Responses to short comments

(1) What are the scientific issues or scientific assumptions to be addressed? What are the objectives of this current study?

Response: We thank the reviewer for this critique. We substantially reconstruct Abstract and Introduction sections to highlight the objectives and scientific issues of the present study in the revised manuscript. In short, we expect to provide improved characterizations of flood hazard over China from both statistical and physical perspectives, and contribute to improved understandings of flood hydrology and hydroclimatology under a changing environment. Our analysis is carried out by centering on five proposed questions (see Line 88-93 of the revised manuscript). Our analysis is based on an unprecedented dataset that can significantly advance flood science at the global scale (as also highlighted by the other two reviewers). Thanks!

(2) As for detection of change points, results by one statistical method are not certain with considerable uncertainty. This issue was well addressed by Zhang et al. (2009), i.e. Qiang Zhang, Chong-Yu Xu, Yongqin David Chen, Jianmin Jiang, 2009. Abrupt behaviors of the streamflow of the Pearl River basin and implications for hydrological alterations across the Pearl River Delta, China. Journal of Hydrology, 377(3), 274-283.

Response: We thank the reviewer for this critique. Some other change-point detection approaches have been applied, but only show negligible deviations from those by Pettitt's test. There are some variations for specific stations, but the years of change points occur in 1980s and clustered in central China and northern China. We below show comparisons of change points in mean based on Pettitt's test and the one proposed by Matteson and James (2014). Our conclusions remain unchanged using different methods. We clarify this in the revised manuscript. Thanks!

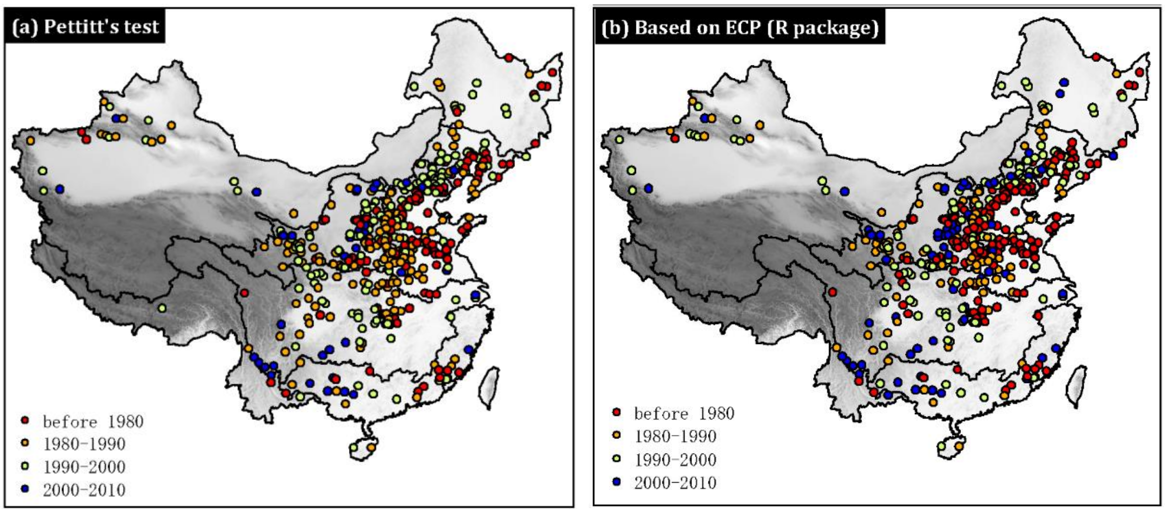

Figure R1. Comparisons between results using different change-point detection methods. (a) Pettitt's test, (b) The approach proposed by Matteson and James (2014).

(3) By the way, the assumption that only one change point can be observed in one streamflow series is not

practically and theoretically correct. It is definitely wrong!

Response: We agree with the reviewer that multiple change points can exist in a flood series. However, we are particularly interested in understanding the dominant mode of nonstationarity in flood series across China, i.e., abrupt change vs. slowly varying trend, rather than locating every single possible change point in the series. As we have mentioned in the manuscript, "we assume the existence of only a single change point in mean for each flood peak series in this study, to avoid dividing the series into too many segments". In addition, the assumption of one single change point is also frequently adopted in previous studies (e.g., Villarini 2009; 2010; 2012). We add references in the revised manuscript. Thanks!

(4) The authors tried to relate GEV parameters to tropical cyclones and fit GEV model to stationary series. This kind of analysis is totally wrong. I suggest stationary GEV model for stationary flood peak series, but nonstationary GEV, i.e. GEV with time-varying parameters, for nonstationary flood peak series. Moreover, flood peak process is not the result of tropical cyclone only, but most flood processes are by extreme precipitation. Therefore, I suggest association of peak flood flows to extreme precipitation but not tropical cyclones. Just as said, some extreme precipitations are by tropical cyclones.

Response: We believe the reviewer has accidentally misunderstood some of the analysis conducted for tropical cyclones and their roles in determining the upper-tail properties of flood peak distributions. GEV analysis (with time-independent parameters) is only carried out for flood series that are stationary (i.e., demonstrating no abrupt changes or monotonic trends). We examine the role of tropical cyclones in determining the upper tails of flood peak distributions mainly through examining changes in the GEV shape parameters after removing tropical cyclone-induced flood peaks from the entire flood series (as shown in Figure 10, the revised manuscript). Nonstationary GEV modeling based on time-dependent parameters is not the focus of our present study.

A distinct feature of tropical cyclones is the spiral rainbands that typically extend from the eye wall towards several hundred or even tens of hundreds of kilometers away from the center of circulation. Climatological analysis based on satellite rainfall products shows that most extreme rainfall is distributed within 500 km around the circulation center (e.g., Rios Gaona et al., 2018). This is the reason why we choose 500 km as the spatial threshold to associate flood peaks with a tropical cyclone, with the essence being actually association of flood peaks with extreme rainfall induced by tropical cyclones. Thanks all the same!

(5) Peak flood flows are heavily influenced by water reservoirs. Actually, it was done by Zhang et al. (2015), i.e. Qiang Zhang, Xihui Gu, Vijay P. Singh, Chong-Yu Xu, Dongdong Kong, Mingzhong Xiao, Xiaohong Chen, 2015. Homogenization of precipitation and flow regimes across China: changing properties, causes and implications. Journal of Hydrology, 530, 462-475. Relevant case studies can be found as: Qiang Zhang, Vijay P. Singh, Chong-Yu Xu and Xiaohong Chen, 2013. Abrupt behaviors of streamflow and sediment load variations of the Yangtze River basin, China. Hydrological Processes, 27(3), 444-452. Impoundment effects of water reservoirs on flood processes cannot be ignored in this study.

Response: We agree with the reviewer that reservoirs play an important role in flood peak magnitudes. We highlight this by showing a flood series in the upper Yellow River basin in Figure 4. However, we also note that the effects of reservoirs on flood peak may depend on some other factors, due to contrasting findings of previous studies (e.g., Smith et al., 2010; Barros et al., 2014). We add the reference Zhang et al. (2015) in the revised manuscript. We specifically discuss the influence of reservoirs in Line 198-202 of the revised manuscript. Thanks!

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On the Flood Peak Distributions over China

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Abstract. ~~Time series of annual maximum instantaneous peak discharge from~~ Here we for the first time present a nation-wide characterization of flood hazard across China. Our analysis is based on an exceptional dataset of 1120 ~~stations with record lengths of~~ stream gauging stations with continuous records of annual flood peaks for at least 50 years ~~are used to examine~~ across the entire country. Our results are organized by centering on various aspects of flood peak distributions~~across China. Abrupt change rather than slowly varying trend is the dominant mode of the violation of stationary assumption for~~ , including temporal changes in flood series and their spatial variations, statistical distribution of extreme values, and properties of storms that lead to annual flood peaks~~over China.~~ . These aspects altogether contribute to improved understandings of flood hydrology under a changing environment over China, and promote the advance of flood science at the global scale. Historical changes in annual flood peaks demonstrate frequent abrupt changes rather than slowly varying trends. The dominance of decreasing ~~trends in~~ annual flood peak ~~series~~ magnitudes indicates a weakening tendency of flood hazard over China in recent decades. ~~Delayed (advanced) occurrence of annual flood peaks in southern (northern) China point to a tendency for seasonal clustering of floods across the entire country.~~ We model the upper tails of flood peaks based on the Generalized Extreme Value (GEV) distributions~~for the stationary series, and evaluate the scale-dependent properties of flood peaks. The relations of GEV parameters and drainage areashow spatial contrasts~~ . The GEV shape parameter is weakly dependent on drainage area, but shows spatial splits tied to rainfall climatology between northern and southern China. ~~Weak dependence of the GEV shape parameter on drainage area highlights the critical role of space-time rainfall organizations in dictating the upper tails of flood peaks. Landfalling tropical cyclones play~~ Landfalling tropical cyclone plays an important role in characterizing the upper-tail properties of flood peak distributions especially in northern China and southeastern coast, while the upper tails of flood peaks are dominated by extreme monsoon rainfall in southern China. Severe flood hazards associated with landfalling tropical cyclones are characterized with ~~tropical cyclones experiencing extratropical transition, and persistent moisture transport/interactions with regional topography as demonstrated by Typhoon Nina (1975)~~ . complex interactions of storm circulation with synoptic environment (i.e., mid-latitude baroclinic disturbances) and regional topography.

1 Introduction

We examine flood peak distributions over China based on 1120 stream gauging stations with continuous records of annual maximum flood peaks for at least 50 years. The ultimate goal of our study is to provide improved ~~understandings on the nature of upper tails of flood peaks and innovative methods for flood frequency analysis in a changing environment. The central themes of this study are (1) stationarity of~~ characterization of flood hazard across China from both statistical and physical perspectives. This involves a comprehensive suite of analyses that investigate temporal nonstationarities in annual flood peaks (~~for both peak magnitude and timing), (2)mixture of flood-generation systems, (3) spatial heterogeneity of flood peak distributions, and (4) the impacts of tropical cyclones on the upper-tail properties of flood peak distributions.~~i.e., temporal distribution), flood peak distribution based on extreme value theory (i.e., statistical distribution) and critical factors (in terms of both physiography and climate) that determine the upper tails of flood peaks (i.e., spatial distribution).

Hydrological regimes in most river basins over China, like the rest of the world, have experienced strong anthropogenic influences (i.e., river regulations, land use changes). Human-related impacts on flood hydrology are further complicated by detectable changes in external factors that are critical for flood-generation processes, such as temperature and extreme rainfall, even though it remains unsettled whether the changes are due to natural climate variability or human-induced climate change (e.g., Held and Soden, 2006; Marvel and Bonfils, 2013; Trenberth et al., 2015; Schaller et al., 2016; Risser and Wehner, 2017; Eden et al., 2017). The ~~staionarity~~ stationarity assumption of flood series has been questioned and debated in ~~the~~ scientific community (Milly et al., 2008; Montanari and Koutsoyiannis, 2014; Salas et al., 2018). Extensive studies on the stationarity of annual ~~maximum~~ flood peaks have been carried out in many parts of the world ~~(e.g., Robson et al., 1998; Robson, 2002; Franks and Kuczera,~~ ~~. There are also~~ (e.g., Robson et al., 1998; Robson, 2002; Franks and Kuczera, 2002; Villarini et al., 2009; Petrow and Merz, 2009; Villarin , including some efforts in global-scale investigations of historical changes in flood series (e.g., Arnell and Gosling, 2016; Do et al., 2017, 2 . Due to the limitation of observational datasets, existing knowledge on flood hazard is significantly biased towards Europe and North America, with the characteristics of other worldwide regions (including China) far from being well represented. There are some regional studies across China (e.g., Zhang et al., 2016, 2014, 2018b; Liu et al., 2018). A nation-wide investigation on the stationarity ~~of annual maximum flood peaks~~ in flood series over China, however, is still missing~~, and is the principal focus of our study~~. The exceptional dataset of ~~flood records in China~~annual flood peaks, as demonstrated in ~~the~~ present study, will provide additional evidence for detectable changes in flood ~~series in~~ hydrology under a changing environment. Better understanding of historical changes in annual flood peaks is of paramount importance for constraining model-based projections of flood hazards (e.g., Milly et al., 2002; Hirabayashi et al., 2013; Dankers et al., 2014; Arnell and Gosling, 2016). In this study, we ~~do not aim to do attribution analysis for the changes in annual flood peaks for each river basin (like e.g., Hodgkins et al., 2019), but to highlight possible~~ expect to explore the dominant mode (i.e., abrupt changes or slowly varying trends) of nonstationarities in flood series, and highlight potential factors that induce the changes ~~. Similar with the study by Villarini and Smith (2010) in the eastern United States , we identify the dominant modes of violation for the stationarity assumption in annual maximum~~ in annual flood peaks.

Improved understanding of flood hazard requires essential knowledge of flood-generation mechanisms. This is also a critical aspect to consider for improved flood frequency analysis (Hirschboeck, 1988; Singh et al., 2005; Leonard et al., 2014; Brooks and Day, 20 . Smith et al. (2018) shows that the most extreme flood peaks are frequently determined by extreme events resulted from anomalous flood agents for particular regions of the United States (which is the notion of "strange floods"). Mixture of flood-generation mechanisms poses great challenges for characterizing the upper tails of flood peaks, as different flood agents might lead to flood regimes with distinct statistics (e.g., magnitude, timing, frequency). This is, however, often the case for many regions in the world (e.g., Jarrett and Costa, 1988; Smith et al., 2011; Villarini, 2016; Blöschl et al., 2017; Smith et al., 2018; England et al . We expect annual flood peaks over China ~~. Better understanding of historical changes in annual flood peaks is of paramount importance for constraining model-based projections of flood hazards in a changing environment(e.g., Milly et al., 2002; Hirabayashi et al., .~~ characterized with a mixture of flood-generation mechanisms, due to its geographic location in a monsoon-climate region and on the margin of the most active ocean in tropical cyclones. China suffers the most frequent landfalling tropical cyclones in the world, with 9 tropical cyclones making landfall on average per year (Jiang and Jiang, 2014). Despite its significance, little is known about the hydroclimatology of flooding associated with landfalling tropical cyclones. Even less effort has been spent on investigating the impacts of different flood-generation mechanisms on the upper-tail properties of flood peaks across China. This is a critical issue for China that shows contrasting rainfall climatology (under combined influences from monsoon and landfalling tropical cyclones) between the northern and southern part of the country (i.e., traditionally take the Yangtze River as the geographic divide) (e.g., Yang et al., 2013; Gu et al., 2017a; Zhang et al., 2018a). Extreme floods for different regions are often associated with contrasting flood agents. This is not merely associated with the nature of flood agents themselves, but is also determined by complex interplay of storms with ambient synoptic and physiographic environment. For instance, extreme rainfall from landfalling tropical cyclones can be amplified through interactions of storm circulation with mid-latitude baroclinic disturbances (e.g., Hart and Evans, 2000) and regional topography (e.g., Houze, 2012). Propagation of monsoon also plays a role in determining the spatial contrasts of flood agents through regulating temporal occurrences of flood peaks over different regions (e.g., Ding and Zhang, 2009). Knowledge in the mixed flood-generation mechanisms and their spatial variations can provide valuable insights into improved procedures for the estimates of Probable Maximum Precipitation (PMP) / Probable Maximum Flood (PMF) in designing flood-control infrastructures (e.g., Smith and Baeck, 2015; Yang et al., 2017).

~~We examine the upper tails of flood peaks over China~~ An important way of characterizing flood hazards is through examining flood peak distributions and factors that determine the upper-tail properties. In this study, we model annual flood peaks based on the statistical framework of the generalized extreme value (GEV) distributions (similarly see e.g., Katz et al., 2002; Morrison and Smith, 2002; Villarini and Smith, 2010; Barros et al., 2014; Bates et al., 2015; Gaume, 2018; Smith et al., 2018). ~~Special~~ The key focus is placed on the ~~spatial heterogeneity of flood peak distributions over~~ upper tails of flood peaks across China. Previous studies show strong dependence of location and scale parameters for the GEV distributions on drainage area, while the GEV shape parameters only weakly depend on drainage area (Morrison and Smith, 2002; Villarini and Smith, 2010). Weak dependence of the GEV shape parameters on drainage area indicate scale-independent properties of the upper ~~tail of flood peak distributions~~tails of flood peaks, and highlight additional factors (e.g., ~~space-time rainfall organizations~~spatio-temporal rainfall variability) in determining the upper tails of flood peaks. Yang et al. (2013) identified a spatial contrast of extreme rainfall distributions between northern and southern China and point pointed to contrasting flood hydroclimatology across the country. We therefore propose that similar spatial contrasts also exist in flood peak distributions across China, and highlight the necessity of improved procedures for regional flood frequency analysis with spatial heterogeneity in flood hydroclimatology considered.

