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Nonstationarity in the occurrence rate of floods in the Tarim River basin, China, and related impacts of climate indices

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ABSTRACT

Amplification of floods in the Xinjiang, China, has been observed, but reports on their changing properties and underlying mechanisms are not available. In this study, occurrence rates of floods in the Tarim River basin, the largest inland arid river basin in China, were analyzed using the Kernel density estimation technique and bootstrap resampling method. Also analyzed were the occurrence rates of precipitation extremes using the POT (Peak over Threshold)-based sampling method. Both stationary and non-stationary models were developed using GAMLSS (Generalized Additive Models for Location, Scale and Shape) to model flood frequency with time, climate index, precipitation and temperature as major predictors. Results indicated: (1) two periods with increasing occurrence of floods, i.e., the late 1960s and the late 1990s with considerable fluctuations around 2–3 flood events during time intervals between the late 1960s and the late 1990s; (2) changes in the occurrence rates of floods were subject to nonstationarity. A persistent increase of flood frequency and magnitude was observed during the 1990s and reached a peak value; (3) AMO (Atlantic Multidecadal Oscillation) and AO (Atlantic Oscillation) in winter were the key influencing climate indices impacting the occurrence rates of floods. However, NAO (North Atlantic Oscillation) and SOI (South Oscillation Index) are two principle factors that influence the occurrence rates of regional floods. The AIC (Akaike Information Criterion) values indicated that compared to the influence of climate indices, occurrence rates of floods seemed to be more sensitive to temperature and precipitation changes. Results of this study are important for flood management and development of mitigation measures.

1. Introduction

Streamflow is one of the most important components of the hydrological cycle. Recent years have witnessed increasing concern for global warming and impacts of warming temperature on environment and society. The warming climate has the potential to accelerate the hydrological cycle at global and continental scales (Alan et al., 2003; Bates et al., 2008; Zhang et al., 2013a). Observed changes of extreme weather and climatic events, such as more extreme precipitation, lengthening dry span, higher peak flows, and increased intensity of most extreme tropical cyclones since the 1950s (Zhang et al., 2013b; IPCC, 2013; World Bank, 2013; Apurv et al., 2015) have increased risks of floods and droughts. Increasing occurrences of floods have been arousing considerable concern in recent years. Caspary and Bárdossy (1995) analyzed yearly maximum runoff time series from the Enz River (SW Germany) at two stations from 1930 to 1994 by making a polynomial regression and fitting the Gumbel extreme value distribution to various time intervals. They showed an increase in flood risk and attributed it to an increase in the occurrence of zonal westerly circulation systems. Jacobeit et al. (2003) analyzed the same flood data and their relation to sea level pressure (SLP) fields and confirmed the relevance of westerly zonal circulation type for the occurrence of winter floods. Mudelsee et al. (2004) hypothesized that anthropogenically induced climate change would add to the risk of extreme river floods because a warmer atmosphere carries more water. Thus, more attentions should be paid to understanding of the flood processes and occurrences of floods, which will be conducive to reduce the losses caused by floods. The objective of this study is to investigate the validity of the stationarity assumption in the occurrence rate of floods. Stationarity of a hydrologic time series is often defined as “free of trends, shifts, or periodicity (cyclicity)” (Salas, 1993). Therefore, most studies have check whether this assumption is valid or not based on analysis of slowly-varying changes (trend

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analysis) or change point due to climate change and intensifying human activities, such as construction of water reservoirs and urbanization (Milly et al., 2008; Gilroy and McCuen, 2012; Silva et al., 2012; Zhang et al., 2014a, 2015a). Villarini et al. (2009b) performed the flood frequency analysis for nonstationary annual peak records in an urban drainage basin from the point of trend analysis. The stationarity of annual flood peaks was also checked based on trend and change point analysis in the continental United States during the 20th century (Villarini et al., 2009a). However, an element that is often overlooked in analyses of stationarity of flood records is the presence of long-term persistence in the flood series (Koutsoyiannis, 2002). Koutsoyiannis (2006) pointed out that in particular, some of the patterns observed in hydrologic series could be better explained by accounting for long-term persistence. Because the occurrence rates of floods are not the original flood series but estimated by kernel function (Mudelsee et al., 2003, 2004), the stationarity in occurrence rates of floods may be not suitable to analyze presence of long-term persistence, although the concepts of stationarity and persistence of long-term should be analyzed jointly. In addition, Mudelsee et al. (2003, 2004) analyzed the stationarity of occurrence rates of floods in central Europe over the past 500 years without considering the long-term persistence, too. Therefore, we investigate the stationarity in occurrence rates of floods mainly in terms of slowly-varying changes.

