**Magnitude, frequency and timing of floods in the Tarim River basin,
China: changes, causes and implications**

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**Magnitude, frequency and timing of floods in the Tarim River
basin-a high altitude basin in China: changes, causes and
implications**

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Abstract: The flood magnitude, frequency and timing were analyzed using daily
flow data for a period of 1950-2007 from 8 stations in the Tarim River basin, a
typical arid inland river basin in China. The causes for flood occurrences were
investigated using daily meteorological data. Results indicated that precipitation and
temperature were increasing persistently since the 1980s and significant increases in

precipitation and temperature were observed after the 1990s. As a result, floods amplified at annual and seasonal time scales in most tributary basins after the 1980s. The floods in the basin are mainly attributed to rainstorms and melting of glaciers and snowpack, and rainstorm-induced floods and temperature-induced floods were dominant in the basin. Extreme floods, such as the three largest recorded floods and floods with return periods > 10 years occurred mainly after the 1990s, with significant increase in flood-induced crop and livestock losses. It was found that heavy floods in many tributary basins often occurred about the same time. The Tarim River basin is a typical arid inland river basin in a high altitude zone and amplifying floods in recent decades, particularly after 1990s, is arousing considerable concern for mitigation of flood hazards. Results of this study shed light on hydrological response of arid regions to warming climate at higher latitudes in the northern hemisphere.

Key words: Heavy floods; Flooding magnitude and frequency; Trends; Abrupt behaviors; Tarim River basin

1. Introduction

The global mean surface temperature change for the period 2016-2035 in comparison to 1986-2005 will likely be in the range of $0.3-0.7^{\circ}\text{C}$ (IPCC, 2013). The warming climate has the potential to accelerate the hydrological cycle at global and continental scales (Alan et al., 2003; Zhang et al., 2013a). Observed variations in extreme weather

1 and climate events since 1950s suggest increased risks of floods and droughts because
2 of more extreme precipitation, lengthening dry span, higher peak flows, and increased
3 intensity of most extreme tropical cyclones (Mirza, 2002; Zhang et al., 2013b; IPCC,
4 2013; World Bank, 2013; Apurv et al., 2015). Climatic extremes are one of the crucial
5 drivers of meteorological and hydrological hazards, such as floods and droughts (Li et
6 al., 2015). Hence, changes in climatic extremes, especially precipitation extremes,
7 may alter the occurrence, duration, and intensity of floods and droughts (e.g. Mirza,
8 2002; Zhang et al., 2012). Climate models suggest that extreme precipitation events
9 will become more common (Allan and Soden, 2008). In recent years increasing losses
10 due to catastrophic natural hazards have aroused public awareness of extreme events
11 (e.g. Beniston and Stephenson, 2004; Zolina et al., 2004).

12 Studies show that moist regions are becoming wetter and dry regions drier (e.g.
13 Chou et al., 2007; Zhang et al., 2007). However, different regional changes in
14 precipitation or floods due to warming climate have been observed over the globe.
15 Sillmann et al. (2013) used the Coupled Model Intercomparison Project Phase 5
16 (CMIP5) multimodel ensembles to analyze changes in extreme precipitation indices
17 over the 21st century for the period of 1981-2000, and found that extreme precipitation
18 generally increased in most regions, except for Australia, Central America, South
19 Africa and the Mediterranean region. Using an atmospheric Global Circulation Model
20 (GCM) under enhanced greenhouse conditions, Kothavala (1997) concluded that
21 more wet and dry spells would occur and the frequency of extreme precipitation
22 would increase in the Midwest United States. Analyzing precipitation extremes under

1 A2 scenario by six European Regional Climate Models (RCMs), Frei et al. (2006)
2 indicated that winter precipitation extremes would increase in north to about 45°N,
3 and decrease or change insignificantly in south. Besides, the lengthening of
4 consecutive wet events was observed in Europe (Zolina et al., 2010), but the
5 lengthening of maximum consecutive wet days was not evident in China (Zhang et al.,
6 2011).

7 Xinjiang is a typical arid region and the Tarim River basin therein is the largest
8 arid inland river basin in China. The source of water in the basin is mainly
9 glacial/snow melt which accounts for 48.2% of the total water volume (Chen et al.,
10 2007). About 10 million people, including ethnic minorities-Uyghurs and Mongolians
11 live in the basin. More than 8 million people live in oases along the river banks and in
12 alluvial plains downstream (Zhang et al., 2010). The basin is characterized by low
13 precipitation and high evaporation (Zhang et al., 2010; Sun et al., 2012). In lowlands,
14 the river is the most important source of water. Due to its exceptional and unique role
15 in the economic development, the Chinese government launched a five-year
16 emergency water diversion program in 2000 with 10.7 billion yuan (US\$1.3 billion)
17 earmarked for reclamation of the river and Taitema Lake (Tao et al., 2008). However,
18 recent studies indicate that the number of heavy rainfall events and the frequency of
19 rainstorm flood disasters have been on the rise since the 1980s, and the increasing
20 trend in flood disasters in Xinjiang since the mid-1980s can be attributed to the
21 increasing trend in annual precipitation (Jiang et al., 2005). Observations further
22 indicate that glacier melt-induced floods in the basin have been increasing in recent

years (e.g. Zhang et al., 1992).