In addition to annual maximum flood peak magnitude, we examine the timing of annual maximum flood peak (as represented by day of the year) in this study. Analysis on the timing of annual flood peaks (e.g., seasonality) can shed light on flood-generating mechanisms, and is an important aspect of flood frequency analysis (Hirschboeck, 1988; Singh et al., 2005; Leonard et al., 2014; Brooks an . Annual flood peaks resulted from different flood-generation mechanisms violate the assumption of homogeneous flood population that most conventional methods for flood frequency analysis rely on. This is, however, often the case for many regions in the world (e.g., Jarrett and Costa, 1988; Villarini, 2016; Blöschl et al., 2017; Smith et al., 2018; England et al., 2018) . For instance, flooding in the eastern United States is under mixed controls of extratropical systems and landfalling tropical cyclones, with relative importance varies spatially (Smith et al., 2011). The upper-tail properties of flood peak distributions are frequently determined by extreme events resulted from anomalous flood agents for particular regions (the notion of "strange floods", see Sm . We expect annual flood peaks to be characterized with a mixture of flood-generating mechanisms over China, due to the geographic location of China in a monsoon-climate region and on the western margin of the north Pacific basin for tropical cyclones. We characterize the relative importance of monsoon-related systems and tropical cyclones in dictating the upper tails of flood peaks across China. Consistent changes in flood peak timing over Europe indicate a clear signal of climate impact on the seasonality of European flood records (Blöschl et al., 2017). Villarini (2016) does not find a strong signal of temporal changes in the seasonality of annual maximum discharge over the continental United States. Changes in the seasonality of annual flood peaks across China is still lacking, despite its strong implication for flood hazards and water resources management. In this study, we examine changes in the timing of annual maximum flood peak across China, to shed more light on the stationarity of annual maximum floods and the changing flood hazards over the country.

Our study is also motivated by Typhoon Nina and the resultant August 1975 flood in central China. The August 1975 flood in central China, with 26000 direct fatalities, is one of the most destructive floods in the world history (Yang et al., 2017). The August 1975 flood plays a key role in shaping the envelop curve of floods in China and different versions of the world envelop curve (Yang et al., 2017; Costa, 1987). The unit peak discharge is 17 $m^3 s^{-1} km^{-2}$ (which is i.e., flood peak discharge divided by drainage area) for a 760 km^2 drainage basin, and is on the list of the world maximum floods. The maximum 6-hour rainfall accumulation of 830 mm is comparable to the world record (840 mm, Teegavarapu, 2013). Central China lies in the region with relatively less frequent visits of tropical cyclones in the western North Pacific basin (Wu et al., 2005; Jiang and Jiang, 2014). Previous studies show that landfalling tropical cyclones can make great contributions to extreme rainfall in inland regions, even though the frequency of occurrence is not as comparative as coastal regions (e.g., Zhang et al., 2018a). This is closely linked to a couple of factors, such as the interplay of tropical cyclone and baroclinic disturbances (i.e., known as extratropical transition, Hart and Evans, 2000), interactions with mid-latitude systems (e.g., easterly, Shu et al. , and impact of regional topography (as demonstrated by Typhoon Nina, Yang et al., 2017). The devastating August 1975 flood plays a key role in shaping the envelop curve of floods in China and different versions of the world envelop curve (Yang et al., 2017; Costa, 1 . Devastating consequences of Typhoon Nina and the August 1975 flood partially resulted from cascading collapses of dozens of dams, and expose inadequacies of conventional approaches for flood frequency analysis (e.g., fitting historical flood records with assumed distribution function) , and highlight the importance of hydrometeorological approaches for Probable Maximum Precipitation (PMP) / Probable Maximum Flood (PMF) analyses for better designs of flood-control infrastructures (e.g., Smith and Baeck, 2 . In this study, we examine the impact of tropical cyclone on the upper tail properties of flood peak distribution over China. We provide characterizations of landfalling tropical cyclones that produced severe historical floods over China, focusing on the nature of the storm and relative locations of flood peaks to the circulation center. Results presented in this study can promote a predictive understanding of flood hazards associated with landfalling tropical cyclones. This is especially a critical issue over Chinadue to its high frequency of landfalling tropical cyclones (i.e., with 9.3 tropical cyclones making landfall on average per year) (Jiang and Jiang, 2014). Economic functions) (e.g., Smith and Baeck, 2015; Yang et al., 2017). This is an urgent issue for China, as statistics show socio-economic damages caused by landfalling tropical cyclones are rapidly increasing in recent decadesacross China, with a large portion of the damages resulted from extreme tropical cyclone rainfall and flooding (Zhang et al., 2009)riverine flooding (Zhang et al., 2009; Rappaport, 2014).

The rest of the paper is structured as follows. In section 2, we introduce the dataset of annual maximum flood peaks, followed by section Based on the aforementioned gap of our knowledge in flood hydrology, we examine flood peak distributions across China by centering on the following questions: (1) What is the dominant mode of the violation of stationarity in annual flood peak series? (2) How do dominant flood-generation mechanisms vary across China? (3for detailed descriptions of methods, including change point and trend analyses, Generalized Extreme Value distribution, and association of annual maximum floods with particular tropical cyclones . Results and discussions are provided in section 3, followed by summary and conclusions in section 4.) How do upper-tail properties of flood peak distributions depend on drainage areas (i.e., scale-dependence) and rainfall climatology? (4) What is the impact of landfalling tropical cyclones on the upper tails of flood peaks across China? (5) What are the characteristics of the most severe flood hazards (i.e., as represented by the number of stations with annual flood peaks) in the history of China and the tropical cyclones that induce them? Even though these questions are examined based on an exclusive dataset over China, timely answers to these questions will undoubtedly contribute to the compliment of our limited understandings on flood hazard under a changing environment, and promote the advance of flood science at the global scale.

2 Data

Our analysis is based on observations of annual maximum instantaneous peak discharge from 1120 stream gauging stations with continuous records of at least 50 years . The longest flood record is 145 years.(i.e., no missing data consecutively throughout the entire periods). There are relatively more stations distributed in eastern China than the western part of the country (Figure 1). The dataset is comprehensively collected from local hydrographic offices of nine major river basins across China. All these stations are nation-level control stations with little evidence of site re-location during the observational periods. Strict the records that have been through strict quality control procedures are implemented to ensure to ensure data consistency and accuracyof the records. There are relatively more stations distributed in the eastern China than the western part of the country (Figure 1). The record . For instance, the dates of annual maximum flood peak and highest stage should be comparable, with records of missing flood peak timing discarded to ensure data accuracy. Stations with notable site re-locations (i.e., that lead to changes in drainage area) during the observational periods are not included in this dataset. The flood records demonstrate a variety of ways in data collection, mainly include intermittent direct measurements of discharge during flood season, indirect inferences through stage-discharge rating curves, and post-flood field surveys.

Time series of total number of available stations are shown in Figure 2a. The longest flood record is 153 years, with approximately more than 90% stations fully available during the period from 1960 to 2017. The record length of 66% stations exceeds 60 years starting from 1950s till the year of 2017 (Figure 2ab). There are considerable variabilities in the spatial scales of represented river basins, with a large percentage (approximately 64%) of stations representing small and medium river basins (with drainage areas less than 5000 km^2, Figure 2b). c). Previous studies found contrasting climate regimes and extreme rainfall distributions between northern and southern China (e.g., Yang et al., 2013; Ma et al., 2015). To facilitate analyses and comparisons, we further classify the 1120 stations into two sub-groups, i.e., northern and southern China, based on their geographic locations (Figure 1). The northern group includes stations mainly in northeastern river basins, the Yellow River basin, the Huaihe River basin, and the Haihe River basin, while the southern group includes southeastern river basins, southwestern river basins, the Yangtze River basin, and the Pearl River basin. Previous studies found contrasting climate regimes and extreme rainfall distributions between northern and southern China (e.g., Yang et al., 2013; Ma et al., 2015).

3 Methodology

3.1 Change point and trend analysis

We use the nonparametric non-parametric Pettitt's test (Pettitt, 1979) to examine the presence of abrupt changes in annual flood peak series. Pettitt's test is a rank-based test that relies on the Mann-Whitney statistic to test whether two samples come from the same population. There are no assumed distributions for the test, which makes it less sensitive to outliers and skewed distributions. It allows for the detection of a single change point in mean at an unknown point in time, with the test significance computed using the given formulation. We further apply the Pettitt's test on the squared residuals derived with respect to the local polynomial regression line (loess function, Cleveland, 1979) to detect change point in variance in annual flood peak series (similarly see, e.g., Villarini et al., 2009; Villarini and Smith, 2010; Yang et al., 2013).

We use the nonparametric We also adopted a different change-point detection approach, i.e., the one proposed by Matteson and James (20 , but only found negligible deviations from the results based on Pettitt's test (results not shown).

Monotonic trends can be induced by existence of abrupt change points in mean rather than indicating slowly varying trend for the flood series. For those series that do not show significant abrupt change points in mean, we directly use the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) to examine the presence of monotonically increasing or decreasing trends in annual flood peak series. For the series with change point in mean, we divide it into two sub-groups and test monotonic trends for each of the two sub-groups (i.e., before and after the change point). Additional trend analysis for the sub-series can highlight stations that show both abrupt changes and slowly varying trend in the entire flood series. We assume the existence of only a single change point in mean for each flood peak series in this study, to avoid dividing the series into too many segments . (similarly see, e.g., Villarini et al., 2009, 2012). Only sub-series with record lengths exceeding 10 years are considered in the trend analysis. We set a significance level of 5% (i.e., two-tailed) for both the change-point and trend tests. Pettitt's test and Mann-Kendall test are further applied in the series of timing of annual maximum flood peaks (represented by day of the year) to investigate changes in flood peak timing across China.

3.2 Generalized Extreme Value distribution

The Generalized Extreme Value (GEV) distribution is used to statistically model distributions of annual maximum flood peaks (e.g., Coles, 2001; Villarini and Smith, 2010). The GEV, based on extreme value theory, has been widely used in flood frequency analysis (e.g., Coles, 2001; Katz et al., 2002; Morrison and Smith, 2002; Villarini and Smith, 2010). The cumulative distribution function of the GEV takes the form:

$$F(x|\mu,\sigma,\xi) = exp\left\{-[1+\xi(\frac{x-\mu}{\sigma})]^{-1/\xi}\right\} \quad (1)$$

where μ, σ, and ξ represents the location, scale, and shape parameter, respectively. The location (μ) and scale (σ) parameter is related to the magnitude and variability of the records, respectively. The shape parameter (ξ) indicates the tail properties of the distribution, with positive (negative) values pointing to heavy and unbounded (light and bounded) upper tails tail of flood peak distribution. The GEV parameters are estimated based on the maximum likelihood estimators (e.g., Coles, 2001). We fit the GEV distributions only for stations without statistically significant change points in mean and variance and monotonic trends.

We examine the dependence of GEV parameters on drainage area.Villarini and Smith (2010) examined annual flood peaks in the eastern US, and found a strong dependence of locationand scale parameter on drainage area, while the shapeparameter only shows a weak dependence on drainage area (Villarini and Smith, 2010). We further test whether or not drainage area can explain the spatial variability of GEV parameters over , following the basic assumption of probability theory that data samples should be independent and identically distributed. The three fitted GEV parameters (i.e., location, scale and shape) will be further used to examine their correlations with drainage areas, shedding light on the scale-dependence of the upper-tail properties of flood peak distributions across China.

3.3 Association of flood peaks with tropical cyclones

We associate an annual flood peak of a given stream gauging station with a particular tropical cyclone following procedures in Villarini and Smith (2010) and Smith et al. (2011)by following the procedures, i.e., if the center of a tropical cyclone is within 500 km of the gauging station during a time window of two weeks centered on the occurrence time of the flood peak. The thresholds (500 km and two weeks) spatial and temporal thresholds reflect the mean spatial extent of tropical cyclone rainfall (e.g., Rios Gaona et al., 2018), and the upper limit of flood response time in the representing river basins(similarly also see, e.g., Hart and E . We obtain the information of tropical cyclones for the west Pacific basin from the International Best Track Archive for Climate

Stewardship (IBTrACS, see https://www.ncdc.noaa.gov/ibtracs/ for details). The dataset provides records of the circulation center location (latitude and longitude) and storm intensity (represented by minimum sea level pressure) at a temporal interval of 6 hours. An additional attribute provided by IBTrACS for each tropical cyclone at each time interval is the nature of the storm, i.e., extratropical transition ~~(ET)~~ or tropical storm~~(TS)~~. Extratropical transition (ET) characterizes the changing properties of a tropical cyclone from a warm-core, symmetric structure to a cold-core, asymmetrical structure (e.g. Hart and Evans, 2000). Physical process associated with extratropical transition plays an important role in determining the spatial distribution of tropical cyclone rainfall ~~(e.g. Hart and Evans, 2000; Atallah and Bosart, 2003; Atallah et al., 2007; Liu and Smith, 2016)~~(e.g. Atallah and Bosart, 2003; At . Tropical storm (TS), as a contrast, indicates the maintenance of a warm-core, symmetric structure during the entire life cycle of the storm.

4 Results and discussion

The structure of this section is organized as follows. We first detect change points and monotonic trends to shed light on the long-term changes in flood series across China, and discuss possible drivers that induce them (subsection 4.1). We move on to subsection 4.2 to examine seasonal distribution of annual flood peaks, highlighting the mixture of flood-generation mechanisms across China and its spatial variation. Results from both subsection 4.1 and 4.2 will serve the basis for the analysis of subsection 4.3 that delves into the upper-tail properties of flood peak distributions across China, focusing on the spatial distributions of the GEV parameters as well as their dependence on drainage areas and rainfall climatology. Subsection 4.4 will specifically examine the impacts of tropical cyclones on extreme floods, to shed light on the statistical and physical characteristics of most extreme floods in the history of China.

4.1 Stationarity~~for flood peak magnitude~~

4.1.1 Abrupt changes

Figure 3 shows the results of change-point analyses for annual flood ~~peak magnitudes~~ peaks based on the Pettitt's test. There are 436 (38%) and 398 (35%) stations with significant change points in mean and in variance, respectively. 27% stations show change points both in mean and in variance. The majority of stations tend to show smaller values in mean ~~and/or variance after~~ (383 stations) and variance (305 stations) after than before the change point (figure not shown). Change points in both mean and variance show striking spatial concentration in northern China (i.e., the lower Yellow River basin, the upper Huaihe River basin, and the entire Haihe River basin). Change points in both mean and in variance are frequently observed during the period 1980-2000, with slightly larger frequency of occurrence during the period 1990-2000. We observe an additional amount of change points in mean distributed in the downstream of southwestern river basins and in the upper and middle portion of the Yangtze River and Pearl River basins (Figure 3a). These change points tend to occur in the period 2000-2010 instead of the period of dominant change-point occurrence in northern China.

Spatial and temporal clustering of change points demonstrate evidence of anthropogenic influences on flood hydrology (e.g., Vogel et al., 2011; Hodgkins et al., 2019). We Through meta-data inspection of selected stations, we are able to relate some of the abrupt changes in annual flood peaks series to intentional human activities. For instance, the change point in mean at the year of 1986 in the upper Yellow River, the Guide hydrological station, is due to the construction of a large hydropower-generation dam, the Longyangxia Dam (Figure 4a). The Longyangxia Dam is a multi-purpose dam (e.g., flood control, water supply), and controls runoff variability of the entire Yellow River basin (Si et al., 2019). The Guide station is approximately 30 km downstream of the Longyangxia Dam. There are a couple of other hydrological stations distributed further downstream (e.g., Xunhua hydrological station, 120 km downstream), and show change points in mean around the year of 1986 for the annual flood peak series. Anthropogenic regulations on rivers in northern China (especially the middle/lower portion of the Yellow River basin and the upper Haihe River basin) is often characterized with a cascade construction of small reservoirs. We show a flood peak series in the upper Haihe River basin that experienced significant decrease in annual maximum flood peak magnitudes (smaller values both in mean and variance after the change point) around early 1990s, associated with extensive construction of small reservoirs due to an increased demand for irrigation and domestic water supply (Figure 4b). The impact of regulation by dams or reservoirs on flood hydrology has been discussed and debated in previous studies (e.g., Yang et al., 2008; Barros et al., 2014; Ayalew et al., 2017; Lu et al., 2018)(e.g., Yang et al., 2008; Barros et al., 2014; Zhang et al., 20 . For instance, Smith et al. (2010) found limited impacts of dams on flood hydrology in the Delaware River basin, which is not the case for the upper Yellow River basin in our study. This might be related to contrasting physiographic properties of the river basins and/or functions of the dams, and needs further analysis.

