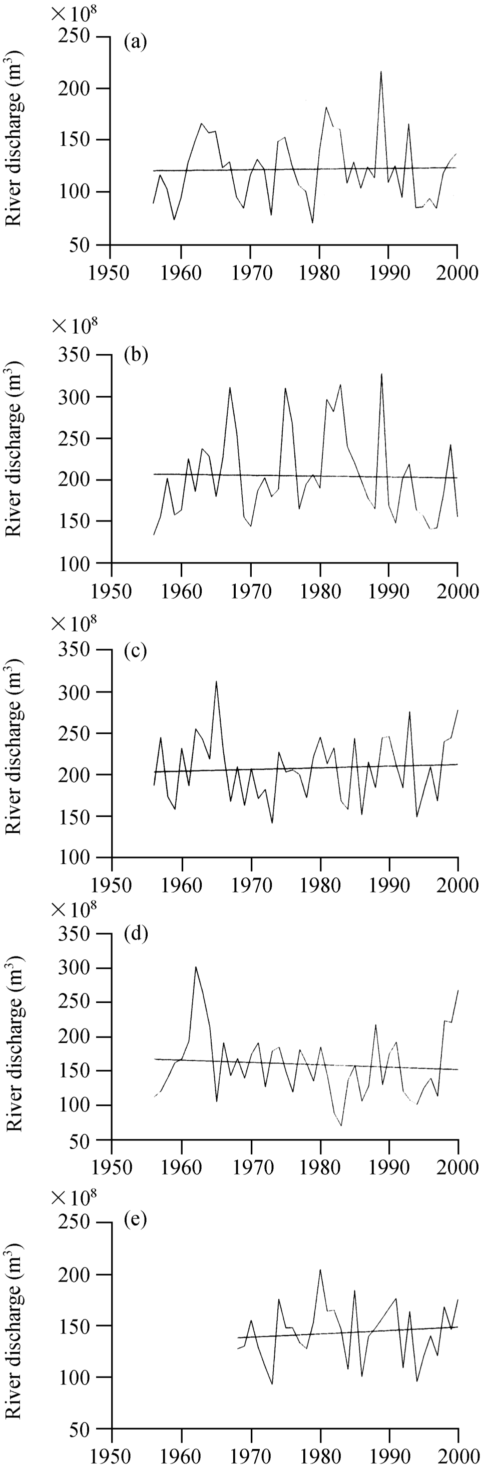

Fig. 2. Discharge variation process of the rivers in the Qinghai-Tibet Plateau. (a)—(e) are Tongtian River, Yellow River, Yalong River, Yarlung Zangbo River and Lancang River, respectively, and the line shows trend.

The discharge of the Tangnaihai Hydrological Station in the upper reach of the Yellow River are seen at relatively high stages during 1960s, 1970s and 1980s, with the anomalies 7.4%, 4.4% and 19.7% respectively; but the discharge of the Yellow River decreased greatly from $239.1\times10^8\,m^3$ in 1980s to $174.7\times10^8\,m^3$ in 1990s, and the annual mean discharge anomaly, compared with the mean value during 1956 to 2000, was –13% in the 1990s.

2.2 The seasonal discharge

Monthly discharge trends were analyzed by means of Mann-Kendall trends test and the results are shown in Table 3, of which the monthly series of the Lancang River is from 1968 to 2000, other rivers from 1956 to 2000.

Table 3 Z_c of Mann-Kendall trends test for the monthly discharge

Monthly series	Tongtian River	Yellow River	Yalong River	Lancang River	Yarlung Zangbo River
January	–0.49	–0.82	–0.01	–1.02	–2.46
February	–0.41	–0.37	0.27	–0.54	–2.46
March	0.61	–0.28	0.28	–1.38	–3.61
April	0.41	1.20	0.79	0.09	–4.31
May	1.38	0.92	1.94	1.41	–2.38
June	0.93	1.22	–0.90	0.37	–0.15
July	0.00	–0.34	1.27	0.34	0.01
August	–0.67	–0.30	–0.69	0.31	–1.12
September	–0.08	–0.83	–0.07	0.51	0.15
October	–0.67	–0.94	–0.55	0.36	–0.22
November	0.00	–0.86	0.01	1.19	–0.69
December	–0.25	–0.35	0.50	0.68	–1.24

As shown in Table 3, Z_c values of the Tongtian River, Yellow River and the Yalong River in the spring (from March to May) are positive, which indicates an increasing trend. Z_c value of the Yarlung Zangbo River in the spring is negative, reflecting a decreasing trend. It should especially be highlighted that the increasing trends of spring discharge for the Yellow River and the Tongtian River were in the context of their annual discharge decrease. In autumn and winter most of the Z_c values are negative except the Lancang River, which indicates the discharges of the rivers, except the Lancang River, have a decreasing trend.