Agriculture in the Tarim River basin is dependent on irrigation and is vulnerable to hydrologic extremes in the headwaters, such as floods and droughts (e.g. Zhang et al., 1992; Jiang et al., 2005). Therefore, an investigation of flood magnitude, frequency and timing is critically important in the sustainable development of irrigated agriculture and the assessment of variability and availability of water resources. The objectives of this study therefore are to: (1) analyze characteristics and trends of floods defined by 9 flood indices; (2) investigate return periods of floods and related temporal variations; and (3) analyze precipitation and temperature changes with the aim to understand possible causes for the changing properties of rainstorm floods, glacier floods, and so on. Results of this study would shed new light on the changing properties of floods in both space and time in a typical arid region, such as the Tarim River basin.

2. Data

Daily streamflow and meteorological data from 8 hydrological stations (Fig. 1) were analyzed and information on the meteorological and hydrological data is given in Table 1. Data were provided by the Hydraulics Bureau of the Tarim River basin, China. The quality of data is firmly controlled before its release and the missing data were processed based on the method by Zhang et al. (Zhang et al., 2011). Meteorological data from the stations near the hydrological stations were analyzed to investigate causes of changes in the flood regime. Data on rainstorm-induced floods

(RainF), temperature-induced floods (TempF), and dam bursting-induced floods (DamF) and related flood-induced economic and life losses were collected from Shi and Wen (2006).

3. Methodology

3.1 Flood indices

Table 2 shows 9 indices reflecting changes in flood magnitude, frequency and timing at annual and seasonal time scales. The streamflow in the Tarim River is mainly from melting glacial/snow after March. At the same time, the daily discharge begins to increase with simultaneous occurrence of floods. In addition, seasonal floods were also analyzed including spring flood from March to May and winter floods from December to February of the next year. Annual maximum flood is in accordance with the seasonal maximum flood in time scale, which benefits direct analysis and comparison between annual maximum flood and seasonal flood at the same time scale. Therefore, the hydrological year in this study was from March to February of the next year. Annual and seasonal maximum flood series (AMF, AMFSp, AMFSu, AMFAu and AMFWi, Table 2) and Days of annual maximum flood (AMFD, Table 2) were obtained from the daily flow series to show magnitude and timing of floods (Wilson et al., 2010; Mediero et al., 2014). However, the AMF series can only be used to identify the largest flood during a hydrological year without information of the other large floods. The annual maximum flood series was subject to the limitation of excluding information on floods with magnitudes lower

than the annual maximum floods. POT series greatly overcome this drawback by accounting for all the floods that exceed a given threshold regardless of the time when they occurred (Mediero et al., 2014). In this study, the peaks-over-threshold (POT) sampling method was adopted to compensate for the annual maximum flood series. Combined with maximum sampling and POT sampling, these 9 widely-used flood indices were chosen to analyze characteristics of floods. The independence of flood peak was evaluated by (Lang et al., 1999):

$$\begin{cases} D > 5 + \log(A) \\ Q_{\min} < \frac{3}{4} \min(Q_1, Q_2) \end{cases} \quad (1)$$

where D denotes the waiting time between two flood peaks; A denotes the drainage area in km^2 ; and Q_1 and Q_2 denote the magnitudes of two flood peaks, respectively, in m^3/s .

The Mean Exceedance above Threshold (MET) technique and Dispersion Index (DI) method were used to determine the range of threshold values. These two methods, together with the mean number of over-threshold flood events (MnT), were used to define the threshold value which satisfied the condition that the mean number of flood events ranged between 2.4-3 (Lang et al., 1999). The choice of the threshold value should satisfy the following three conditions: (1) MET should be in a linear relationship with threshold values; (2) In addition, DI with corresponding thresholds should be at a confidence interval (for example 95% confidence interval in this paper) making POT series follow the Poisson distribution; (3) MnT has a number ranging between 2.4 and 3 with corresponding thresholds. The biggest

1 threshold value which satisfies those three aforementioned conditions was accepted
2 as the right threshold value.

3 The mean day of flood was used to describe the timing of flood events based on
4 the POT sampling technique (Macdonald et al., 2010) as:

$$5 \quad \theta_i = WD \frac{2\pi}{LENYR} \quad 0 \leq \theta_i \leq 2\pi \quad (2)$$

6 where WD is the timing of flood, and LENYR is the number of days of one
7 year (365 days or 366 days). The flood timing every year, based on the POT
8 sampling technique, was transferred to the angle vector, θ_i , and MDF was
9 computed by:

$$10 \quad \begin{cases} \bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}} \right) \\ MDF = \bar{\theta} \frac{LENYR}{2\pi} \end{cases} \quad (3)$$

11 where:

$$12 \quad \begin{cases} \bar{x} = \frac{1}{N} \sum_{i=1}^N \cos(\theta_i) \\ \bar{y} = \frac{1}{N} \sum_{i=1}^N \sin(\theta_i) \end{cases} \quad (4)$$

13

14 3.2 Meteorological variables

15 There were altogether 8 hydrological stations in the Tarim River basin and the
16 hydrological processes measured by these stations are free of human interference.
17 The causes for flood changes were investigated by analyzing meteorological
18 variables. Generally, floods in Xinjiang are subject to three types:
19 rainstorm-induced floods, temperature-induced floods, and dam bursting-induced

floods (Shi and Wen, 2006). To fully reflect the impact of climate change on flood occurrences, 21 meteorological and precipitation indices were analyzed (Table 3). Meteorological variables were standardized to reflect precipitation and temperature changes:

$$CI_{norm} = \frac{CI_i - Mean(CI)}{Sd(CI)} \quad (5)$$

where CI_i is the climate index in the i th year, $Mean(CI)$ is the mean value of the climate index and $Sd(CI)$ denotes standard deviation of the climate index. $CI_{norm} < 0$ denotes that the climate index is lower than the mean value and is decreasing, and vice versa.