The accuracy of hydrologic analysis and design may be influenced with violation of the stationarity assumption (Douglas et al., 2000). With this point in mind, Galloway (2011) asked: what do we do now if stationarity is dead? Therefore, he called for not only supporting additional study of the death of stationarity, its implications, and new approaches, but also providing more information to plan, design, and operate today's projects. Clarke (2007) indicated that the next few decades should witness a substantial increase in our understanding of the processes causing climate change, not only for the purpose of forecasting the development of such changes, but also for predicting the frequency of an event of a certain magnitude. Thus, a number of investigators have attempted to incorporate nonstationarity in flood frequency analysis (Silva et al., 2012; Zhang et al., 2014b, 2015b). Reports on occurrence rates of floods in arid regions with the consideration of nonstationarity are lacking. Therefore, our understanding of flooding processes in arid regions, particularly nonstationary flood behavior, under the influence of changes in climate is limited. Studies addressing this issue will help understand regional hydrological responses of floods to global climate indices and management of water resources and agricultural irrigation, in arid areas such as the Tarim River basin (e.g. Jiang et al., 2005).

The Tarim River basin is the largest arid inland river basin in China. The total area of the basin is 1.02×106 km^2 (996,000 km^2 within Xinjiang), in which the land is divided into mountains (47%), plains (22%), deserts (31%), and an arable land area of 1.36×106 hm^2 (Fan et al., 2011). The source of water in the basin is mainly glacial/snow melt which accounts for 48.2% of the total water volume (Chen et al., 2007). About 10 million people, including ethnic minorities — Uyghurs and Mongolians, live in the basin. >8 million people live in oases along the river banks and in alluvial plains downstream (Zhang et al., 2010). The basin is characterized by low precipitation and high evaporation (Zhang et al., 2010; Sun et al., 2012). In lowlands, the river is the most important source of water. Due to its exceptional and unique role in the economic development, the Chinese government launched a five-year emergency water diversion program in 2000 with 10.7 billion yuan (US$1.3 billion) earmarked for reclamation of the river and Taitema Lake (Tao et al., 2008). However, the number of heavy rainfall events and the frequency of rainstorm flood disasters have been on the rise since the 1980s, and the increasing trend in flood disasters in Xinjiang since the mid-1980s can be attributed to the increasing trend in annual precipitation (Jiang et al., 2005). Observations further indicate that glacier melt-induced floods in the basin have been increasing in recent years (e.g. Zhang, 1992).

Only limited attention was paid to the relations between the occurrence rates of floods and climate indices. This study investigates the spatiotemporal relations between occurrence rates of floods and climate indices in the Tarim River basin with considering nonstationarity. The objectives of this study therefore are: (1) to analyze occurrence rates of floods with consideration of nonlinearity; (2) to probe into causes behind occurrence rates of floods by building relations between occurrence rates of floods and climate indices; and (3) to investigate at-site probabilistic forecasting of flood frequency with climate indices as major influencing factors by the development of GAMLSS-based model. Results of this study are important for management of water resources and agricultural irrigation under the influence of climate indices.

2. Data

Data collected were streamflow, flood occurrences, precipitation, and temperature. Daily streamflow data of at least 37 years covering different periods from 8 hydrological stations, shown in Table 1, were obtained from the Hydrological Bureau of the Tarim River basin which firmly controls the quality of data before release. Locations of the hydrological stations are shown in Fig. 1. The flood series in hydrological stations were obtained from Peak-over-Threshold (POT) sampling of daily streamflow data, which were used to analyze the nonstationarity in occurrence rates of floods in stations. Data on occurrences of floods and their timing for a period of 1950–2000 from 5 states, simply called as subregions, i.e., Aksu, Kezhou, Kashi, Hotan and Bazhou, were also collected from *Encyclopedia of Meteorological Disasters in China* (Wen, 2005). Each recorded flood with corresponding occurrence date in each state was collected, which was used to analyze the nonstationarity in occurrence rates of floods in regions. Also, daily precipitation and temperature data covering a period of 1961–2010 were collected from the meteorological stations closest to the hydrological stations (Fig. 1, Table 1).

Climate indices have a significant influence on climate change and hydrological cycle. Ran et al. (2015) indicated that Southern Oscillation Index (SOI) and North Atlantic Oscillation (NAO) impact climate change and hydrological processes in Xinjiang. Kalra et al. (2013) developed a data-driven model incorporating oceanic atmospheric oscillations to increase the streamflow lead time in the Kaidu River, a major tributary of the Tarim River basin. The interannual and decadal scale oceanic-atmospheric oscillations, i.e., Pacific decadal oscillation (PDO), North Atlantic oscillation (NAO), Atlantic multidecadal oscillation (AMO), and El Niño-southern oscillation (ENSO), were used to generate streamflow volumes for the peak season (April–October) and the water year. In this case, NAO, AO (Atlantic Oscillation), SOI and AMO during winter season (December to March of the subsequent year) were taken as the major climate indices influencing hydrological processes in the basin. Monthly data of NAO, AO, SOI and AMO were extracted from http://www.esrl.noaa.gov/psd/data/climateindices/list/, and the period of aforementioned climate indices data was 1950–2010.

3. Methodology

3.1. Peak-over-threshold (POT) based sampling

Flood series were obtained by two methods, i.e., annual peak flow and POT-based sampling technique. POT sampling helps obtain information on flood magnitude, occurrence rate and timing of flood events. The independence of flood peak was evaluated as (Lang et al., 1999):

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