Changes in land use/land cover (e.g., urbanization, deforestation/afforestation) can also contribute to change points in the series of annual flood peaks. This is especially the case for stations in the lower Haihe River basin (where the Beijing-Tianjin-Hebei metropolitan region is distributed) and Yangtze River delta region (where Shanghai and other major cities are located). Figure 4c shows a small urban watershed in the lower Yangtze River basin) that experienced rapid urbanization in recent decades. Trans-boundary water transfer Transboundary water-transfer project demonstrates another form of anthropogenic influence on flood hydrology. Abrupt increases in flood peak magnitudes are mainly tied to the elevated base flows transferred from neighbouring neighboring river basins. We provide the annual flood peak series for a station in the lower Yellow River basin (Figure 4d). Increasing water demand from domestic and agricultural sectors in the lower Yellow River basin lead to extensive implementation of water-transfer projects.

Abrupt changes in the series of annual flood peaks can also originate from the changes in extreme rainfall across China. One However, one of our previous studies investigated changes in annual maximum daily rainfall over China, but found no clear signature of spatial clustering for change points in either mean or variance for the rainfall series, although abrupt changes in annual maximum daily rainfall frequently occur occurred in the 1990s (see Figure 2 in Yang et al., 2013). Inconsistent spatial patterns of change points in annual maximum flood peak and annual maximum daily rainfall series may indicate a weak signal role of climate shifts in producing abrupt changes in annual flood peaks.

4.1.2 Monotonic trends

We further examine the monotonic trends of annual flood peak series based on the Mann-Kendall test for those stations that do not show significant change points in mean. There are only 69 stations (accounting for approximately 6% of the total stations) with significant linear trends (Figure 5a). For those stations with significant linear trends, 62 (7) of them exhibits decreasing (increasing) trends. The 62 stations are uniformly distributed across the entire country, indicating a weakening tendency of annual maximum flood peaks over China in recent decades. Abrupt change rather than slowly varying trend is a common mode of ~~the~~ violation of the stationarity assumption for the annual flood peak series over China. For those stations with significant change points in mean, we test the ~~liner~~ linear trends for each sub-series of flood peaks before and after the change point. Almost all stations show decreasing trends for the sub-series either before or after the change point with only a few exceptions (Figure 5b and 5c). Similar with change points in mean and in variance, stations with significant decreasing trends after change points spatially concentrate in northern China, especially the middle and lower portion of the Yellow River basin and the upper Haihe River basin. The decreasing trend in the middle and lower portion of the Yellow ~~river~~ River is most likely due to the implementation of soil conservation practices in its tributary regions (e.g., Bai et al., 2016). There are few stations in southern China that show significant linear trends either before or after change points.

Changes in annual rainfall extremes (i.e., annual maximum daily rainfall) show a “dipole-like" spatial structure over China, with decreasing trends in northern China and increasing trends in the south (e.g., Yang et al., 2013; Ma et al., 2015; Gu et al., 2017b). The decreasing annual maximum flood peaks in northern China may be partially attributed to the weakening rainfall intensity in recent decades. The opposite trends in annual rainfall extremes and annual maximum flood peaks in southern China seem contradictory to our perception. Contrasting trends between intense rainfall and annual high flows are also found over United States (mainly eastern of the Mississippi River), which are attributed to inconsistent changes of intense rainfall in different seasons (Small et al., 2006), i.e., changes in fall precipitation mainly contributes to the trend in annual rainfall extremes, while annual high flows are often observed in spring with no significant changes in rainfall. This is, however, not the case for southern China. Changes in rainfall extremes among all four seasons are dominated by significant or relatively weak increasing trends over southern China (Gu et al., 2017b). Disconnections between changes in annual maximum rainfall and annual flood peaks are also identified in other previous studies (e.g., Ivancic and Shaw, 2015; Berghuijs et al., 2016; Wasko and Nathan, 2019), and point to the additional roles of antecedent watershed wetness and changes in space-time rainfall properties in dominating flood-generation processes (i.e., storm extent, Sharma et al., 2018). Disconnection of changes in rainfall extremes and ~~flood~~ floods as exhibited for the gauges across southern China highlight the complex drivers for flood-generation process, and ~~is worthwhile for~~ merits further investigation.

~~Analysis on the stationarity of annual flood peaks across China point to mixed controls of human activities, external climate factors (i.e., extreme rainfall), and changes in soil moisture on flood hydrology. We note that further attribution analysis can provide additional insights into flood drivers and their changes, but can be challenging. The homogeneity of flood population for flood frequency analysis need to be carefully revisited in a changing environment. This is especially proposed by England et al. (2018) in Hydrology Subcommittee Bulletin 17C as an imminent need to “define flood potentials~~

for watersheds altered by urbanization, wildfires, deforestation, and by reservoirs". Our results highlight the importance of state-of-art process-based approaches (e.g., Wright et al., 2014; Yu et al., 2018) and statistical modeling approaches (Salas et al., 2018; Ser for flood frequency analyses

4.2 Mixture of flood-generation mechanisms

Long-term changes in annual flood peak series highlight the need for better understanding on flood-generation mechanisms across China, especially for northern China that exhibits an overwhelming frequency of stations with nonstationarities.

4.3 Seasonality of annual flood peaks

We examine which can be pursued through the examination of seasonal distribution of annual flood peaksto highlight the mixture of flood-generating systems over China. There are three (two) distinct peaks in the seasonal distribution of annual flood peaks for southern (northern) China (Figure 6). The first peaks peak for both southern and northern China occur around late April, but are resulted from different flood-generating systems. Frequent occurrence flood-generation mechanisms. Frequent occurrences of annual flood peaks around late April in southern China are observed mainly in the southeastern coast, and are caused by frontal systems or associated with early onset of the East Asia Summer Monsoon (e.g., Ding and Chan, 2005; Ding and Zhang, 20 . The April peak of flood frequency in northern China is contributed by localized storm events associated with mid-latitude weather systems in the northwestern part of the country, or related to snow melt in high-altitude regions (Ding and Zhang, 2009). The East Asia Summer Monsoon onsets around early May over mainland China, and moves stepwise northward/northeastward driven by the West Pacific Subtropical High (e.g., Ding and Chan, 2005; Zhang et al., 2017). The monsoon system is characterized with “two abrupt northward jumps and three stationary periods", and plays a deterministic role in the seasonal distribution of flood peaks in both northern and southern China. Frequent flood peaks around late June in the middle and lower portion of the Yangtze River basin contribute to the second peak of seasonal distribution of flood frequency in southern China. Further northward propagation of the monsoon system leads to frequent annual flood peaks in northern China around late July and early August. The summer monsoon retreats back to the south and is weakened afterwards, transferring the dominance in flood-generating flood-generation systems to tropical cyclones and post-monsoon synoptic systems.

Annual flood peaks that are caused by tropical cyclones show a very sharp seasonal distribution, with 70% of them observed in August alone (Figure 6, see section 3 for the association of annual flood peaks with a tropical cyclone). Strong pressure gradients along the western flank of the West Pacific Subtropical High provide favorable synoptic conditions for large-scale moisture transport and north-westward northwestward propagation of tropical cyclones. Interactions of tropical cyclones with mid-latitude systems (e.g., mid-latitude upper-level trough) and regional topography (i.e., Qinling and Tainhang Taihang Mountains) can further enhance tropical cyclone rainfall extreme rainfall associated with landfalling tropical cyclones and the resultant flooding over eastern China (e.g., Svensson and Berndtsson, 1996; Yang et al., 2017; Gu et al., 2017a)China (mainly the eastern part of the country, e.g., Svensson and Berndtsson, 1996; Yang et al., 2017; Gu et al., 2017a). The seasonal distribution of annual flood peaks in northern China is almost overlapped with that of flood peaks caused by tropical cyclones, while tropical cyclones mainly contribute to the third peak of the seasonal distribution for annual flood peaks in southern China (Figure 6). The concurrency of monsoon-controlled storm events and tropical cyclones is a key element of flood hydrometeorology and hydroclimatology in eastern China . As we will further demonstrate in section 4.4, even though landfalling tropical cyclones are relatively more frequent in southern China, annual flood peaks caused by relatively infrequent tropical cyclone visits play a vital role in determining the upper tail properties of flood peak distributions in northern China. Monsoon-related extreme rainfall dominates the upper tail of flood peaks in southern China.

Figure ?? shows stations with significant change points in mean and monotonic trends for the series of annual flood peak timing. Compared to flood peak magnitude, flood peak timing exhibits weak decadal variations. There is a considerably small number of stations with significant change points in mean (and in variance, figure not shown) for flood peak timing. For those stations with significance, they show similar spatial concentration with that for flood peak magnitude (Figure ??a). Abrupt changes in flood peak timing tend to occur during the period 1980-1990, consistent with what we previously found for the annual maximum daily rainfall series over China (Yang et al., 2013). There is a notable spatial split in terms of monotonic trends for flood peak timing, with decreasing (increasing) trends in northern (southern) China (Figure ??b). Villarini (2016) found limited impact of urbanization and river regulations on the average timing of flooding across the continental United States, even though the strength of seasonality is weakened. Delayed occurrence of annual flood peaks is consistent with changes in the seasonality of heavy precipitation across China related to the delayed occurrence of annual maximum daily rainfall in southern China (Gu et al., 2017b). Previous studies show that later onset of East Asia Summer Monsoon and intensified rainfall during the monsoon and post-monsoon season might have leads to the changing seasonality of extreme rainfall over China (Day et al., 2018). Changes in flood peak timing can be resulted from changes in both rainfall and antecedent soil moisture, but are not necessarily related to changes in annual peak rainfall. Contrasting changes in the timing of annual flood peaks point to a tendency for a more centralized hydroclimatology across China Analysis on the seasonal distribution of annual flood peaks over the entire country through minimizing the current shift of seasonal distributions highlight contrasting rainfall climatology between northern and southern China (as presented in Figure 6). Changes in the flood peak timing highlight the necessity of revisiting operation rules for multi-objective dams (i.e., flood-control, hydropower, irrigation, water supply) across China. For instance, reservoir managers in southern China possibly need to consider to delay the release of water storage in reservoirs so that sufficient water be maintained for irrigation and domestic water use. A centralized seasonal distribution of annual flood peaks calls for coordinated flood-control practices across the as well as mixture of flood-generation mechanisms across the entire country.

4.3 Generalized Extreme Value distributionDistribution

We model distributions of annual flood peak magnitudes peaks using the GEV distribution. We only focus on the stations without significant change points in mean or in variance, and without significant monotonic trends . (i.e., the stationary stations). There are 486 stations that satisfy these requirements. These stations are densely located in southern rather than northern China (Figure 7), mostly due to the spatial clustering of stations with abrupt change points in annual flood peaks in northern China (Figure 3). The stationary stations represent a wide range of spatial scales of river drainage basins for both northern and southern China. Figure 8 shows the dependence of GEV parameters on drainage area for the 486 stationary stations. Location and scale parameters are positively correlated with drainage area in a log-log domain. The correlations are all significant at the level of 5%. The shape parameter, however, generally decreases with drainage area but shows only weak dependence in a log-log domain (no statistical significancewith a correlation coefficient of -0.15 for northern China and -0.16 for the south, neither being statistically significant). The upper tail upper-tail properties (as represented by the shape parameter) of flood peak distributions are weakly determined by drainage areaareas, while the magnitude and variability of annual flood peaks can be well explained by drainage area. Our results are consistent with the study in the eastern US United States by Villarini and Smith (2010), and contribute to generalized understandings on the upper tails understanding on the upper-tail properties of flood peak distributions.

An interesting finding for annual flood peaks over China is that there are striking spatial splits in terms of the dependence of the GEV parameters on drainage area areas between northern and southern China (Figure 8). The location and scale parameters for stations in southern China are consistently larger than their counterparts in the north (with a few exceptions, Figure 8a and 8b). The shape parameters in northern China are comparatively larger than that in southern China. Large shape parameters indicate heavier upper tails of flood peak distributions in northern than southern China, even though the magnitudes and variability of flood peaks are relatively smaller in the north. One of our previous studies on the distribution of annual maximum daily rainfall found similar spatial splits for the dependence of GEV parameters on elevation between northern and southern China (Yang et al., 2013) (see also a most recent study by Gu et al., 2017a)(Yang et al., 2013; Gu et al., 2017a). Spatial splits in extreme rainfall distributions highlight spatial heterogeneity in flood hydroclimatology across China (which is also represented by the contrasting seasonal distributions of annual flood peaks shown in section 4.2). Spatial contrasts of extreme rainfall distribution further lead to different relations between the relationships between three GEV parameters and drainage area areas for flood peak distributions between northern and southern China. Regional flood frequency analysis should explicitly address the spatial splits through considering spatial heterogeneity in flood hydroclimatology.

We further show the spatial splits for the shape parameter in Figure 7. The majority of the northern stations show positive shape parameters, while the southern stations are mixed with both negative and positive shape parameters. Contrasting space-time rainfall organizations Spatial contrast in rainfall climatology between northern and southern China seems to be a more effective predictor in explaining the spatial variability of the shape parameter shape parameter rather than drainage area. Our results highlight the importance of hydrometeorological analyses for better characterizations of the upper tail properties of flood peak distributions physical processes that lead to most extreme floods (similarly see e.g., Smith and Baeck, 2015; Yang et al., 2017). Positive shape parameters in northern China indicate flood peak distributions with unbounded upper tails, while negative shape parameters for most southern stations show flood peak distributions with upper boundsare characterized with a bounded upper tail of flood peak distribution. Understandings remain poor pertaining to the nature of the upper tails of flood peak distributions (e.g., Smith et al., 2018)tail of flood peaks (see detailed discussion in e.g., Smith et al., 2018). The bounded upper tails of flood peak distributions tail of flood peaks in the south can be associated with physical constrains over river drainage basins (for instance, large dams for flood-control purposes) and/or the upper bounds to the hydroclimatological processes (see, e.g., Enzel et al., 1993; O'Connor et al., 2002; Serinaldi and Kilsby, 2014)hydrometeorological processes (e.g., Enzel et al.

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4.4 Tropical cyclones and upper ~~tail properties~~tails of flood peaks

~~In this section, we focus on tropical cyclones and their impacts on~~ We examine the impacts of tropical cyclones on the upper-tail properties of flood peak distributions across China in this subsection. As mentioned in previous sections, some of the most extreme floods in the history of China are associated with landfalling tropical cyclones in the western North Pacific basin (e.g., Typhoon Nina). Better characterizations of tropical cyclones and flood hazards associated with them can provide physical insights into the upper-tail properties of flood peak distributions~~over China.~~ .

Tropical cyclones contribute to approximately 18% of annual flood peaks over China. Figure 9 shows the map of the percentage of annual flood peaks that are caused by tropical cyclones to total annual flood peaks for each station. More than 50% of the annual flood peaks are caused by tropical cyclones in the southeastern coast of China, with the percentage even attaining 90% over the Hainan Island. The percentage gradually decreases when we move further inland and to higher latitudes. Less than 10% annual flood peaks can be associated with landfalling tropical cyclones in the middle portion of the Yellow River and Yangtze River basins (Figure 9). The percentage of annual flood peaks caused by tropical cyclones is closely tied to the spatial distribution of tropical cyclone rainfall and frequency of tropical cyclone occurrence over China ~~(Wu et al., 2005; Ren et al., 2010; Gu et al., 2017b)~~(Wu et al., 2005; Ren et al., 2010; Gu et al., 2017b). More than 30% of the extreme rainfall events are induced by tropical cyclones along the coastal regions ~~(Gu et al., 2017a, b)~~(Gu et al., 2017a, b), with the percentage gradually decreased moving inland due to rapid weakening of storm intensity (e.g., surface roughness, insufficient moisture transport).

We ~~further~~ show the stations with record floods (i.e., the largest flood peak for the entire record of a station) that are caused by tropical cyclones in Figure 9 to highlight the impacts of tropical cyclones on the most extreme floods. Stations with record floods caused by tropical cyclones are spatially clustered in the southeastern coast, central and northeastern China (Figure 9). Tropical cyclone-induced record floods in the southeastern coast are mainly associated with abundant moisture and energy supply for extreme rainfall right after tropical cyclones making landfall. However, the spatial clustering of record floods by tropical cyclones in northern China (more specifically, the upper Huaihe River and northeastern China) can be partially related to extratropical transition processes during the life cycle of the storm and/or interactions with regional topography~~(i.e., Taihang and Qinling Mountains),~~ , as will be elaborated below. We do not observe a comparable distribution of record floods caused by tropical cyclones in southern China (e.g., the Yangtze River basin) excluding the coastal regions, even though the percentage of annual flood peaks caused by tropical cyclone is comparable to that in northern China (less than 30%, Figure 9). Our results highlight the impacts of tropical cyclones on flood peak distributions in northern China with a large percentage of record floods caused by relatively infrequent visits of landfalling tropical cyclones.