3.3 Trends and abrupt behavior of floods

Trends were tested by non-parametric trend detection methods which are less sensitive to outliers than are parametric statistics. The rank-based nonparametric Mann-Kendall test (MK) (Mann, 1945; Kendall, 1975; Jhajharia et al., 2014) is able to test trends without requiring normality or linearity. However, the results of the M-K test are affected by serial correlation. Hamed and Rao (1998) proposed a modified MK (MMK) test based on effective or Equivalent Sample Size (ESS) to eliminate the effect of autocorrelation (Dinpashoh et al., 2014). Actually, MMK has been used in analyzing the effect of global warming on small aquatic ecosystems (Daufresne et al., 2009). In this study MMK was employed to explore trends in flood series, with the significance level set at 5%. For details on the computation procedure one can refer to Daufresne et al. (2009). In order to analyze trends in floods in different periods, moving MMK trends were determined with a time

1 window of 21 years.

2 Detection of change points can be done based on parametric or nonparametric
3 methods. Each method has its own advantages and disadvantages in the detection of
4 change points (Zhang et al., 2014) and more than one method is often used for the
5 identification of change points. Killick and Eckley (2014) developed the R package,
6 changepoint, which involves a single change point detection method, AMOC, based
7 on the likelihood function. This method can be free of limitations arising from the
8 assumption of normality and can extend to the detection of multiple change points.
9 Erdman and Emerson (2007) developed the bcp R software package, introducing the
10 Bayesian analysis of change points that has the advantage of showing the probability
11 of the change point detected. This study used these two methods for identifying
12 change points and the reasonableness of these points was evaluated in order to avoid
13 subjectivity and uncertainty in the results (Zhang et al., 2014).

14

15 **4. Results**

16 4.1 Decision of POT-based sampling threshold

17 Fig. 2 illustrates the threshold values for the POT-based flood series at 8
18 hydrological stations in the basin. The changes of MnT and related threshold curves,
19 MET and related threshold curves, and DI and its threshold curves are shown in Fig.
20 2. Taking Tongguzlok as an example (Fig. 2a), when the threshold values ranged
21 between 200-300 m³/s as shown by MnT and its threshold curves, MnT ranged
22 between 2.4-3. Meanwhile MET increased with the decrease in the threshold values,

and linear relations were clearly observed. Based on DI and its threshold values, when the threshold value was $292 \text{ m}^3/\text{s}$, the DI ranged within the 95% confidence interval, in other words POT series followed the Poisson distribution. The threshold value of the flood series at the Tongguzlok should be $292 \text{ m}^3/\text{s}$. Based on the same evaluation procedure, the threshold values of the Yuzimenleke, Kaqung, Sharikilank, Xehera, Huangshuigou, Dashankou and Alar stations were $137 \text{ m}^3/\text{s}$, $659 \text{ m}^3/\text{s}$, $330.5 \text{ m}^3/\text{s}$, $290 \text{ m}^3/\text{s}$, $40.5 \text{ m}^3/\text{s}$, $225.65 \text{ m}^3/\text{s}$ and $534.5 \text{ m}^3/\text{s}$, respectively (Figs. 2b-2h).

4.2 Trends and abrupt behavior of floods

Trends and abrupt behavior of floods are shown in Fig. 3. The flood indices mentioned in Fig. 3 are given in Table 2. It can be seen from Fig. 3 that AMF exhibited an increasing trend and significant trends of floods were observed at the Huangshuigou and Dashankou stations in the Kaidu River basin and Xehera station in the Aksu River basin. Abrupt changes of AMF were identified in the mid- and late-1980s and till the early 1990s, e.g. the change point of flood series at the Xehera station in the Aksu River basin occurred in 1980. The day of AMF (AMFD) was delayed at the Tongguzlok, Yuzimenleke, and Dashankou stations. These stations are located in the southwest and southeast corners of the Tarim River basin (Fig. 1), and the delay of AMFD at the Dashankou station in the Kaidu River basin was statistically significant. AMFD at other stations was decreasing, implying earlier AMFD. Spring temperature in the basin was increasing and hence the increased frequency of temperature-induced floods as a result glacier and snowpack melting.