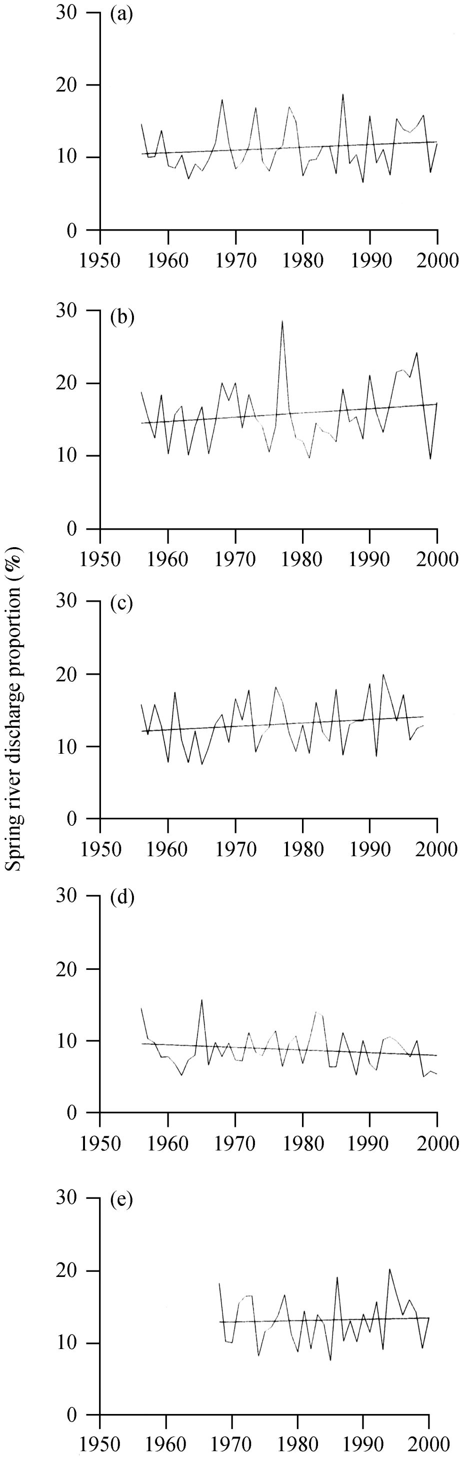

Fig. 3. Percentage of spring discharge vs that of the total year. (a)—(e) are Tongtian River, Yellow River, Yalong River, Yarlung Zangbo River and Lancang River respectively, and the line shows trend.

The proportions of the spring discharge to the total annual discharge for each river are also calculated to analyze the seasonal change of discharge. Only the spring discharge proportion during the past decades was expressed by Fig. 3 for concise reason. As seen in Fig. 3, the proportions of spring discharge to the annual discharge of the Tongtian River, the Yellow River, the Yalong River and the Lancang River have an increasing trend in spring, except that of the Yarlung Zangbo River with a decreasing trend. The increasing proportion of the Yellow River is the largest among the five rivers, during the period from 1956 to 1970, the annual mean proportion of spring discharge was 15.4%, and has increased to 18.2% during the 1990s.

The percentage of summer (from June to August) discharge in the five rivers *vs* the total annual discharge is more than 43% on average, which was almost steady during the last 45 years.

The percentages of discharge in autumn (from September to November) were different. In the Yellow River, the annual mean was 34% during the period from 1956 to 1970, and decreased to an annual mean 30% during 1990s. In the Yarlung Zangbo River, the percentage of discharge had an increasing trend, with an annual mean 31.8% during the period 1956—1970 and increased to annual mean 35.6% during 1990s. The percentages of the autumn discharges in other rivers changed slightly.

The percentages of winter (January, February and December) discharge *vs* the total year are very small in the five rivers, less than 10% on average, and the values changed slightly during the past 45 years (1956—2000). The winter discharges of four rivers show a very small decreasing trend, except the Yalong River in the east part with increasing trend.