The ~~impacts~~ impact of tropical cyclones on the upper tail properties of flood peak distributions ~~are~~ is further examined through the shape parameter of the GEV distribution. We compare the shape parameters between the entire annual flood peak series and the series with annual flood peaks caused by tropical cyclones removed (Figure 10). We focus on the series with record length exceeding 30 years after annual flood peaks caused tropical cyclones being removed from the series. This leads to the exclusion of most stations in the southeastern coast due to the high percentage of tropical cyclone-induced ~~annual~~ flood peaks (Figure 9). As can be seen from Figure 10, the scatters are generally distributed along the 1:1 line, indicating overall small changes in the shape parameters between two series. However, if we restrict our attention to the stations with record floods caused by tropical cyclones (mainly those stations in northern China), we observe significantly smaller shape parameters (see the insert box plot in Figure 10) for the series with annual flood peaks caused by tropical cyclones removed. Smaller shape parameter implies a lighter tail of flood peak distribution. Small variations in the shape parameters as demonstrated for the rest of the stations indicate relatively weak impacts of tropical cyclones on the upper tail properties of flood peak distributions. These stations are mainly located in inland regions of southern China. Our results are different from the study of Villarini and Smith (2010) in eastern United States that shows significant decreases in shape parameters for the majority of stations when annual flood peaks caused by tropical cyclones are removed from the series. The differences are tied to contrasting flood-generation mechanisms between China and the eastern USUnited States. Tropical cyclones and extratropical systems play central roles in the mixture of flood-generation mechanisms for the flooding in the eastern US United States (Smith et al., 2011). Extreme rainfall associated with East Asia Summer Monsoon, rather than landfalling tropical cyclones, can be a more important player in characterizing the upper tails tail of flood peak distributions in most inland regions of southern China (e.g., the middle and lower portion of the Yangtze River basin) (Zhang et al., 2017). Tropical cyclones in northern China, even though characterized with low frequency of occurrence, pose significant influences on the upper tail upper-tail properties of flood peak distributions. Contrasting roles of tropical cyclones in flood peak distributions highlight the necessity of tailored procedures for flood-control practices and flood hazard assessment across China. For instance, landfalling tropical cyclones can be good candidates for PMP/PMF designs for river basins in northern rather than southern China.

We focus on tropical cyclones that produced relatively large numbers of flood peaks over China, to shed light on the physical attributes of most severe flood hazards associated with landfallling landfalling tropical cyclones. There are 9 tropical cyclones that produced more than 100 annual flood peaks over China since late 1950s till present. The 9 tropical cyclones alone contribute to approximately 50% of total annual flood peaks caused by tropical cyclones. Figure 11 and Table 1 provide Table 1 provides a summary of the 9 tropical cyclones. Typhoon Herb (1996) produced the largest number of annual flood peaks (167 in total), followed by Typhoon Wendy (1963) and Typhoon Tim (1994). Typhoon Herb (1996) produced a large number of annual flood peaks right after its landfall in mainland China (Figure 11a). Almost all the annual flood peaks caused by other tropical cyclones are distributed over the most inland regions (Figure 11). The percentage of stations with annual flood peaks caused by tropical cyclones relative to total storm-affected stations (i.e., located within 500 km buffer zone of each tropical cyclone track) varies between 14% (Typhoon Doris) and 35% (Typhoon Herb). Typhoon Andy (1982) and Typhoon Russ (1994) lead to annual flood peaks for more than 30% storm-affected stations (Table 1).

The 9 tropical cyclones can be further categorized into two groups according to the nature of the storm and spatial patterns of their tracks. The first group includes Typhoon Herb (1996), Typhoon Andy (1982), and Typhoon Nina (1975). The three tropical cyclones did not experience extratropical transition during the entire life cycle of the storms, and are characterized with two landfalls (i.e., Taiwan and mainland China). The tracks of these three tropical cyclones do not fall into the prevailing tropical cyclone tracks in the Western North Pacific basin (Wu et al., 2005). Typhoon Nina (1995) produced the largest number of record floods (24 in total) among all historical tropical cyclones over China, followed by Typhoon Polly (1960) (14 in total) and Typhoon Andy (1982) (10 in total). Annual flood peaks and record floods caused by tropical cyclones in the first group are frequently observed in northern China (mainly the middle portion of the Yellow River and the upper Huaihe River basins). This region is characterized with complex terrain~~(~~, i.e., Taihang and Qinling Mountains~~)~~. Interactions of tropical cyclones with regional topography can significantly enhance rainfall intensity through orographic lifting, as demonstrated by Typhoon Nina (1975). For instance, historical records of extreme rainfall (e.g., three-day rainfall accumulation exceeding 1000 mm) from Typhoon Nina (1975) were observed in the windward topographic ~~regions~~ region (Yang et al., 2017). The other 6 tropical cyclones ~~in Table 1~~ are categorized into the second group (Figure 11). A common feature for the tropical cyclones in the second group is extratropical transition process during the life cycle of the storms. Annual flood peaks are frequently observed after the extratropical transition process (see the curvatures of tropical cyclone tracks in the latitudes around 30° in Figure 11), and are frequently observed in northern China. Except Typhoon Herb (1996), 4 of the top 5 largest number of annual flood peaks are caused by tropical cyclones with extratropical transition.

There ~~are no strong preferences~~ is no strong preference for the spatial distribution of annual flood peaks with respect to storm tracks (i.e., left or right of the track), even though the records floods caused by tropical cyclones tend to be frequently observed in the left-front quadrant (typically the down-shear side) of the circulations. This is related to the preferable distribution of extreme tropical cyclone rainfall, due to enhanced moisture convergence and updraft on the down-shear side of the circulation (e.g., Atallah et al., 2007; Shu et al., 2018). ~~Future studies need to investigate variabilities in the physical properties of river basins (i.e., drainage area, slope, shape) and their relationships with flood peaks (i.e., frequency and magnitude) caused by tropical cyclones, to shed more light on flood hazards associated with landfalling tropical cyclones over China.~~

5 Summary and Conclusions

In this study, we examine flood peak distributions over China based on 1120 stream gauging stations with continuous records of annual maximum instantaneous discharge for more than 50 years. The principal findings of this study can be summarized as follows.

(1) There are 38% and 35% stations exhibiting significant change points in mean and in variance, respectively. Change points tend to occur during the period 1980-2000, and show strong a spatial concentration in the lower Yellow River, upper Huaihe River, the entire Haihe River, upper Yangtze and Pearl River basins. Hydrological regimes in these regions demonstrate intensive anthropogenic influences, for instance, large ~~hydropower generation dam~~hydro-power generation dams, cascade constructions of small-capacity reservoirs, ~~trans-boundary water transfer~~ transboundary water-transfer projects, soil-water conservation projects, urbanization. There is a weak signal of climate impacts on the abrupt changes in annual flood ~~peaks~~ series across China. Abrupt change is the dominant mode of ~~the violation of~~ violation of the stationary assumption for annual flood peaks over China.

(2) Approximately 6% stations (69 in total) show significant linear trends in the annual flood peak series. Those stations with significant trends are uniformly distributed across the country, with 62 of them exhibiting significantly decreasing trends. The decreasing trends of flood peak magnitude in northern China may be at least partially tied to changes in extreme rainfall.

Disconnections between changes in annual rainfall extremes and annual maximum floods are identified in southern China, and highlight complex flood-generation processes across China. The dominance of decreasing trends in annual flood peak series indicates weakening tendencies of severe flood hazards (i.e., annual maximum floods) over China, even though flood-affected area and economic damages are on the rise in recent decades (Kundzewicz et al., 2019). Future studies need to further examine changes in flood frequency for a complete assessment on flood hazards (based on peaks-over-threshold flood series, similarly see, e.g., Mallakpour and Villarini, 2015).

(3) ~~Flood-generation systems over China show a mixture of East Asia Summer Monsoon, tropical cyclones, and extratropical systems. There is a temporal shift in the seasonal distribution of flood peaks between northern and southern China. Compared to flood peak magnitude, there are fewer stations exhibiting significant change points and/or linear trends in flood peak timing. For those stations with significant linear trends in flood peak timing, the decreasing trends tend to occur in northern China, while the opposite is true for southern China. Changes in flood peak timing tend to minimize the shift of seasonal distribution of annual flood peaks between northern and southern China, leading to centralized seasonality of annual maximum floods over China.~~

~~(4) We fitted~~ We fit GEV distribution for the stationary time series of annual flood peaks, and examined the dependence of its parameters on drainage area. We ~~found~~ find that the location and scale parameters are linearly scaled with drainage area in a log-log domain. There is only a weak tendency for the shape parameters to decrease as a function of drainage area. Our results ~~are consistent with previous studies, and~~ highlight scale-independent properties of upper tails of ~~annual~~ flood peaks. The relationships between GEV parameters and drainage area show strong spatial splits between northern and southern China, indicating space-time rainfall organization as an important player in determining the upper-tail properties of flood peak distributions over China. Procedures for regional flood frequency analysis ~~over China~~ should explicitly address ~~spatial~~ the spatial splits through considering spatial heterogeneity in flood hydroclimatology.

(~~5)~~ 4) Flood-generation systems over China show a mixture of monsoon, tropical cyclones, and extratropical systems. Tropical cyclone plays an important role in characterizing spatial-temporal variability of flood peaks and the upper-tail properties of flood peak distributions over China. More than 50% of the annual flood peaks in the southeastern coast are caused by tropical cyclones. The percentage progressively decreases when we move further inland and to higher latitudes. Tropical cyclones lead to heavier tails of flood peak distributions (with larger shape parameters of the GEV distribution) in northern China. Those regions are characterized with record floods frequently associated with tropical cyclones, despite that tropical cyclone visits relatively infrequently compared to the southern China. Record floods in southern China are more frequently associated with monsoon-related extreme rainfall ~~events rather than~~ rather than landfalling tropical cyclones. We highlight the importance of considering the mixture of ~~flood-generating~~ flood-generation mechanisms in flood frequency analyses especially in northern China. Contrasting roles of tropical cyclones in flood peak distributions highlight the necessity of tailored procedures for flood-control practices and flood hazard assessment across China. For instance, landfalling tropical cyclones can be good candidates for PMP/PMF designs for drainage basins in northern rather than southern China.

(~~6)~~ 5) Tropical cyclone plays an important role in most severe flood hazards in the history of China. There are 9 tropical cyclones that produced more than 100 annual flood peaks over China~~. The 9 tropical cyclones contribute~~ , contributing to approximately 50% of total annual flood peaks caused by all historical tropical cyclones. Large The large number of annual flood peaks is associated with extended spatial coverages of extreme rainfall after the storms going through the processes of extratropical transition. It can also be An additional feature for severe flood hazards is tied to favorable synoptic set-up for persistent moisture transport after the storm making landfall, as demonstrated by Typhoon Herb (1996), Typhoon Andy (1982), and Typhoon Nina (1975). Interaction of tropical cyclone with regional topography (i.e., Taihang and Qinling Mountains) is a key element for severe flood hazards most extreme floods in central China (mainly the middle/lower Yellow River basin and upper Huaihe River basin). Annual flood peaks caused by tropical cyclones do not show strong spatial preference preferences with respect to the tracktracks, even though the record floods tend to be frequently observed in the left-front quadrant of the circulation. Typhoon Nina (1975) produced the largest number of record floods, and plays a critical role in shaping the envelope curve of floods over China. Hydrometeorological analyses can provide improved characterization on the physical attributes of flood hazards associated with Hydrometeorological analyses can provide improved physical characterization on severe flood hazards associated with landfalling tropical cyclones (see e.g., Yang et al., 2017).

Attribution analysis on the nonstationarities of annual flood peaks across China point to mixed controls of human activities, external climate factors (i.e., extreme rainfall), and changes in soil moisture on flood hydrology. The homogeneity of flood population for flood frequency analysis needs to be carefully revisited in a changing environment. This is especially proposed by England et al. (2018) in Hydrology Subcommittee Bulletin 17C as an imminent need to “define flood potentials for watersheds altered by urbanization, wildfires, deforestation, and by reservoirs". Innovative approaches that explicitly address the nonstationarities should be embraced for flood frequency analysis across China, for instance, process-based approaches that rely on physically-based hydrological modelling which can represent the processes of nonstationarities in flood series (see e.g., Wright et al., 2014; Yu et al., 2018) , statistical modelling approaches that mathematically parametrize the role of human regulations in flood series based on the framework of probability theory (Salas et al., 2018; Serago and Vogel, 2018; Gao et al., 2019; Dong et al., 2019; Barth et al., 2019) . These approaches should be especially in great needs for northern China that exhibits an overwhelming portion of stations with nonstationarities in flood series.

Our results highlight the important role of landfalling tropical cyclones (e.g., Yang et al., 2017)in determining the upper tails of flood peak distributions across China, especially the northern China and the southeastern coast. Previous studies show strong teleconnections between the activities of tropical cyclones over tropical cyclone activity in the western North Pacific basin and large-scale atmospheric forcingclimate variability, e.g., the El Niño-Southern Oscillation (ENSO, e.g., Chan and Shi, 1996; Chan, 2000) (e.g., Chan and Shi, 1996; Chan, 2000), Madden-Julian Oscillation (MJO, Kim et al., 2008). (e.g., Kim et al., 2008). Statistical models that adopt varying parameters on time or other predictors (such as, large-scale climate indices) can provide predictive tools of understanding future changes in flood hazards associated with landfalling tropical cyclones (e.g., Zhang et al., 2018c). Future studies need to investigate the linkage between tropical cyclone floods and remote atmospheric forcing (similarly see, e.g., Aryal et a to better understand decadal changes in flood hazards zoom into watershed scales, and explore physical connections between extreme flood processes and key tropical cyclone features (e.g., space-time structures of tropical cyclone rainfall, tropical cyclone intensity), to provide additional insights into flood hazard associated with landfalling tropical cyclonesover China.

A unique feature of our study is a nation-wide assessment of flood hazard based on an unprecedented network of stream gauging stations across China. Comprehensive analysis based on the exceptional dataset over China, together with studies by Villarini et al. (2009) and Burn and Whitfield (2018) in North America, Blöschl et al. (2017, 2019) in European countries, among others, promotes improved understandings on flood hydrology and hydroclimatology under a changing environment from a global perspective. A future endeavor will further exploit the dataset through developing a data archive of key hydrological indices that is accessible to worldwide research community.

Data availability. The data used in this research are collected from distributed hydrological offices of major river basins over China. The dataset is unavailable to access due to licensing issues at the moment.

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Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Summary of tropical cyclones that produced more than 100 annual flood peaks over China. All the stations that are located within the 500 km buffer zone of each tropical cyclone track are counted. The “storm type" column shows whether the tropical cyclone experienced extratropical transition (ET) or not (TS).

Rank	Storm name	Total No. of storm-affected stations	Total No. of annual flood peaks	No. of record floods	Storm type
1	Herb (1996)	465	167	4	TS
2	Wendy (1963)	622	159	6	ET
3	Tim (1994)	591	156	2	ET
4	Freda (1984)	634	144	2	ET
5	Doris (1961)	836	119	2	ET
6	Winnie (1997)	482	114	0	ET
7	Andy (1982)	375	111	10	TS
8	Russ (1994)	330	104	1	ET
9	Nina (1975)	441	102	24	TS

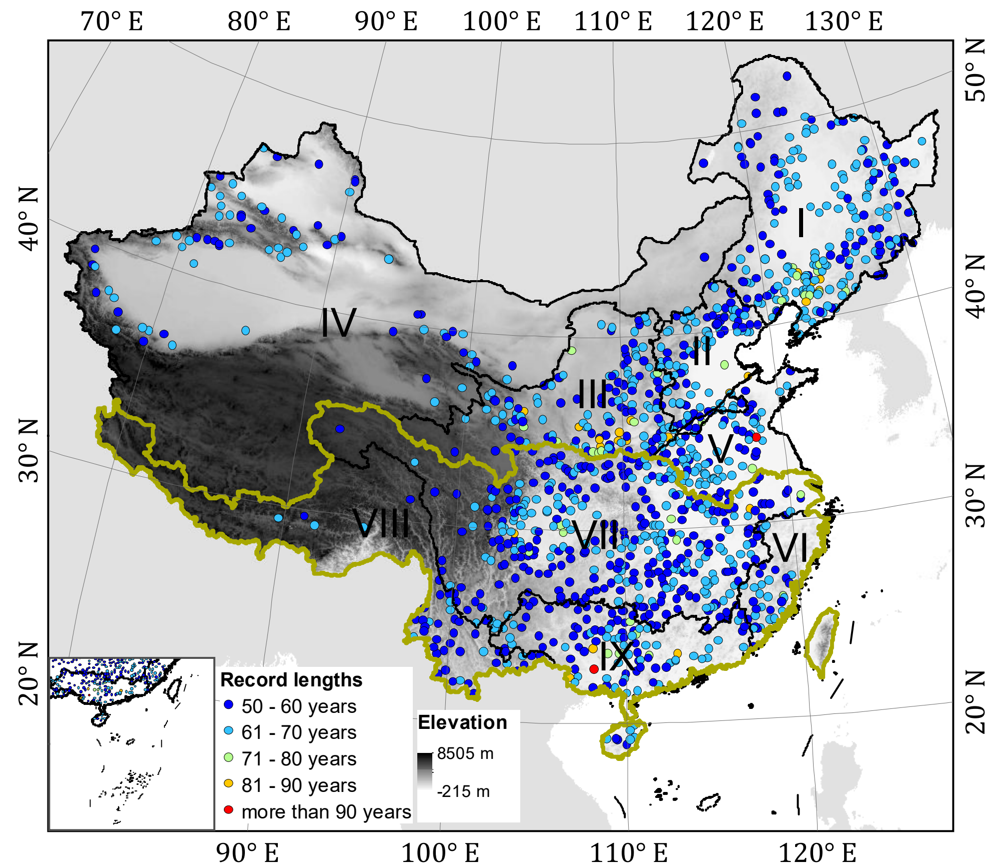

Figure 1. Overview of the stream gauging stations ~~(blue dots)~~ with record lengths of more than 50 years over China (1120 gauges in total). ~~Shaded color~~ Scatter shading represents the record length (in years) for each station. The grey shading represents topography, while the black lines represent the first-level hydrologic units. The Roman numerals highlight the nine major hydrologic units in China: I-Northeastern river basins, II-Haihe River basin, III-Yellow River Basin, IV-Northwestern river basins, V-Huaihe River basin, VI-Southeastern river basins, VII-Yangtze River basin, VIII-Southwestern river basin, and IX-Pearl River basin. ~~Red~~ Olive line shows the boundary of river basins in southern China (VI-IX), with the rest of the river basins in northern China (I-V).