1 Thus, spring floods at the Kaqung, Sharikilank, Xehera stations had significant
2 increasing trends with change points during about the 1980s (AMFSp in Fig. 3).
3 Summer is the flooding season in the Tarim River with a higher probability of
4 rainstorms. Therefore, rainstorm-induced floods usually occur during summer season
5 with larger magnitudes, and so flood peak values were usually observed during
6 summer. It was seen that the changes in AMF and AMFSu similar to changes in
7 trends and abrupt variations. Besides, AMFAu at the Yuzimenleke station in the
8 Yarkant River basin, the Sharikilank station in the Aksu River basin, and the
9 Dashankou station in the Kaidu River basin had significant increasing trends with
10 changes points in 2000, 1997, and 1987, respectively (AMFAu in Fig. 3).

11 In winter, however, the glacier-lake bursting was usually the main cause for the
12 occurrence of flash floods, i.e, dam bursting-induced floods in this study, and such
13 floods were observed mainly in the Yarkant River basin. It can be observed from
14 AMFWi in Fig. 3 that AMFWi at the Yuzimenleke and Kaqung stations in the
15 Yarkant River basin, and at the Dashankou station in the Kaidu River basin had
16 significant increasing trends with change points in 1971, 1986 and 1993, respectively,
17 implying intensifying floods in these basins. Nevertheless, AMFWi at the Alar
18 station on the Tarim River had significant decreasing trends with the change point in
19 1996. It can be seen from Fig. 1 that the arable land is large and irrigation activities
20 are intensive (e.g. Zhang 2012). There is also a large water reservoir upstream of the
21 Alar station whose storage effects greatly reduce streamflow to the lower Tarim
22 River basin. These two factors combine to cause a significant decrease in AMFWi.

1 For the POT-based flood series, POT3M was increasing at most of the
2 hydrological stations, except for the Tongguzlok and Kaqung stations. The change
3 point of POT3M at the Huangshuigou station in the Kaidu River basin was observed
4 in 1993 (POT3M in Fig. 3). POT3F at the Tongguzlok, Xehera, and Alar stations
5 was decreasing and significant decreasing trend of POT3F was found at the Xehera
6 station with the change point in 1998. Other stations were characterized by
7 increasing POT3F and significant increasing POT3F was observed at the Sharikilank
8 and Huangshuigou stations with change points in 1963 and 1995, respectively
9 (POT3F in Fig. 3). Changes in MDF were not statistically significant. In comparison
10 with AMFD, MDF and POT3M were occurring earlier at the Xehera station but the
11 contrary was at the Dashankou station (MDF in Fig. 3).

12 Flood variations posterior to the change point when compared to those prior to
13 the change point were analyzed to show relative changes in floods posterior to the
14 change point except MDF (Fig. 4). Generally, most flood indices were increasing at
15 most of the hydrological stations except AMFD, implying that the timing of AMF
16 was earlier. Specifically, AMF in spring, autumn and winter at the Tongguzlok
17 station posterior to the change point was 54%, 31% and 37% larger than that prior to
18 the change point and other flood indices had no evident changes. All the flood
19 indices at the Yuzimenleke station were increasing after the change point with
20 increasing magnitude. Particularly evident was the increase in the changes of
21 seasonal and annual flood indices and also frequency of floods with increases of
22 36%, 55%, 36%, 57%, 34% and 61%. The autumn peak flood flow at the Kaqung

1 station decreased 29% and other flood indices had increasing tendency. Besides, a
2 significant increase was found in AMSp, POT3M and POT3F with increases of 26%,
3 63% and 42%, respectively. A decrease of AMFD was identified at the Sharikilank
4 station and the other flood indices had increasing tendency. Specifically, the increase
5 of AMF, AMFSp, AMFSu, AMFAu, AMFWi and POT3F was, respectively, 48%,
6 63%, 45%, 53%, 106% and 177%. The increasing magnitude of peak flood flow at
7 the Xehera station during spring and winter seasons was larger posterior to the
8 change point than that at other hydrological stations and the increasing magnitude
9 reached 71% and 149% in spring and winter, respectively. At the Huangshuigou and
10 Dashankou stations in the Kaidu River basin, almost all the flood indices were
11 increasing after change points when compared those before change points.
12 Specifically, increases in AMF, AMFSu, AMFAu, POT3M and POT3F were found at
13 the Huangshuigou station with increasing magnitudes of 100%, 100%, 90%, 42%
14 and 62%, respectively. However, the largest increase in flood flow was observed at
15 the Dashankou station during autumn and winter seasons with increasing magnitudes
16 of 55% and 109%, respectively. Besides, the delay in the occurrence of flood flow
17 was substantially evident after the change point as compared to that before the
18 change point at the Dashankou station when compared to other 7 hydrological
19 stations analyzed. The peak flood flow behavior at the Alar station was different
20 when compared to the peak flood flow at other stations, i.e. the peak flood flow at
21 the Alar station was decreasing with a decreasing magnitude of 38%.

4.3 Temporal changes in flood index anomalies

Temporal variations of 8 flood indices, i.e. AMFD, AMF, AMFSp, AMFSu, AMFAu, AMFWi and POT3F, are illustrated in Fig. 5. It can be seen from Fig. 5 that AMF at almost all hydrological stations was at a higher level after the mid- and late-1990s, implying an amplification of floods after the 1990s within the Tarim River basin. The amplification of floods after the 1990s was observed mainly at the Yuzimenleke, Sharikilank, Huangshuigou, Dashankou stations. Comparatively, all flood indices were lower than their average during the mid-1970s and late 1980s, indicating a reduction of flood events. Generally, except for the time interval after the 1990s, the time intervals before the 1990s were dominated by the intermittent occurrence of floods defined by flood indices.