2.3 Relation between discharge anomaly and mean Northern Hemisphere temperature

Climate change is an important factor influencing river discharge. Global warming is one of the most prominent problems in climatic change. Instrument record data of the past several decades in the Qinghai-Tibet Plateau indicate that the surface air temperature has an increasing trend and the increasing rate and amplitude are higher than that of global mean air temperature[9,10]. As the terrestrial area in the Northern Hemisphere is prominent over that of the Southern Hemisphere, the mean surface air temperature in the Northern Hemisphere is slightly higher than that of the globe. In this paper the relationship between river discharge anomaly in the Qinghai-Tibet Plateau and the mean Northern Hemisphere surface air temperature is analyzed, which can help to reveal the hydrological cycle response to global warming.

Based on the hydrological data of the selected gauging stations in the five rivers, the anomalies of the river discharge in the Qinghai-Tibet Plateau during 1956—2000 are calculated annually. Then the anomalies are compared with the mean temperature of the Northern Hemisphere in each corresponding year[1] (Fig. 4). The trend line, the linear regression of the discharge anomaly and temperature, indicates that the discharge anomaly in the Qinghai-Tibet Plateau has nearly no change, namely river discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the North Hemisphere surface air temperature.

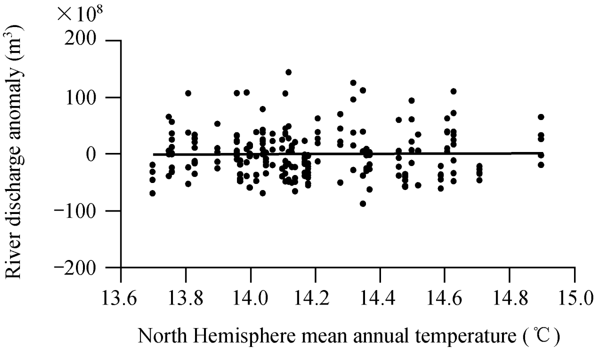

Fig. 4. Annual discharge of rivers in the Qinghai-Tibet Plateau vs the North Hemisphere mean surface air temperature.

3 Analysis on the climate data within the basins

In order to detect the reason of the river discharge change, climatic data concerning the river watershed are analyzed. Climatic data from 28 meteorological stations within or near the basins indicate that annual temperature increased during the past several decades. The mean annual air temperatures of all stations have increasing trends, among which 24 meteorological stations increase with a significance level less than 0.1. During the past 40 years the temperature of Naqu Meteorological Station increased especial prominence. The mean annual air temperature increased from –2.4℃ during 1960s to –0.81℃ during the 1990s. During the past 21 years (1980—2000) the temperature of Lhasa increased by 0.062℃ annually.

The trends of precipitation are analyzed with the Mann-Kendall test and the results are shown in Table 4. There are 24 meteorological stations that have increasing precipitation among which four stations have a 0.05 level of significance. The mean annual precipitations of Garzê Station, one of the four meteorological stations, were 598 mm, 656 mm, 652 mm and 670 mm during the 1960s, 1970s, 1980s and 1990s respectively. There were 7 stations with a weak decreasing trend of precipitation. In general, the precipitation in the Qinghai-

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[1] Temperature data from Goddard Institute for Space Studies, http://www.giss.nasa.gov/data/.

Table 4 Results of Mann-Kendall test for precipitation data

Meteorological Station	Location		First year	Last year	Series length	Test Z_c	Significance
	Long.	Lat.					
Dari	99.65°	33.75°	1956	2000	45	0.42	
Changdu	97.17°	31.15°	1956	2000	45	1.17	
Dingqing	95.60°	31.42°	1960	2000	41	0.33	
Dege	98.56°	31.73°	1957	2000	44	1.00	
Dangxiong	91.10°	30.48°	1962	2000	38	–0.16	
Garzê	100.00°	31.61°	1956	2000	45	2.27	a)
Jiali	93.28°	30.66°	1961	2000	40	1.29	
Jiangzi	89.60°	28.91°	1957	2000	44	0.05	
Lhasa	91.13°	29.66°	1956	2000	45	0.50	
Linzhi	94.46°	29.56°	1960	2000	41	2.52	a)
Dingri	87.08°	28.63°	1971	2000	30	0.50	
Nangqian	96.48°	32.20°	1959	2000	42	0.83	
Nimu	90.17°	29.43°	1974	2000	27	1.58	
Pali	89.08°	27.73°	1957	2000	44	2.30	a)
Maduo	98.22°	34.91°	1956	2000	45	1.63	
Naqu	92.07°	31.48°	1956	2000	45	2.34	a)
Rikaze	88.88°	29.25°	1956	2000	45	0.60	
Seda	100.33°	32.28°	1961	2000	40	1.41	
Shiqu	98.10°	32.98°	1961	2000	40	–0.07	
Suoxian	93.78°	31.88°	1957	2000	44	–0.01	
Qingshuihe	97.13°	33.80°	1957	2000	44	–0.68	
Qumalai	95.78°	34.13°	1957	2000	44	0.11	
Wudaoliang	93.08°	35.22°	1957	2000	44	1.12	
Yushu	97.02°	33.02°	1956	2000	45	0.06	
Zaduo	95.30°	32.90°	1957	2000	44	1.45	
Zedang	91.76°	29.25°	1960	2000	41	–0.39	
Tongde	100.65°	35.27°	1959	2000	41	–0.17	
Tuotuohe	92.43°	34.22°	1959	2000	42	–0.35	