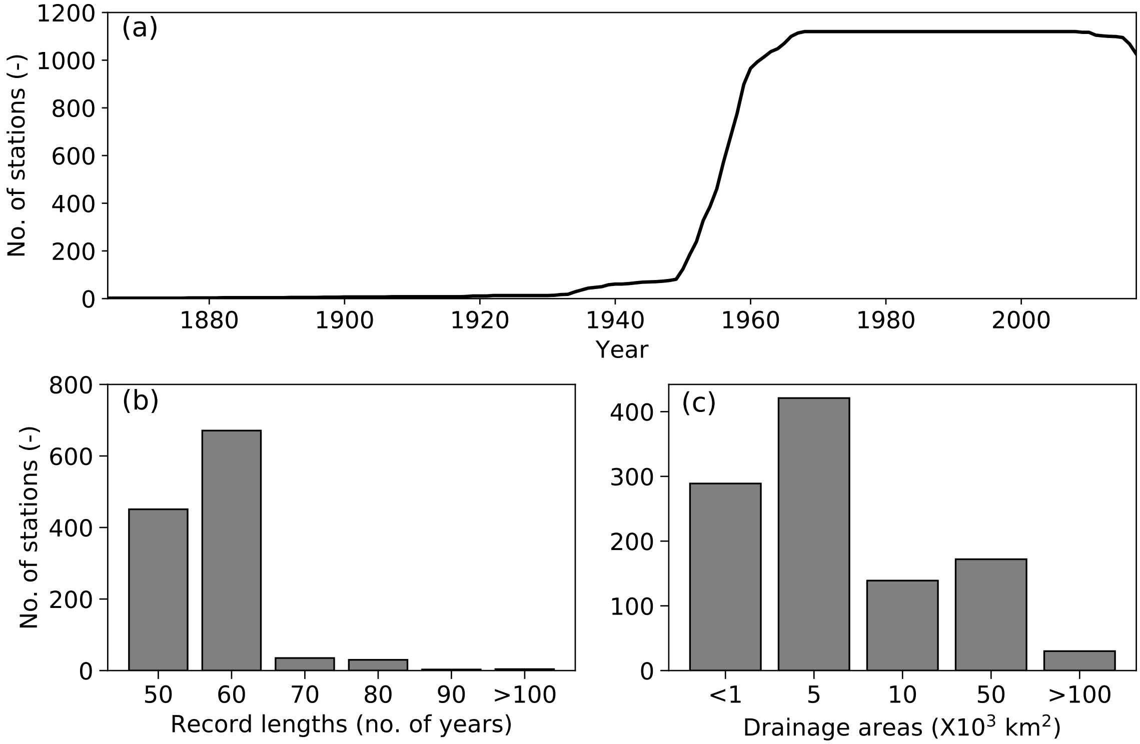

Figure 2. (a) Time series of total number of available stations (with record lengths of more than 50 years) for each year. Histograms of all the 1120 stream gauging stations sorted by (ab) record lengths and (bc) drainage areaareas.

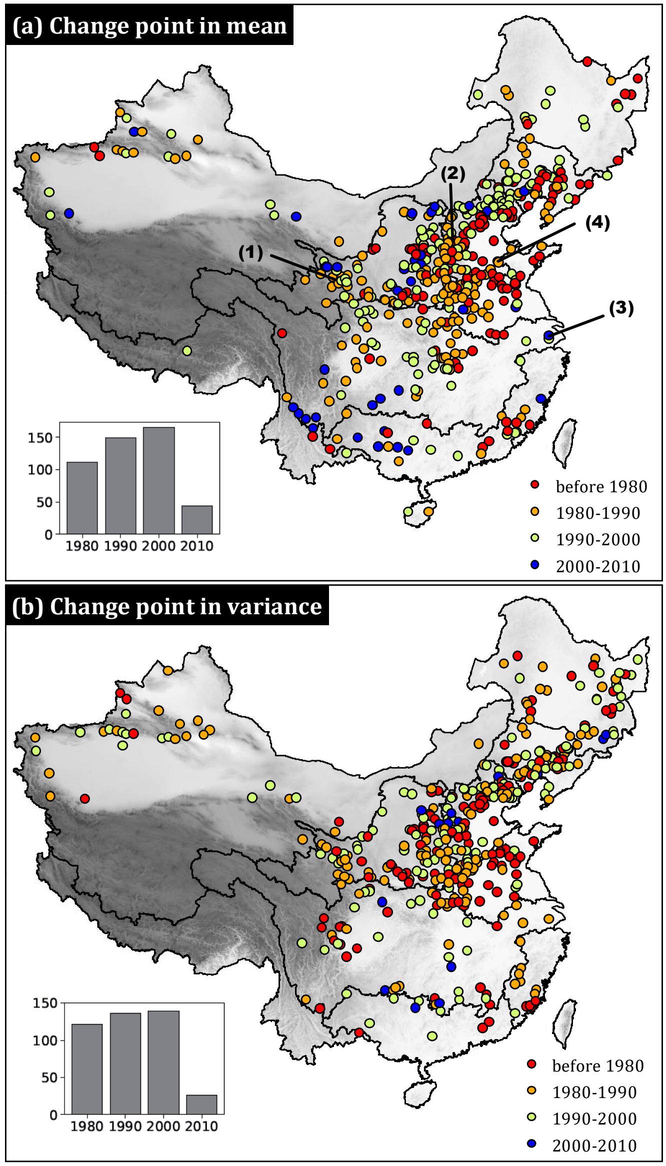

Figure 3. Change points in (a) mean and (b) variance. Color represents the year of change-point occurrence. The insert plot shows the histogram of the years of change-point occurrence (y-axis represents the number of change points, while x-axis represents the ending year of a 10-year period, e.g., 1990 actually means 1980-1990). ~~Results are~~ Only stations with results being statistically significant (at the level of 5%) are shown.

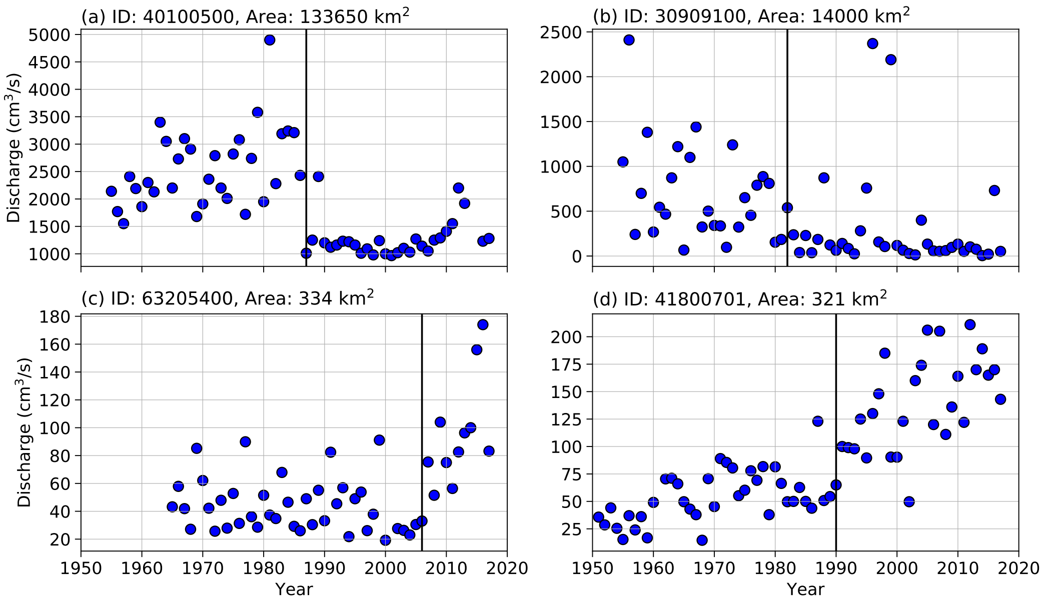

Figure 4. Time series of annual flood peaks for four stream gauging stations with strong human interventions: (a) large hydroelectric dams (upper Yellow River, ID: 40100500~~, 36.00^{o}N, 101.40^{o}E~~), (b) a cascade of small reservoirs (upper Haihe River, ID: 30909100~~, 38.39^{o}N, 113.71^{o}E~~), (c) urbanization (a tributary in the lower Yangtze River, ID: 63205400~~, 31.20^{o}E, 120.66^{o}E~~), and (d) ~~water transfer~~ transboundary water-transfer project (a tributary in the lower Yellow River, ID: 41800701). Locations of the four stations are represented by the numbers in brackets in Figure 3, ~~36.71^{o}N, 117.07^{o}E~~with (1) to (4) corresponding to (a) to (d), respectively. Black lines indicate the year of occurrence for change point in mean. Results are based on the Pettitt's test~~, and are~~. Only stations with Pettitt's test being statistically significant (at the level of 5%) are shown.

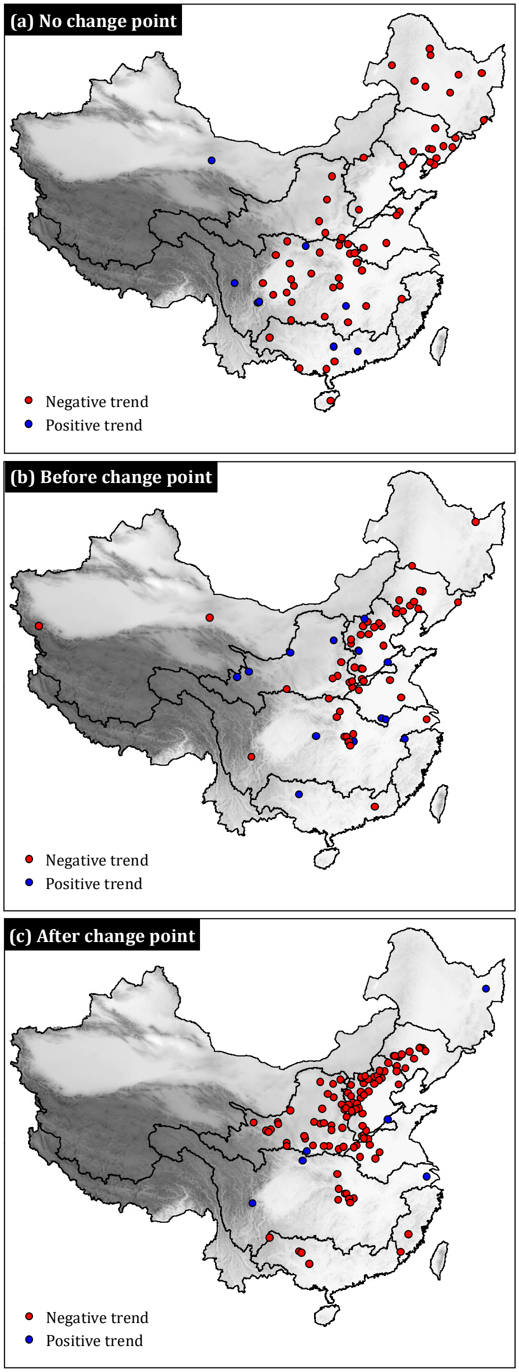

Figure 5. Mann-Kendall test results for stations (a) without change point in mean and (b,c) with change point in mean. Results are statistically significant at the level of 5%. Different number of data points between (b) and (c) are associated with (1) insufficient record lengths for sub-groups before or after change points, (2) linear trends for either sub-group being not statistically significant.

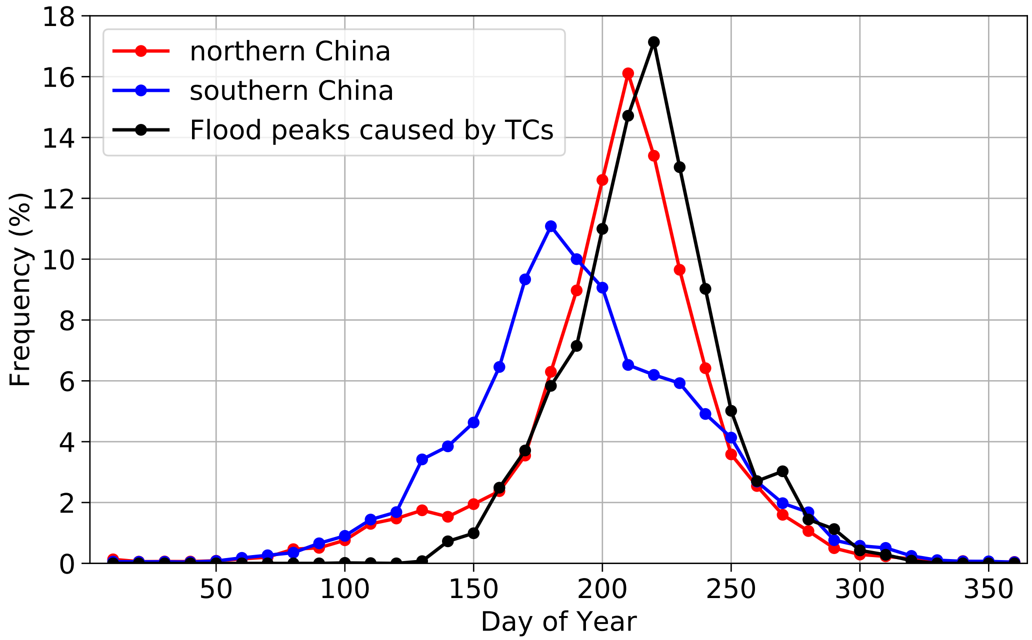

Figure 6. Seasonality of annual maximum flood peaks for northern China (red), southern China (blue), and annual flood peaks caused by tropical cyclones (black).

(a) Change point in mean for time series of annual flood peak timing (represented by day of the year). Color represents the year of change-point occurrence. (b) Mann-Kendall test for stations without change point in mean for the annual flood peak timing. Results are statistically significant at the level of 5%.