Different time intervals were dominated by different changes in flood magnitude and frequency: high-frequency flood period and low-frequency flood period. The moving modified Mann-Kendal trends were analyzed with a time window of 21 years to test the significance of different flood levels and the duration of different flood periods or non-flood periods (Fig. 6). Specifically, the peak flood flow in autumn and winter at the Tongguzlok station increased from 1962-1972 to 1972-1992. However, annual, spring and summer floods decreased from 1967-1987 to 1978-1998. It should be noted here that floods in winter at the Tongguzlok station increased abruptly after 1975 (TG in Fig. 6). Increasing flood indices after 1975 were also observed at the Sharikilank and Huangshuigou stations and this increasing tendency was relatively steady (HS and SL in Fig. 6). Besides, persistently

1 increasing flood indices were also detected at the Xehera and Dashankou stations
2 and the difference was that the starting time of the increase of flood indices at
3 Xehera and Dashankou stations was 1972 (XH and DS in Fig. 6). The starting time
4 for the increase of flood indices at Yuzimenleke and Kaqung stations was,
5 respectively, 1982 and 1983. Floods at the Alar station did not exhibit changing
6 patterns without an increasing or a decreasing tendency (AL in Fig. 6). The different
7 flood behavior was attributed to different influences of climate change and human
8 activities.

10 4.4 Variation of flood magnitude and frequency

11 Floods were usually larger than normal floods from the standpoint of
12 flood-induced losses and flood-affected areas. Investigation of temporal variations of
13 heavy floods is of considerable merit for evacuation. Fig. 7 illustrates the
14 spatiotemporal variation of ten-year floods, HQ10, and the 3 heaviest recorded
15 floods, top 3 events, at annual and seasonal time scales. It can be observed from Fig.
16 7 that the top 3 events at the Tongguzlok station were observed mainly during
17 1969-1978. After 2000, large occurrences of 10-year floods and top 3 events were
18 observed at the Tongguzlok station in winter (TG in Fig. 7), implying that winter
19 floods tended to be intensifying and this phenomenon should of considerable
20 concern. At the Yuzimenleke station, 10-year floods and top 3 events were observed
21 mainly during two time intervals, i.e. 1972-1983 and after 1992. In particular, recent
22 decades were witnessed amplification of floods, as reflected by occurrences of top 3

1 events and 10-year floods in summer, and after 2002 amplification of floods was
2 observed in winter (YZ in Fig. 7). No confirmed patterns of extreme floods, top 3
3 events and 10-year floods were detected before 1992 at the Kaqung and Xehera
4 stations. After 1992, however, top 3 events and 10-year floods burst in every season.
5 Floods behaved differently at the Sharikilank, Huangshuigou and Dashankou
6 stations when compared to those at the Kaqung and Xehela stations. Extreme floods
7 were rare before 1987 and the occurrence of extreme floods was frequent after 1987
8 at the Sharikilank, Huangshuigou and Dashankou stations (Fig. 7) and it was
9 particularly the case after 1993, implying sharply increasing flood risk at these three
10 hydrological stations. Besides, distinctly different flooding behavior was found at the
11 Alar station when compared to other stations. The top 3 events and 10-year floods
12 occurred persistently even in periods without any evident changing patterns (AL in
13 Fig. 7).

14 Interestingly the top 3 events usually occurred in a clustering way, e.g. intensive
15 occurrence of top 3 events at the Tongguzlok station during 1969-1978 (Fig. 7).
16 Even more interesting is the phenomenon that extreme floods often occurred
17 simultaneously at all hydrological stations in the Tarim River basin. In other words,
18 extreme floods in the basin were most likely to occur in a clustering way in both
19 space and time. An example is the occurrence of top 3 events in 1999 at 7
20 hydrological stations, except Tongguzlok station. This kind of occurrence of extreme
21 floods in 1999 was attributed to abnormal climate conditions. July 13-30, 1999,
22 witnessed abnormally higher temperature which triggered an intensive melting of

1 glaciers and snowpack. Meanwhile, rainstorm occurred in most mountainous regions.
2 These factors combined to trigger the occurrence of floods. Extreme floods occurred
3 with the recorded largest flood volumes in 25 river basins in Xinjiang, including
4 Aksu and Kaidu River basins (Shi and Wen, 2006).

5 Three types of floods, i.e. rainstorm-induced floods, temperature-induced floods
6 and dam bursting-induced floods, due to three influencing factors, such as rainstorm,
7 increasing temperature and burst of dams or glacier lakes, during 1950-2000 were
8 analyzed (Fig. 8) and temporal variations of flood-induced losses and related flood
9 types that caused these losses were investigated (Fig. 8). Altogether 5 administrative
10 regions were analyzed, i.e. Aksu state, Kezhou state, Kashi state, Hotan state and
11 Bazhou state (Fig. 8). It can be seen from Fig. 8 that the Aksu state was dominated
12 by frequent floods. The time interval after 1985 witnessed frequent and serious
13 flood-induced losses. Floods caused losses almost every year after 1985. Fig. 8 also
14 shows that loss-related floods in the Aksu state were mostly due to rainstorm or
15 heavy precipitation. And then followed the Kashi state, floods in the Kezhou, Kashi
16 Hotan and Bazhou states were relatively rare with limited flood-induced losses. After
17 1980, however, floods became highly frequent and occurred every year. Particularly,
18 rainstorm-induced floods intensified. Rainstorm-induced floods were dominant and
19 then followed temperature-induced floods. Amplification of rainstorm-induced
20 floods in arid region should stimulate interest in different regional hydrological
21 responses to warming climate over the globe. This study provides a unique case
22 study in terms of hydrological responses, particularly extreme hydrological regimes,

of an arid region at a higher latitude to warming climate.