a) indicates 0.05 level of significance; the blank indicates the significance level greater than 0.1.

Tibet Plateau is increasing from 1956 to 2000, but the increasing trend was not as significant as that of surface air temperature, which is in accordance with the recent research result[11].

The precipitations data in March, April and May are also analyzed. There are 21 meteorological stations with increasing trend of precipitation, among which 17 stations, for at least one month, have a precipitation increasing trend at 0.1 levels. In general, precipitations in winter also have an increasing trend during the period 1956—2000, but the increase quantity is very limited, because the precipitation during the winter is very small.

4 Discussion and conclusions

In general, river discharge tends to increase with precipitation increasing and decrease with precipitation decreasing over the past few years. Variations in discharge from year to year have been found to be much more strongly related to precipitation changes than to temperature changes[21−23]. There are some more subtle patterns, however. In large parts of eastern Europe, central Canada, and California, a major shift in discharge from spring to winter has been associated not only with a change in precipitation totals but more particularly with a rise in temperature: Precipitation has fallen as rain, rather than snow, and therefore has reached rivers more rapidly than before[24,25]. The information of the discharge trends of the five large rivers in the Qinghai-Tibet Plateau had a weak decreasing trend, especially the discharge of the Yellow River and the Tongtian River, perhaps this reflects that the air temperature rising may have much more influence than that of precipitation of the river basin.

Regional differences in river discharge change in the Qinghai-Tibet Plateau probably reflect different effects of climatic change. The discharge change pattern shows the increases in the Yalong River in southeast of the Qinghai-Tibet Plateau, and slight decrease in the Tongtian River, Yellow River in the northern part, and adverse changes in the Lancang River in southeastern part and the Yarlung Zangbo River in southwestern part. The increasing discharges in southeast rivers in the Qinghai-Tibet Plateau probably are the result of the speeding up of hydrological cycling because of global warming. If the assumption, that the southeast region of the Qinghai-Tibet Plateau is a climatic change startup region is correct [26], it may be suggested that the discharge in other regions of the Qinghai-Tibet Plateau will increase in the near future.

As a whole, during the past several decades, the spring discharges in the rivers of the Qinghai-Tibet Plateau increased in the selected rivers, especially in the upper reaches of the Yellow River, which coincides with increasing spring precipitation and the early ice-melt. Although the precipitation increased weakly in winter, the discharge in winter still decreased during the past decades because precipitation continued to fall as snow in winter and the increased temperature strengthened the evaporation.

The trend line of the relationship between the discharge anomaly and the Northern Hemisphere temperature variability shows that the anomaly does not change much with the mean temperature in the Northern Hemisphere rising. The result is neither in accordance with the anticipated ideas, which supposes that river discharge increases significantly by increasing ice melting caused by the temperature rising, nor like other regions where the extreme precipitation events happen frequently resulting in the greatly increasing discharge[27]. The reason that the discharge of rivers in the Qinghai-Tibet Plateau has no significant increasing trend probably lies in two aspects. One is discharge replenished from glacier melt occupying very little proportion in the total discharge, for example, the proportion of glacier melt water only occupied 1.9% of the discharge in the upper reach of Yellow River[28]. The other is the increasing evaporation resulting from the rising temperature offsetting the hydrological effect of the increasing precipitation.

Acknowledgements The authors would like to thank the anonymous reviewers for their helpful opinion. This work was supported by the Special Foundation for Climatic Change Study, China Meteorological Administration.

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(Received June 10, 2005; accepted July 29, 2005)