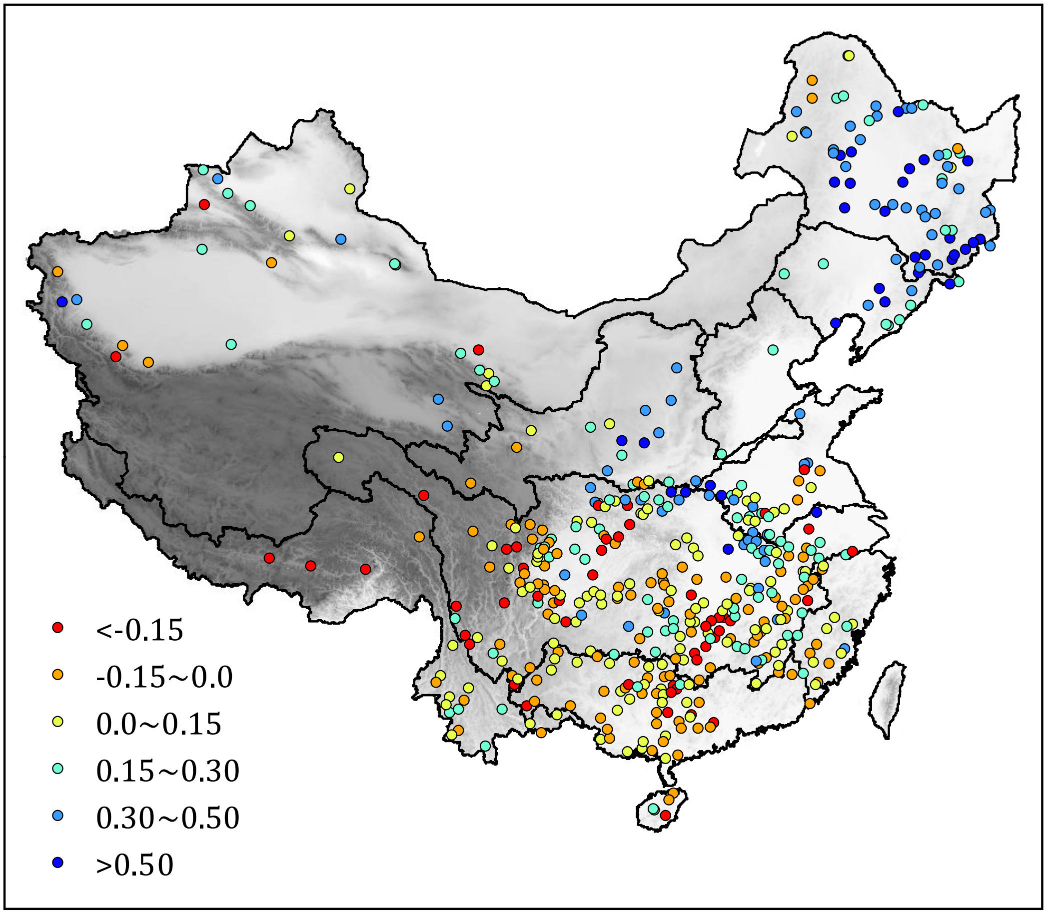

Figure 7. Map of the GEV shape parameters for the stationary time series of annual flood peaks.

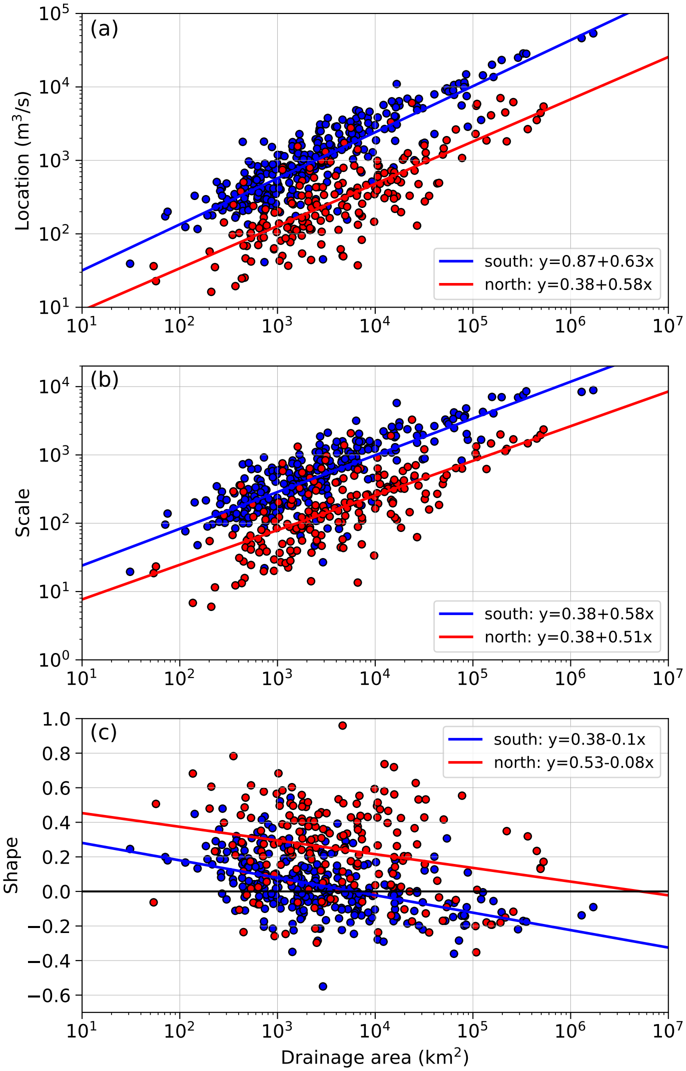

Figure 8. Scatterplots of GEV parameters (a) location, (b) scale, and (c) shape, as a function of drainage areas. Blue (red) scatters represent stations over south (north) China.

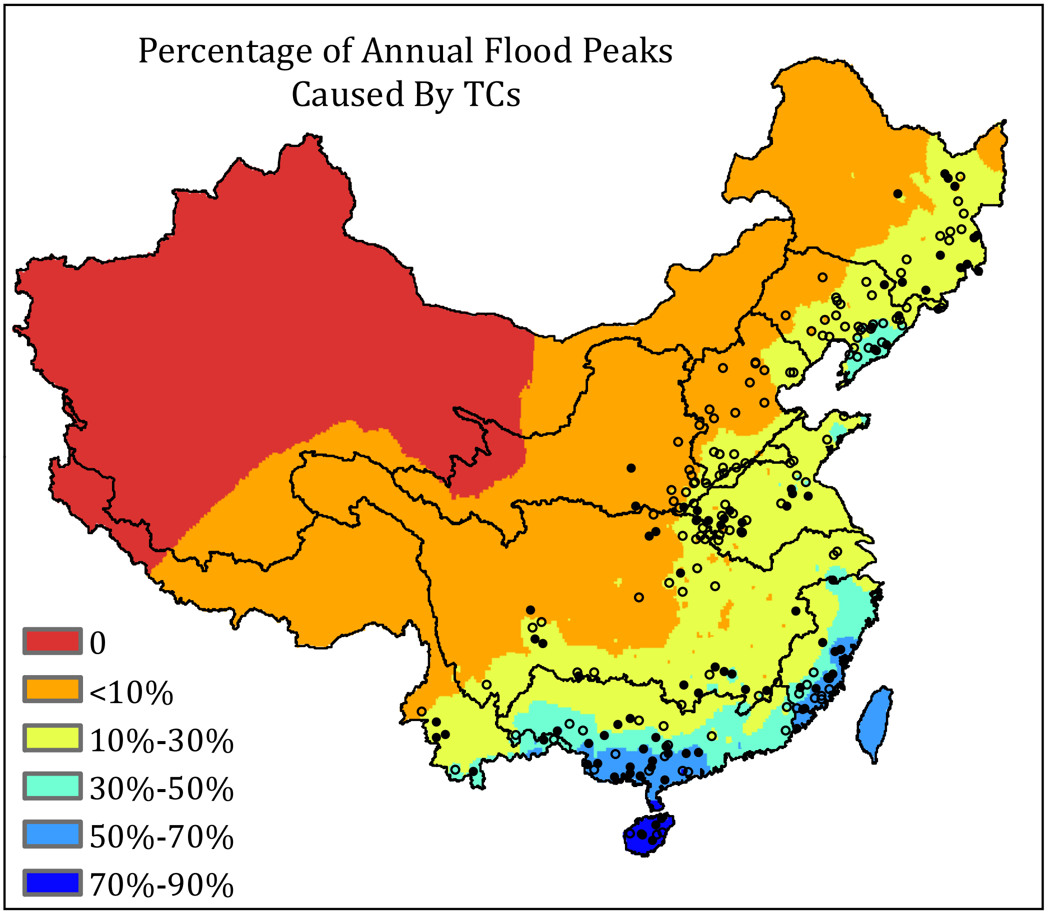

Figure 9. Percentage of annual flood peaks that are caused by tropical cyclones. The black dots and circles represent the stations with record floods caused by tropical cyclones. The black dots further highlight stations with stationary time series of annual flood peaks.

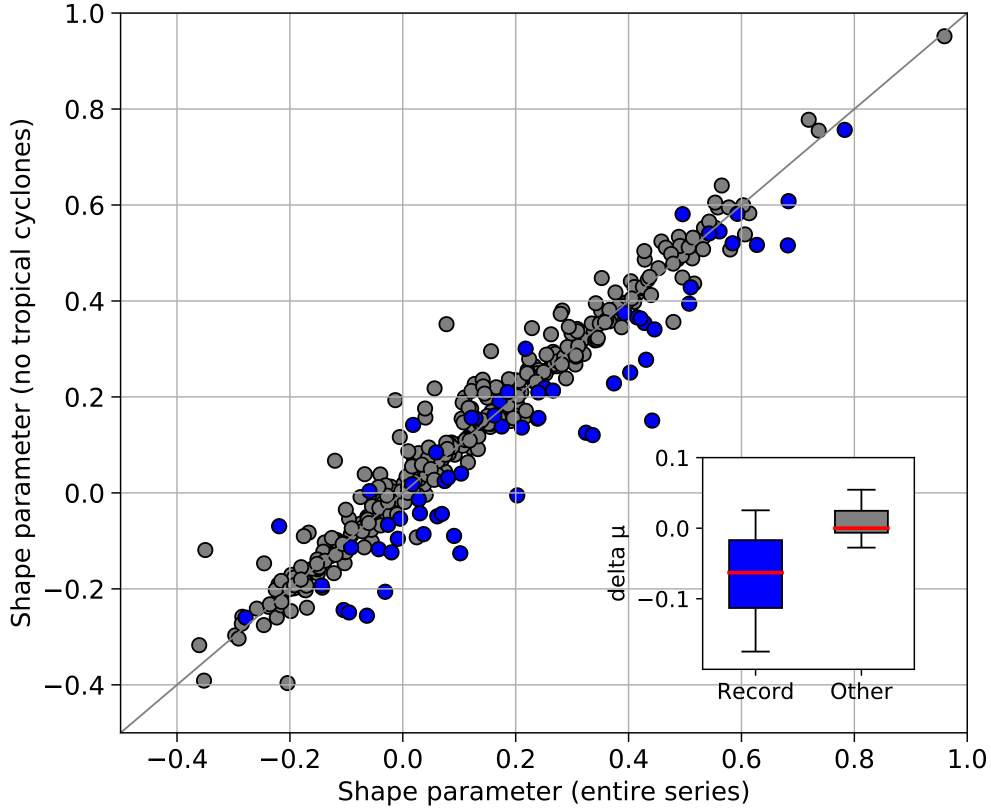

Figure 10. Scatterplot of the shape parameters for the entire series versus the series with annual flood peaks caused by tropical cyclones removed. Blue dots highlight the stations with record floods that are caused by tropical cyclones (see Figure 1 for locations). The insert boxplot shows the differences of shape parameter (series with TC flood peaks removed minus the entire series) for stations with (blue) and without (grey) TC-induced record floods.

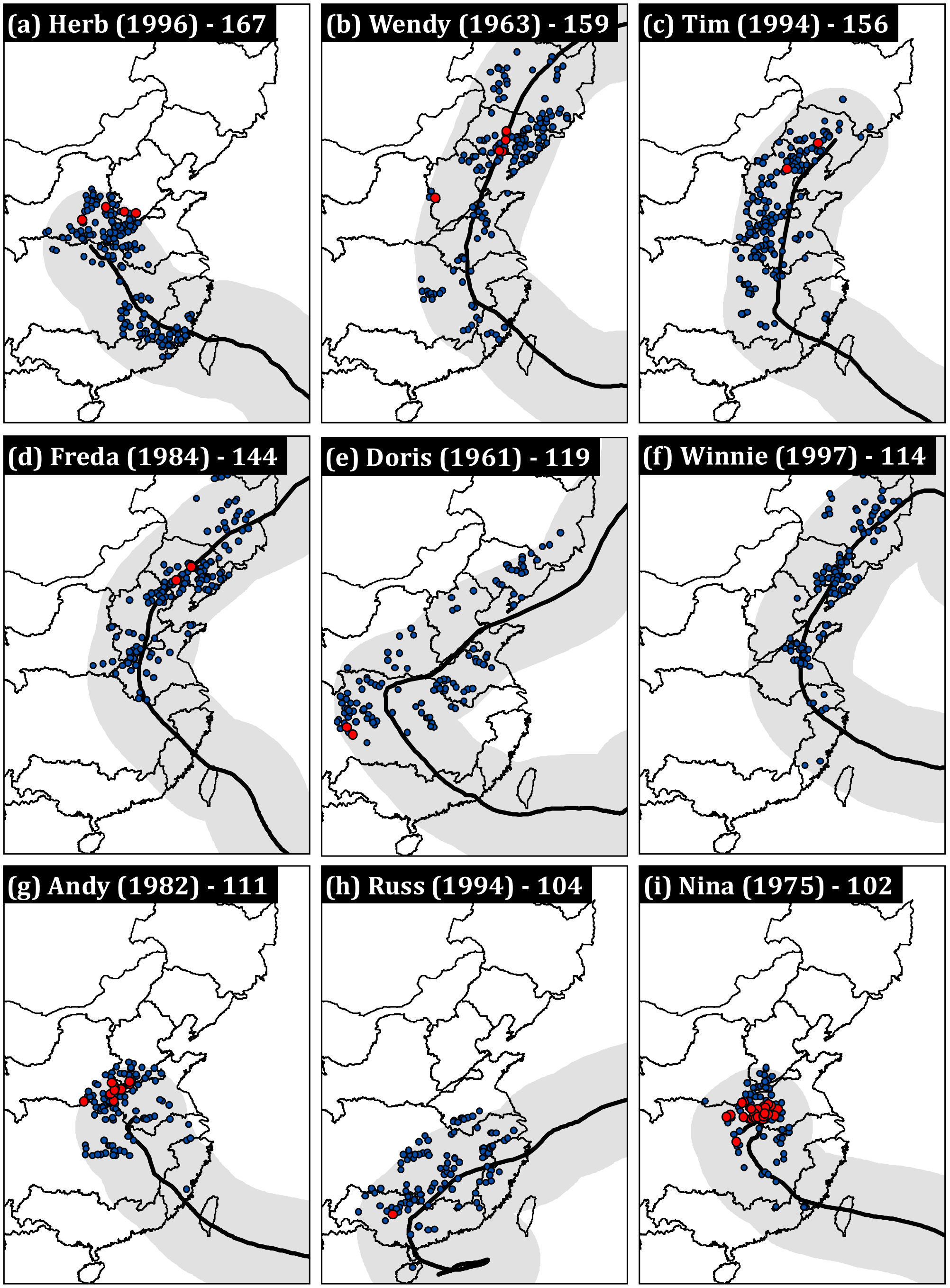

Figure 11. Tropical cyclones that produced more than 100 annual flood peaks (blue dots) over China. Red dots highlight that the annual flood peak is also the record flood of the station. Dark black line shows tropical cyclone track. Grey shading represents 500 km buffer zone of each track. See Table 1 for more details.

On the Flood Peak Distributions over China

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Abstract. Here we for the first time present a nation-wide characterization of flood hazard across China. Our analysis is based on an exceptional dataset of 1120 stream gauging stations with continuous records of annual flood peaks for at least 50 years across the entire country. Our results are organized by centering on various aspects of flood peak distributions, including temporal changes in flood series and their spatial variations, statistical distribution of extreme values, and properties of storms that lead to annual flood peaks. These aspects altogether contribute to improved understandings of flood hydrology under a changing environment over China, and promote the advance of flood science at the global scale. Historical changes in annual flood peaks demonstrate frequent abrupt changes rather than slowly varying trends. The dominance of decreasing annual flood peak magnitudes indicates a weakening tendency of flood hazard over China in recent decades. We model the upper tails of flood peaks based on the Generalized Extreme Value (GEV) distributions. The GEV shape parameter is weakly dependent on drainage area, but shows spatial splits tied to rainfall climatology between northern and southern China. Landfalling tropical cyclone plays an important role in characterizing the upper-tail properties of flood peak distributions especially in northern China and southeastern coast, while the upper tails of flood peaks are dominated by extreme monsoon rainfall in southern China. Severe flood hazards associated with landfalling tropical cyclones are characterized with complex interactions of storm circulation with synoptic environment (i.e., mid-latitude baroclinic disturbances) and regional topography.

1 Introduction

We examine flood peak distributions over China based on 1120 stream gauging stations with continuous records of annual maximum flood peaks for at least 50 years. The ultimate goal of our study is to provide improved characterization of flood hazard across China from both statistical and physical perspectives. This involves a comprehensive suite of analyses that investigate temporal nonstationarities in annual flood peaks (i.e., temporal distribution), flood peak distribution based on extreme value theory (i.e., statistical distribution) and critical factors (in terms of both physiography and climate) that determine the upper tails of flood peaks (i.e., spatial distribution).