Trends of rainstorm-induced floods, temperature-induced floods, and dam bursting-induced floods, as well as the occurrence frequency of floods and flood-induced losses were analyzed (Fig. 9). The solid column denotes significant trends and blank column not significant trends. It can be seen from Fig. 9 that 3 out of 5 states were characterized by significant increasing AnFF, i.e. Bazhou, Hotan and Kashi. Increasing AnFF in other two states was not significant. Similarly, rainstorm-induced floods increased in the Tarim River basin, and significant increasing rainstorm-induced floods were detected mainly in Kashi, Bazhou and Aksu. Amplified heavy precipitation was the main driving factor for the occurrence of extreme floods in the basin. Besides, flood-induced crop and livestock losses were also increasing and significant increasing trends of flood-induced losses were observed mainly in three states, such as Aksu, Bazhou and Kashi. This suggests that mitigation of flood hazards in the Tarim River basin should be strengthened in order to reduce flood-induced losses.

5. Discussions

Floods in the Tarim River basin are caused mainly by precipitation changes, temperature variations, and melting of snowpack and glacier. Rainstorm-induced floods, temperature-induced floods, and rainstorm and temperature mixed types of floods account for 24%, 39% and 34% of total floods occurring in the basin (Shi and Wen, 2006). Flooding at all hydrological stations, except the Alar station, are almost

1 free of human interferences. In recent 50 years, increasing precipitation and
2 temperature have been observed in Xinjiang and the Tarim River basin (Zhang et al.,
3 2010). Transition from “warm-dry climate” to “warm-humid climate” has been
4 confirmed (Shi et al., 2003). To further understand meteorological causes for
5 changes in flood characteristics, precipitation and temperature data from 8
6 meteorological stations were analyzed by defining 21 precipitation and temperature
7 indices (Figs. 10 and 11). The Hotan and Yarkant River basins were covered by
8 relatively thin snow cover and the snow depth was usually below 10 cm. These two
9 river basins, however, were covered by thick glaciers with areas of respectively,
10 5336.98 km² and 5313.31 km² (Shen et al., 2013). Thus, glacier melting was the
11 principal source of floods and increasing temperature was causing the melting of
12 glaciers and hence the occurrence of extreme floods. Glacier-lakes often triggered
13 outburst of flash floods which had a decisive impact on scale and degree of floods at
14 the Kaqung station in the Yarkant River. Because the temperature in summer has
15 been decreasing and precipitation in winter has been increasing in recent 20 years,
16 the glaciers in the Yarkant River have been advancing causing evident amplification
17 of floods in amount and magnitude (Shen et al., 2004). Therefore, the glaciers
18 blocking the upstream of the Yarkant became more and more serious, which was the
19 main reason behind increasing trends in both magnitude and frequency of the annual
20 maximum floods at the Kaqung station (Fig. 3). Temperature at the Tongguzlok,
21 Yuzimenleke and Kaqung stations has been abruptly increasing since 1991 (Fig. 11),
22 and abrupt increases of temperature greatly intensify the melting of glaciers.

1 Meanwhile, extreme precipitation indices, such as CWD, PRCPTOT, R1 and R5
2 amplified greatly after mid-1980s (Fig. 10). All these climatic factors combined to
3 trigger an increasing or even a significantly increasing tendency in summer, autumn
4 and winter floods (Fig. 3).

5 Aksu River basin is located on the south side of the Tianshan Mountains and
6 floods occurring in the basin were mainly due to glacier or snowpack melting and
7 precipitation. The precipitation indices (Table 3) at the Sharikilank and Xehera
8 stations were simultaneously increasing (Fig. 10), and temperature indices (Table 3)
9 at these stations were also increasing (Fig. 11). A large part of flood disasters was
10 mainly the results of glacier melting and glacier-lake outburst in the header water
11 region of the Aksu River basin. The glaciers were melting faster due to increased
12 temperature in the Aksu River basin. Besides, the storage capacity of glacier-lakes
13 tended to grow large with thinning and degrading of glaciers (Shen et al., 2013). The
14 volume of the melting glacier melting is massive, resulting in increased magnitude
15 of the glacier-induced flood. Therefore, annual and summer floods at the Sharikilank
16 and Xehera stations were increasing, and the timing of the occurrence of floods
17 became earlier. Further, increased temperature intensified the melting of glaciers and
18 hence the increased flood flow in spring (Fig. 3). The Kaidu River basin is on the
19 north side of the Tianshan Mountains with large snowpack and the largest snow
20 depth can reach above 30 cm (Shen et al., 2013), being the major source of floods in
21 the basin. It can be seen from Figs. 10 and 11 that precipitation and temperature
22 indices at the Huangshuigou and Dashankou stations were increasing synchronously