Hydrological regimes in most river basins over China, like the rest of the world, have experienced strong anthropogenic influences (i.e., river regulations, land use changes). Human-related impacts on flood hydrology are further complicated by detectable changes in external factors that are critical for flood-generation processes, such as temperature and extreme rainfall, even though it remains unsettled whether the changes are due to natural climate variability or human-induced climate change (e.g., Held and Soden, 2006; Marvel and Bonfils, 2013; Trenberth et al., 2015; Schaller et al., 2016; Risser and Wehner, 2017; Eden et al., 2017). The stationarity assumption of flood series has been questioned and debated in scientific community (Milly et al., 2008; Montanari and Koutsoyiannis, 2014; Salas et al., 2018). Extensive studies on the stationarity of annual flood peaks have been carried out in many parts of the world (e.g., Robson et al., 1998; Robson, 2002; Franks and Kuczera, 2002; Villarini et al., 2009; Petrow and Merz, 2009; Villarini et al., 2011; Ishak et al., 2013; Tan and Gan, 2014; Mediero et al., 2014; Hodgkins et al., 2019), including some efforts in global-scale investigations of historical changes in flood series (e.g., Arnell and Gosling, 2016; Do et al., 2017, 2019). Due to the limitation of observational datasets, existing knowledge on flood hazard is significantly biased towards Europe and North America, with the characteristics of other worldwide regions (including China) far from being well represented. There are some regional studies across China (e.g., Zhang et al., 2016, 2014, 2018b; Liu et al., 2018). A nation-wide investigation on the stationarity in flood series over China, however, is still missing. The exceptional dataset of annual flood peaks, as demonstrated in present study, will provide additional evidence for detectable changes in flood hydrology under a changing environment. Better understanding of historical changes in annual flood peaks is of paramount importance for constraining model-based projections of flood hazards (e.g., Milly et al., 2002; Hirabayashi et al., 2013; Dankers et al., 2014; Arnell and Gosling, 2016). In this study, we expect to explore the dominant mode (i.e., abrupt changes or slowly varying trends) of nonstationarities in flood series, and highlight potential factors that induce the changes in annual flood peaks.

Improved understanding of flood hazard requires essential knowledge of flood-generation mechanisms. This is also a critical aspect to consider for improved flood frequency analysis (Hirschboeck, 1988; Singh et al., 2005; Leonard et al., 2014; Brooks and Day, 2015; Yan et al., 2017, 2019). Smith et al. (2018) shows that the most extreme flood peaks are frequently determined by extreme events resulted from anomalous flood agents for particular regions of the United States (which is the notion of “strange floods"). Mixture of flood-generation mechanisms poses great challenges for characterizing the upper tails of flood peaks, as different flood agents might lead to flood regimes with distinct statistics (e.g., magnitude, timing, frequency). This is, however, often the case for many regions in the world (e.g., Jarrett and Costa, 1988; Smith et al., 2011; Villarini, 2016; Blöschl et al., 2017; Smith et al., 2018; England et al., 2018). We expect annual flood peaks over China characterized with a mixture of flood-generation mechanisms, due to its geographic location in a monsoon-climate region and on the margin of the most active ocean in tropical cyclones. China suffers the most frequent landfalling tropical cyclones in the world, with 9 tropical cyclones making landfall on average per year (Jiang and Jiang, 2014). Despite its significance, little is known about the hydroclimatology of flooding associated with landfalling tropical cyclones. Even less effort has been spent on investigating the impacts of different flood-generation mechanisms on the upper-tail properties of flood peaks across China. This is a critical issue for China that shows contrasting rainfall climatology (under combined influences from monsoon and landfalling tropical cyclones) between the northern and southern part of the country (i.e., traditionally take the Yangtze River as the geographic divide) (e.g., Yang et al., 2013; Gu et al., 2017a; Zhang et al., 2018a). Extreme floods for different regions are often associated with contrasting flood agents. This is not merely associated with the nature of flood agents themselves, but is also determined by complex interplay of storms with ambient synoptic and physiographic environment. For instance, extreme rainfall from landfalling tropical cyclones can be amplified through interactions of storm circulation with mid-latitude baroclinic disturbances (e.g., Hart and Evans, 2000) and regional topography (e.g., Houze, 2012). Propagation of monsoon also plays a role in determining the spatial contrasts of flood agents through regulating temporal occurrences of flood peaks over different regions (e.g., Ding and Zhang, 2009). Knowledge in the mixed flood-generation mechanisms and their spatial variations can provide valuable insights into improved procedures for the estimates of Probable Maximum Precipitation (PMP) / Probable Maximum Flood (PMF) in designing flood-control infrastructures (e.g., Smith and Baeck, 2015; Yang et al., 2017).

An important way of characterizing flood hazards is through examining flood peak distributions and factors that determine the upper-tail properties. In this study, we model annual flood peaks based on the statistical framework of the generalized extreme value (GEV) distributions (similarly see e.g., Katz et al., 2002; Morrison and Smith, 2002; Villarini and Smith, 2010; Barros et al., 2014; Bates et al., 2015; Gaume, 2018; Smith et al., 2018). The key focus is placed on the upper tails of flood peaks across China. Previous studies show strong dependence of location and scale parameters for the GEV distributions on drainage area, while the GEV shape parameters only weakly depend on drainage area (Morrison and Smith, 2002; Villarini and Smith, 2010). Weak dependence of the GEV shape parameters on drainage area indicate scale-independent properties of the upper tails of flood peaks, and highlight additional factors (e.g., spatio-temporal rainfall variability) in determining the upper tails of flood peaks. Yang et al. (2013) identified a spatial contrast of extreme rainfall distributions between northern and southern China and pointed to contrasting flood hydroclimatology across the country. We therefore propose that similar spatial contrasts also exist in flood peak distributions across China.

Our study is also motivated by Typhoon Nina and the resultant August 1975 flood in central China. The August 1975 flood in central China, with 26000 direct fatalities, is one of the most destructive floods in the world history (Yang et al., 2017). The unit peak discharge is 17 $m^3s^{-1}km^{-2}$ (i.e., flood peak discharge divided by drainage area) for a 760 km^2 drainage basin, and is on the list of the world maximum floods. The August 1975 flood plays a key role in shaping the envelop curve of floods in China and different versions of the world envelop curve (Yang et al., 2017; Costa, 1987). Devastating consequences of Typhoon Nina and the August 1975 flood partially resulted from cascading collapses of dozens of dams, and expose inadequacies of conventional approaches for flood frequency analysis (e.g., fitting historical flood records with assumed distribution functions) (e.g., Smith and Baeck, 2015; Yang et al., 2017). This is an urgent issue for China, as statistics show socio-economic damages caused by tropical cyclones are rapidly increasing in recent decades, with a large portion of the damages resulted from riverine flooding (Zhang et al., 2009; Rappaport, 2014).

Based on the aforementioned gap of our knowledge in flood hydrology, we examine flood peak distributions across China by centering on the following questions: (1) What is the dominant mode of the violation of stationarity in annual flood peak series? (2) How do dominant flood-generation mechanisms vary across China? (3) How do upper-tail properties of flood peak distributions depend on drainage areas (i.e., scale-dependence) and rainfall climatology? (4) What is the impact of landfalling tropical cyclones on the upper tails of flood peaks across China? (5) What are the characteristics of the most severe flood hazards (i.e., as represented by the number of stations with annual flood peaks) in the history of China and the tropical cyclones that induce them? Even though these questions are examined based on an exclusive dataset over China, timely answers to these questions will undoubtedly contribute to the compliment of our limited understandings on flood hazard under a changing environment, and promote the advance of flood science at the global scale.

2 Data

Our analysis is based on observations of annual maximum instantaneous peak discharge from 1120 stream gauging stations with continuous records of at least 50 years (i.e., no missing data consecutively throughout the entire periods). There are relatively more stations distributed in eastern China than the western part of the country (Figure 1). The dataset is comprehensively collected from local hydrographic offices of nine major river basins across China. All these stations are nation-level control stations with the records that have been through strict quality control procedures to ensure data consistency and accuracy. For instance, the dates of annual maximum flood peak and highest stage should be comparable, with records of missing flood peak timing discarded to ensure data accuracy. Stations with notable site re-locations (i.e., that lead to changes in drainage area) during the observational periods are not included in this dataset. The flood records demonstrate a variety of ways in data collection, mainly include intermittent direct measurements of discharge during flood season, indirect inferences through stage-discharge rating curves, and post-flood field surveys.

Time series of total number of available stations are shown in Figure 2a. The longest flood record is 153 years, with approximately more than 90% stations fully available during the period from 1960 to 2017. The record length of 66% stations exceeds 60 years starting from 1950s till the year of 2017 (Figure 2b). There are considerable variabilities in the spatial scales of represented river basins, with a large percentage (approximately 64%) of stations representing small and medium river basins (with drainage areas less than 5000 km^2, Figure 2c). Previous studies found contrasting climate regimes and extreme rainfall distributions between northern and southern China (e.g., Yang et al., 2013; Ma et al., 2015). To facilitate analyses and comparisons, we further classify the 1120 stations into two sub-groups, i.e., northern and southern China, based on their geographic locations (Figure 1). The northern group includes stations mainly in northeastern river basins, the Yellow River basin, the Huaihe River basin, and the Haihe River basin, while the southern group includes southeastern river basins, southwestern river basins, the Yangtze River basin, and the Pearl River basin.

3 Methodology

3.1 Change point and trend analysis

We use the non-parametric Pettitt's test (Pettitt, 1979) to examine the presence of abrupt changes in annual flood peak series. Pettitt's test is a rank-based test that relies on the Mann-Whitney statistic to test whether two samples come from the same population. There are no assumed distributions for the test, which makes it less sensitive to outliers and skewed distributions. It allows for the detection of a single change point in mean at an unknown point in time, with the test significance computed using the given formulation. We further apply the Pettitt's test on the squared residuals derived with respect to the local polynomial regression line (loess function, Cleveland, 1979) to detect change point in variance in annual flood peak series (similarly see, e.g., Villarini et al., 2009; Villarini and Smith, 2010; Yang et al., 2013). We also adopted a different change-point detection approach, i.e., the one proposed by Matteson and James (2014), but only found negligible deviations from the results based on Pettitt's test (results not shown).

Monotonic trends can be induced by existence of abrupt change points in mean rather than indicating slowly varying trend for the flood series. For those series that do not show significant abrupt change points in mean, we directly use the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) to examine the presence of monotonically increasing or decreasing trends in annual flood peak series. For the series with change point in mean, we divide it into two sub-groups and test monotonic trends for each of the two sub-groups (i.e., before and after the change point). Additional trend analysis for the sub-series can highlight stations that show both abrupt changes and slowly varying trend in the entire flood series. We assume the existence of only a single change point in mean for each flood peak series in this study, to avoid dividing the series into too many segments (similarly see, e.g., Villarini et al., 2009, 2012). Only sub-series with record lengths exceeding 10 years are considered in the trend analysis. We set a significance level of 5% (i.e., two-tailed) for both the change-point and trend tests.

3.2 Generalized Extreme Value distribution

The Generalized Extreme Value (GEV) distribution is used to statistically model distributions of annual maximum flood peaks (e.g., Coles, 2001; Villarini and Smith, 2010). The GEV, based on extreme value theory, has been widely used in flood frequency analysis (e.g., Coles, 2001; Katz et al., 2002; Morrison and Smith, 2002; Villarini and Smith, 2010). The cumulative distribution function of the GEV takes the form:

$$F(x|\mu,\sigma,\xi) = exp\left\{-[1+\xi(\frac{x-\mu}{\sigma})]^{-1/\xi}\right\} \qquad (1)$$

where μ, σ, and ξ represents the location, scale, and shape parameter, respectively. The location (μ) and scale (σ) parameter is related to the magnitude and variability of the records, respectively. The shape parameter (ξ) indicates the tail properties of the distribution, with positive (negative) values pointing to heavy and unbounded (light and bounded) upper tail of flood peak distribution. The GEV parameters are estimated based on the maximum likelihood estimators (e.g., Coles, 2001). We fit the GEV distributions only for stations without statistically significant change points in mean and variance and monotonic trends, following the basic assumption of probability theory that data samples should be independent and identically distributed. The three fitted GEV parameters (i.e., location, scale and shape) will be further used to examine their correlations with drainage areas, shedding light on the scale-dependence of the upper-tail properties of flood peak distributions across China.

3.3 Association of flood peaks with tropical cyclones

We associate an annual flood peak of a given stream gauging station with a particular tropical cyclone by following the procedures, i.e., if the center of a tropical cyclone is within 500 km of the gauging station during a time window of two weeks centered on the occurrence time of the flood peak. The spatial and temporal thresholds reflect the mean spatial extent of tropical cyclone rainfall (e.g., Rios Gaona et al., 2018), and the upper limit of flood response time (similarly also see, e.g., Hart and Evans, 2000; Villarini and Smith, 2010; Smith et al., 2011; Villarini et al., 2014). We obtain the information of tropical cyclones from the International Best Track Archive for Climate Stewardship (IBTrACS, see https://www.ncdc.noaa.gov/ibtracs/ for details). The dataset provides records of the circulation center location (latitude and longitude) and storm intensity (represented by minimum sea level pressure) at a temporal interval of 6 hours. An additional attribute provided by IBTrACS for each tropical cyclone at each time interval is the nature of the storm, i.e., extratropical transition or tropical storm. Extratropical transition (ET) characterizes the changing properties of a tropical cyclone from a warm-core, symmetric structure to a cold-core, asymmetrical structure (e.g. Hart and Evans, 2000). Physical process associated with extratropical transition plays an important role in determining the spatial distribution of tropical cyclone rainfall (e.g. Atallah and Bosart, 2003; Atallah et al., 2007; Liu and Smith, 2016). Tropical storm (TS), as a contrast, indicates the maintenance of a warm-core, symmetric structure during the entire life cycle of the storm.

4 Results and discussion

The structure of this section is organized as follows. We first detect change points and monotonic trends to shed light on the long-term changes in flood series across China, and discuss possible drivers that induce them (subsection 4.1). We move on to subsection 4.2 to examine seasonal distribution of annual flood peaks, highlighting the mixture of flood-generation mechanisms across China and its spatial variation. Results from both subsection 4.1 and 4.2 will serve the basis for the analysis of subsection 4.3 that delves into the upper-tail properties of flood peak distributions across China, focusing on the spatial distributions of the GEV parameters as well as their dependence on drainage areas and rainfall climatology. Subsection 4.4 will specifically examine the impacts of tropical cyclones on extreme floods, to shed light on the statistical and physical characteristics of most extreme floods in the history of China.

4.1 Stationarity

4.1.1 Abrupt changes

Figure 3 shows the results of change-point analyses for annual flood peaks based on the Pettitt's test. There are 436 (38%) and 398 (35%) stations with significant change points in mean and in variance, respectively. 27% stations show change points both in mean and in variance. The majority of stations tend to show smaller values in mean (383 stations) and variance (305 stations) after than before the change point (figure not shown). Change points in both mean and variance show striking spatial concentration in northern China (i.e., the lower Yellow River basin, the upper Huaihe River basin, and the entire Haihe River basin). Change points in both mean and in variance are frequently observed during the period 1980-2000, with slightly larger frequency of occurrence during the period 1990-2000. We observe an additional amount of change points in mean distributed in the downstream of southwestern river basins and in the upper and middle portion of the Yangtze River and Pearl River basins (Figure 3a). These change points tend to occur in the period 2000-2010 instead of the period of dominant change-point occurrence in northern China.

Spatial and temporal clustering of change points demonstrate evidence of anthropogenic influences on flood hydrology (e.g., Vogel et al., 2011; Hodgkins et al., 2019). Through meta-data inspection of selected stations, we are able to relate some of the abrupt changes in annual flood peaks to intentional human activities. For instance, the change point in mean at the year of 1986 in the upper Yellow River, the Guide hydrological station, is due to the construction of a large hydropower-generation dam, the Longyangxia Dam (Figure 4a). The Longyangxia Dam is a multi-purpose dam (e.g., flood control, water supply), and controls runoff variability of the entire Yellow River basin (Si et al., 2019). The Guide station is approximately 30 km downstream of the Longyangxia Dam. There are a couple of other hydrological stations distributed further downstream (e.g., Xunhua hydrological station, 120 km downstream), and show change points in mean around the year of 1986 for the annual flood peak series. Anthropogenic regulations on rivers in northern China (especially the middle/lower portion of the Yellow River basin and the upper Haihe River basin) is often characterized with a cascade construction of small reservoirs. We show a flood peak series in the upper Haihe River basin that experienced significant decrease in annual maximum flood peak magnitudes (smaller values both in mean and variance after the change point) around early 1990s, associated with extensive construction of small reservoirs due to an increased demand for irrigation and domestic water supply (Figure 4b). The impact of regulation by dams or reservoirs on flood hydrology has been discussed and debated in previous studies (e.g., Yang et al., 2008; Barros et al., 2014; Zhang et al., 2015; Ayalew et al., 2017; Lu et al., 2018). For instance, Smith et al. (2010) found limited impacts of dams on flood hydrology in the Delaware River basin, which is not the case for the upper Yellow River basin in our study. This might be related to contrasting physiographic properties of the river basins and/or functions of the dams, and needs further analysis.