1 after the 1990s. Amplification of extreme precipitation and intensifying glacier
2 melting triggered a significant increase of flood flow at annual and seasonal time
3 scales (Fig. 3). The Alar station is located on the Tarim River, receiving streamflow
4 from the Hotan River, Yarkant River and Aksu River. However, there are many
5 irrigated crop lands and numerous middle- and large-sized water reservoirs (Fig. 1),
6 and changes in peak flood flow were heavily influenced by agricultural irrigation
7 and storage effects of these water reservoirs. Therefore, peak flood flow at the Alar
8 station exhibited moderate variations without clear changing patterns.

9 Figs. 10 and 11 clearly show amplifying precipitation extremes and increasing
10 temperature after 1990. Therefore, glacier melting together with increasing
11 precipitation combined to trigger massive floods in the Tarim River basin after the
12 1990s. Fig. 8 also shows an increase in the frequency of floods due to increasing
13 precipitation and temperature in recent years and hence flood-induced losses were
14 also increasing (Fig. 9). Jiang et al. (2005) indicated that flood-induced crop damage
15 during the 1980s and the 1990s was 5.45 and 6.99 times more than that during the
16 1950s, and flood-affected populations during the 1980s and the 1990s were 190 and
17 198 times more than those during the 1950s. To manage water resources and
18 enhance mitigation of floods in the Tarim River basin is a must now and in the near
19 future.

20 21 **6. Conclusions**

22 This study analyzes changes in flood magnitude, frequency and timing in the

1 Tarim River basin, a typical arid inland river basin in China. Temporal variations of
2 floods with return periods of > 10 years in both space and time are also analyzed.
3 Altogether 21 precipitation and temperature indices are employed to investigate the
4 causes for changing properties of floods. The following conclusions are drawn from
5 this study:

6 (1) Floods during summer and winter seasons have increased after mid- and
7 late-1980s. In particular, floods have amplified mainly after 1990. Further, floods
8 have been occurring earlier after the change point than before the change point.

9 (2) Changes in flood characteristics are observed to be different in different river
10 basins. Floods have been observed mainly during the 1970s at the Tongguzlok and
11 Yuzimenleke stations in the Yarkant and Hotan River basins. During the 1980s and
12 the late 1990s, floods have been decreasing persistently. After the late 1990s, floods
13 have been active again. Floods observed at the Kaqung, Sharikilank, Xehera,
14 Huangshuigou, and Dashankou stations have been significantly intensifying after the
15 early 1990s, and floods before the early 1990s occurred sparsely and intermittently.

16 The floods at the Alar station are heavily influenced by agricultural irrigation and
17 water reservoirs. Thus, comparatively, floods at the Alar station occur moderately
18 without a changing pattern.

19 (3) Floods in the Tarim River basin are subject to three types, i.e. rainstorm-induced
20 floods, temperature-induced floods and dam bursting-induced floods. The
21 rainstorm-induced floods and rainstorm-temperature-induced floods are dominant in
22 the basin. These two types of floods have greatly amplified after the early 1980s and

1 flood-induced crop and livestock losses have been increasing significantly after the
2 1980s. Occurrences of largest three recorded floods and floods with return periods
3 greater than 10 years are relatively even in temporal changes at the Tongguzlok,
4 Kaqung and Xehela stations and are statistically significant at other stations after the
5 1990s. Interestingly, occurrences of heavy floods are usually observed in all river
6 basins synchronously.

7 (4) Significant increase of temperature has been detected after the 1990s, which is
8 the principle driving factor for the amplification of floods after the 1990s in the
9 Tarim River basin. Intensification of precipitation extremes is the direct influencing
10 factor behind the increase of rainstorm-induced floods. A significant increase of
11 temperature is the key cause to the occurrences of dam bursting-induced floods and
12 floods due to the melting of glaciers and snowpack. Precipitation extremes and
13 temperature variations in both space and time in a warming climate should arouse
14 considerable concern.

15

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Fig. 1 Locations of hydrological and meteorological stations across Xinjiang China. The hydrological stations are: 1, Tongguzlok; 2, Yuzimenleke; 3, Kaqung; 4, Sharikilank; 5, Xehera; 6, Huangshuigou; 7, Dashankou and 8, Alar stations.

Fig. 2 Threshold values for the POT-based sampling of the annual flood series at 8 hydrological stations in the Xinjiang, China. (a)-(h) denote Tongguzlok, Yuzimenleke, Kaqung, Sharikilank, Xehera, Hangshuigou, Dashankou and Alar stations.

Fig. 3 Spatial distributions of trends and change points of changes in 9 flood indices across Tarim River basin, Xinjiang, China. Definitions of these 9 flood indices are given in Table 2.

Fig. 4 Changing rates of flood indices posterior to change point when compared to those prior to change point. Definitions of these flood indices are given in Table 2.

Fig. 5 Temporal changes in anomalies of flood indices at the hydrological stations considered in this study. The hydrological stations are: TG: Tongguzlok; YZ: Yuzimenleke; KQ: Kaqung; SL: Sharikilank; XH: Xehera; HS: Hangshuigou; DS: Dashankou and AL: Alar stations. Definitions of these flood indices are given in Table 2.

Fig. 6 Temporal changes of moving MK trends of flood indices at the hydrological stations considered in this study. The hydrological stations are: TG: Tongguzlok; YZ: Yuzimenleke; KQ: Kaqung; SL: Sharikilank; XH: Xehera; HS: Hangshuigou; DS: Dashankou and AL: Alar stations. The time window is 21 years. Definitions of these flood indices are given in Table 2.

Fig. 7 Temporal changes of GEV-based return periods of annual and seasonal floods at all hydrological stations considered in this study. The hydrological stations are: TG: Tongguzlok; YZ: Yuzimenleke; KQ: Kaqung; SL: Sharikilank; XH: Xehera; HS: Hangshuigou; DS: Dashankou and AL: Alar stations. Definitions of these flood indices are given in Table 2.

Fig. 8 Changes of rainstorm-induced floods (RainF), temperature-induced floods (TempF) and dam bursting-induced floods (DamF) and annual frequency of floods (AnFF) within the Tarim River basin.

Fig. 9 Trends of RainF, TempF, DamF and AnFF and trends in flood-affected crop areas, flood-induced damaged houses and flood-induced loss of livestock.

Fig. 10 Temporal variations of precipitation indices defined in this study at meteorological stations within the Tarim River basin. The stations are: TG: Tongguzlok; YZ: Yuzimenleke; KQ: Kaqung; SL: Sharikilank; XH: Xehera; HS: Hangshuigou; DS: Dashankou and AL: Alar stations. The precipitation indices are given in Table 3

Fig. 11 Temporal variations of temperature indices defined in this study at meteorological stations within the Tarim River basin. The stations are: TG: Tongguzlok; YZ: Yuzimenleke; KQ: Kaqung; SL: Sharikilank; XH: Xehera; HS: Hangshuigou; DS: Dashankou and AL: Alar stations. Definitions of these temperature indices are given in Table 3.

Table 1 Information on hydrological and meteorological stations considered in the study

No.	Stations	Abbreviations	Streamflow data	Meteorological data
1	Tongguzlok	TG	1962-2008	1961-2010
2	Yuzimenleke	YZ	1957-2009	1961-2010
3	Kaqing	KQ	1957-2009	1961-2010
4	Sharikilank	SL	1956-2007	1961-2010
5	Xehera	XH	1956-2007	1961-2010
6	Huangshuigou	HS	1957-2008	1961-2010
7	Dashankou	DS	1972-2008	1961-2010
8	Alar	AL	1958-2008	1961-2010

Table 2 Definitions of 9 flood indices considered in this study

Flood indices	Abbreviations	Concepts	Flood characteristics
Annual maximum flow (m^3/s)	AMF	Maximum mean daily flow in a hydrological year (March–February)	Magnitude
Day of AMF (days)	AMFD	Day of occurrence of AMF	Timing
Annual maximum flow in spring (m^3/s)	AMFSp	Maximum mean daily flow in spring (March–May)	Magnitude
Annual maximum flow in summer (m^3/s)	AMFSu	Maximum mean daily flow in summer (June–August)	Magnitude
Annual maximum flow in autumn (m^3/s)	AMFAu	Maximum mean daily flow in autumn (September–November)	Magnitude
Annual maximum flow in winter (m^3/s)	AMFWi	Maximum mean daily flow in winter (December–February)	Magnitude
Peaks-over-threshold magnitude (m^3/s)	POT3M	Flow peaks over the threshold that leads to an average of 2.4 or 3 events per year	Magnitude
Peaks-over-threshold frequency (events per year)	POT3F	Annual number of flow peaks in POT3 series	Frequency
Mean day of flood occurrence (days)	MDF	Mean day of occurrence of the POT3 series for each hydrological year	Timing

Table 3 Definitions of 21 precipitation and temperature indices used in this study.

Abbreviations	Concepts	Unit
CWD	Maximum length of wet spell	d
PRCPTOT	Annual total precipitation in wet days	mm
R1	Annual count of days when $PRCP \geq 1\text{mm}$	d
R5	Annual count of days when $PRCP \geq 5\text{mm}$	d
R10	Annual count of days when $PRCP \geq 10\text{mm}$	d
R95PTOT	Annual total PRCP when $RR > 95\text{p}$	mm
R99PTOT	Annual total PRCP when $RR > 99\text{p}$	mm
Rx1day	Monthly maximum 1-day precipitation	mm
Rx5day	Monthly maximum 5-day precipitation	mm
SDII	Simple prcipitation intensity index	mm/d
DTR	Daily temperature range	°C
GSL	Growing Season Length	d
SU	Number of summer days	d
TN90P	Percentage of days when $TN > 90\text{th percentile}$	%
TNN	Annual minimum value of daily minimum temperature	°C
TNX	Annual maximum value of daily minimum temperature	°C
TR	Number of tropical nights	d
TX90P	Percentage of days when $TN > 90\text{th percentile}$	%
TXN	Annual minimum value of daily maximum temperature	°C
TXX	Annual maximum value of daily maximum temperature	°C
WSDI	Warm speel duration index	d