Changes in land use/land cover (e.g., urbanization, deforestation/afforestation) can also contribute to change points in the series of annual flood peaks. This is especially the case for stations in the lower Haihe River basin (where the Beijing-Tianjin-Hebei metropolitan region is distributed) and Yangtze River delta region (where Shanghai and other major cities are located). Figure 4c shows a small urban watershed in the lower Yangtze River basin) that experienced rapid urbanization in recent decades. Transboundary water-transfer project demonstrates another form of anthropogenic influence on flood hydrology. Abrupt increases in flood peak magnitudes are mainly tied to the elevated base flows transferred from neighboring river basins. We provide the annual flood peak series for a station in the lower Yellow River basin (Figure 4d). Increasing water demand from domestic and agricultural sectors in the lower Yellow River basin lead to extensive implementation of water-transfer projects.

Abrupt changes in the series of annual flood peaks can also originate from the changes in extreme rainfall across China. However, one of our previous studies investigated changes in annual maximum daily rainfall over China, but found no clear signature of spatial clustering for change points in either mean or variance for the rainfall series, although abrupt changes in annual maximum daily rainfall frequently occurred in the 1990s (see Figure 2 in Yang et al., 2013). Inconsistent spatial patterns of change points in annual maximum flood peak and annual maximum daily rainfall series indicate a weak role of climate shifts in producing abrupt changes in annual flood peaks.

4.1.2 Monotonic trends

We further examine the monotonic trends of annual flood peak series based on the Mann-Kendall test for those stations that do not show significant change points in mean. There are only 69 stations (accounting for approximately 6% of the total stations) with significant linear trends (Figure 5a). For those stations with significant linear trends, 62 (7) of them exhibits decreasing (increasing) trends. The 62 stations are uniformly distributed across the entire country, indicating a weakening tendency of annual maximum flood peaks over China in recent decades. Abrupt change rather than slowly varying trend is a common mode of violation of the stationarity assumption for the annual flood peak series over China. For those stations with significant change points in mean, we test the linear trends for each sub-series of flood peaks before and after the change point. Almost all stations show decreasing trends for the sub-series either before or after the change point with only a few exceptions (Figure 5b and 5c). Similar with change points in mean and in variance, stations with significant decreasing trends after change points spatially concentrate in northern China, especially the middle and lower portion of the Yellow River basin and the upper Haihe River basin. The decreasing trend in the middle and lower portion of the Yellow River is most likely due to the implementation of soil conservation practices in its tributary regions (e.g., Bai et al., 2016). There are few stations in southern China that show significant linear trends either before or after change points.

Changes in annual rainfall extremes (i.e., annual maximum daily rainfall) show a “dipole-like" spatial structure over China, with decreasing trends in northern China and increasing trends in the south (e.g., Yang et al., 2013; Ma et al., 2015; Gu et al., 2017b). The decreasing annual maximum flood peaks in northern China may be partially attributed to the weakening rainfall intensity in recent decades. The opposite trends in annual rainfall extremes and annual maximum flood peaks in southern China seem contradictory to our perception. Contrasting trends between intense rainfall and annual high flows are also found over United States (mainly eastern of the Mississippi River), which are attributed to inconsistent changes of intense rainfall in different seasons (Small et al., 2006), i.e., changes in fall precipitation mainly contributes to the trend in annual rainfall extremes, while annual high flows are often observed in spring with no significant changes in rainfall. This is, however, not the case for southern China. Changes in rainfall extremes among all four seasons are dominated by significant or relatively weak increasing trends over southern China (Gu et al., 2017b). Disconnections between changes in annual maximum rainfall and annual flood peaks are also identified in other previous studies (e.g., Ivancic and Shaw, 2015; Berghuijs et al., 2016; Wasko and Nathan, 2019), and point to the additional roles of antecedent watershed wetness and changes in space-time rainfall properties in dominating flood-generation processes (i.e., storm extent, Sharma et al., 2018). Disconnection of changes in rainfall extremes and floods as exhibited for the gauges across southern China highlight the complex drivers for flood-generation process, and merits further investigation.

4.2 Mixture of flood-generation mechanisms

Long-term changes in annual flood peak series highlight the need for better understanding on flood-generation mechanisms across China, which can be pursued through the examination of seasonal distribution of annual flood peaks. There are three (two) distinct peaks in the seasonal distribution of annual flood peaks for southern (northern) China (Figure 6). The first peak for both southern and northern China occur around late April, but are resulted from different flood-generation mechanisms. Frequent occurrences of annual flood peaks around late April in southern China are observed mainly in the southeastern coast, and are caused by frontal systems or associated with early onset of the East Asia Summer Monsoon (e.g., Ding and Chan, 2005; Ding and Zhang, 2009). The April peak of flood frequency in northern China is contributed by localized storm events associated with mid-latitude weather systems in the northwestern part of the country, or related to snow melt in high-altitude regions (Ding and Zhang, 2009). The East Asia Summer Monsoon onsets around early May over mainland China, and moves stepwise northward/northeastward driven by the West Pacific Subtropical High (e.g., Ding and Chan, 2005; Zhang et al., 2017). The monsoon system is characterized with “two abrupt northward jumps and three stationary periods", and plays a deterministic role in the seasonal distribution of flood peaks in both northern and southern China. Frequent flood peaks around late June in the middle and lower portion of the Yangtze River basin contribute to the second peak of seasonal distribution of flood frequency in southern China. Further northward propagation of the monsoon system leads to frequent annual flood peaks in northern China around late July and early August. The summer monsoon retreats back to the south and is weakened afterwards, transferring the dominance in flood-generation systems to tropical cyclones and post-monsoon synoptic systems.

Annual flood peaks that are caused by tropical cyclones show a very sharp seasonal distribution, with 70% of them observed in August alone (Figure 6, see section 3 for the association of annual flood peaks with a tropical cyclone). Strong pressure gradients along the western flank of the West Pacific Subtropical High provide favorable synoptic conditions for large-scale moisture transport and northwestward propagation of tropical cyclones. Interactions of tropical cyclones with mid-latitude systems (e.g., mid-latitude upper-level trough) and regional topography (i.e., Qinling and Taihang Mountains) can further enhance extreme rainfall associated with landfalling tropical cyclones and the resultant flooding over China (mainly the eastern part of the country, e.g., Svensson and Berndtsson, 1996; Yang et al., 2017; Gu et al., 2017a). The seasonal distribution of annual flood peaks in northern China is almost overlapped with that of flood peaks caused by tropical cyclones, while tropical cyclones mainly contribute to the third peak of the seasonal distribution for annual flood peaks in southern China (Figure 6). The concurrency of monsoon-controlled storm events and tropical cyclones is a key element of flood hydroclimatology across China Analysis on the seasonal distribution of annual flood peaks highlight contrasting rainfall climatology between northern and southern China as well as mixture of flood-generation mechanisms across the entire country.

4.3 Extreme Value Distribution

We model distributions of annual flood peaks using the GEV distribution. We only focus on the stations without significant change points in mean or in variance, and without significant monotonic trends (i.e., the stationary stations). There are 486 stations that satisfy these requirements. These stations are densely located in southern rather than northern China (Figure 7), mostly due to the spatial clustering of stations with abrupt change points in annual flood peaks in northern China (Figure 3). The stationary stations represent a wide range of spatial scales of drainage basins for both northern and southern China. Figure 8 shows the dependence of GEV parameters on drainage area for the 486 stationary stations. Location and scale parameters are positively correlated with drainage area in a log-log domain. The correlations are all significant at the level of 5%. The shape parameter, however, generally decreases with drainage area but shows only weak dependence in a log-log domain (with a correlation coefficient of -0.15 for northern China and -0.16 for the south, neither being statistically significant). The upper-tail properties (as represented by the shape parameter) of flood peak distributions are weakly determined by drainage areas, while the magnitude and variability of annual flood peaks can be well explained by drainage area. Our results are consistent with the study in the eastern United States by Villarini and Smith (2010), and contribute to generalized understanding on the upper-tail properties of flood peak distributions.

An interesting finding is that there are striking spatial splits in terms of the dependence of the GEV parameters on drainage areas between northern and southern China (Figure 8). The location and scale parameters for stations in southern China are consistently larger than their counterparts in the north (with a few exceptions, Figure 8a and 8b). The shape parameters in northern China are comparatively larger than that in southern China. Large shape parameters indicate heavier upper tails of flood peak distributions in northern than southern China, even though the magnitudes and variability of flood peaks are relatively smaller in the north. One of our previous studies on the distribution of annual maximum daily rainfall found similar spatial splits for the dependence of GEV parameters on elevation between northern and southern China (Yang et al., 2013; Gu et al., 2017a). Spatial splits in extreme rainfall distributions highlight spatial heterogeneity in flood hydroclimatology across China (which is also represented by the contrasting seasonal distributions of annual flood peaks shown in section 4.2). Spatial contrasts of extreme rainfall distribution further lead to different relationships between three GEV parameters and drainage areas for flood peak distributions between northern and southern China.

We further show the spatial splits for the shape parameter in Figure 7. The majority of the northern stations show positive shape parameters, while the southern stations are mixed with both negative and positive shape parameters. Spatial contrast in rainfall climatology between northern and southern China seems to be a more effective predictor in explaining the spatial variability of shape parameter rather than drainage area. Our results highlight the importance of hydrometeorological analyses for better characterizations of the physical processes that lead to most extreme floods (similarly see e.g., Smith and Baeck, 2015; Yang et al., 2017). Positive shape parameters in northern China indicate flood peak distributions with unbounded upper tails, while negative shape parameters for most southern stations are characterized with a bounded upper tail of flood peak distribution. Understandings remain poor pertaining to the nature of the upper tail of flood peaks (see detailed discussion in e.g., Smith et al., 2018). The bounded upper tail of flood peaks in the south can be associated with physical constrains over drainage basins (for instance, large dams for flood-control purposes) and/or the upper bounds to the hydrometeorological processes (e.g., Enzel et al., 1993; O'Connor et al., 2002; Serinaldi and Kilsby, 2014).

4.4 Tropical cyclones and upper tails of flood peaks

We examine the impacts of tropical cyclones on the upper-tail properties of flood peak distributions across China in this subsection. As mentioned in previous sections, some of the most extreme floods in the history of China are associated with landfalling tropical cyclones in the western North Pacific basin (e.g., Typhoon Nina). Better characterizations of tropical cyclones and flood hazards associated with them can provide physical insights into the upper-tail properties of flood peak distributions.

Tropical cyclones contribute to approximately 18% of annual flood peaks over China. Figure 9 shows the map of the percentage of annual flood peaks that are caused by tropical cyclones to total annual flood peaks for each station. More than 50%

of the annual flood peaks are caused by tropical cyclones in the southeastern coast of China, with the percentage even attaining 90% over the Hainan Island. The percentage gradually decreases when we move further inland and to higher latitudes. Less than 10% annual flood peaks can be associated with landfalling tropical cyclones in the middle portion of the Yellow River and Yangtze River basins (Figure 9). The percentage of annual flood peaks caused by tropical cyclones is closely tied to the spatial distribution of tropical cyclone rainfall and frequency of tropical cyclone occurrence over China (Wu et al., 2005; Ren et al., 2010; Gu et al., 2017b). More than 30% of the extreme rainfall events are induced by tropical cyclones along the coastal regions (Gu et al., 2017a, b), with the percentage gradually decreased moving inland due to rapid weakening of storm intensity (e.g., surface roughness, insufficient moisture transport).

We show the stations with record floods (i.e., the largest flood peak for the entire record of a station) that are caused by tropical cyclones in Figure 9 to highlight the impacts of tropical cyclones on the most extreme floods. Stations with record floods caused by tropical cyclones are spatially clustered in the southeastern coast, central and northeastern China (Figure 9). Tropical cyclone-induced record floods in the southeastern coast are mainly associated with abundant moisture and energy supply for extreme rainfall right after tropical cyclones making landfall. However, the spatial clustering of record floods by tropical cyclones in northern China (more specifically, the upper Huaihe River and northeastern China) can be partially related to extratropical transition processes during the life cycle of the storm and/or interactions with regional topography, as will be elaborated below. We do not observe a comparable distribution of record floods caused by tropical cyclones in southern China (e.g., the Yangtze River basin) excluding the coastal regions, even though the percentage of annual flood peaks caused by tropical cyclone is comparable to that in northern China (less than 30%, Figure 9). Our results highlight the impacts of tropical cyclones on flood peak distributions in northern China with a large percentage of record floods caused by relatively infrequent visits of landfalling tropical cyclones.

The impact of tropical cyclones on the upper tail properties of flood peak distributions is further examined through the shape parameter of the GEV distribution. We compare the shape parameters between the entire annual flood peak series and the series with annual flood peaks caused by tropical cyclones removed (Figure 10). We focus on the series with record length exceeding 30 years after annual flood peaks caused tropical cyclones being removed from the series. This leads to the exclusion of most stations in the southeastern coast due to the high percentage of tropical cyclone-induced flood peaks (Figure 9). As can be seen from Figure 10, the scatters are generally distributed along the 1:1 line, indicating overall small changes in the shape parameters between two series. However, if we restrict our attention to the stations with record floods caused by tropical cyclones (mainly those stations in northern China), we observe significantly smaller shape parameters (see the insert box plot in Figure 10) for the series with annual flood peaks caused by tropical cyclones removed. Smaller shape parameter implies a lighter tail of flood peak distribution. Small variations in the shape parameters as demonstrated for the rest of the stations indicate relatively weak impacts of tropical cyclones on the upper tail properties of flood peak distributions. These stations are mainly located in inland regions of southern China. Our results are different from the study of Villarini and Smith (2010) in eastern United States that shows significant decreases in shape parameters for the majority of stations when annual flood peaks caused by tropical cyclones are removed from the series. The differences are tied to contrasting flood-generation mechanisms between China and the eastern United States. Tropical cyclones and extratropical systems play central roles in the mixture of flood-generation mechanisms for the flooding in the eastern United States (Smith et al., 2011). Extreme rainfall associated with East Asia Summer Monsoon, rather than landfalling tropical cyclones, can be a more important player in characterizing the upper tail of flood peak distributions in most inland regions of southern China (e.g., the middle and lower portion of the Yangtze River basin) (Zhang et al., 2017). Tropical cyclones in northern China, even though characterized with low frequency of occurrence, pose significant influences on the upper-tail properties of flood peak distributions.

We focus on tropical cyclones that produced relatively large numbers of flood peaks over China, to shed light on the physical attributes of most severe flood hazards associated with landfalling tropical cyclones. There are 9 tropical cyclones that produced more than 100 annual flood peaks over China since late 1950s till present. The 9 tropical cyclones alone contribute to approximately 50% of total annual flood peaks caused by tropical cyclones. Table 1 provides a summary of the 9 tropical cyclones. Typhoon Herb (1996) produced the largest number of annual flood peaks (167 in total), followed by Typhoon Wendy (1963) and Typhoon Tim (1994). Typhoon Herb (1996) produced a large number of annual flood peaks right after its landfall in mainland China (Figure 11a). Almost all the annual flood peaks caused by other tropical cyclones are distributed over the most inland regions (Figure 11). The percentage of stations with annual flood peaks caused by tropical cyclones relative to total storm-affected stations (i.e., located within 500 km buffer zone of each tropical cyclone track) varies between 14% (Typhoon Doris) and 35% (Typhoon Herb). Typhoon Andy (1982) and Typhoon Russ (1994) lead to annual flood peaks for more than 30% storm-affected stations (Table 1).

The 9 tropical cyclones can be further categorized into two groups according to the nature of the storm and spatial patterns of their tracks. The first group includes Typhoon Herb (1996), Typhoon Andy (1982), and Typhoon Nina (1975). The three tropical cyclones did not experience extratropical transition during the entire life cycle of the storms, and are characterized with two landfalls (i.e., Taiwan and mainland China). The tracks of these three tropical cyclones do not fall into the prevailing tropical cyclone tracks in the Western North Pacific basin (Wu et al., 2005). Typhoon Nina (1995) produced the largest number of record floods (24 in total) among all historical tropical cyclones over China, followed by Typhoon Polly (1960) (14 in total) and Typhoon Andy (1982) (10 in total). Annual flood peaks and record floods caused by tropical cyclones in the first group are frequently observed in northern China (mainly the middle portion of the Yellow River and the upper Huaihe River basins). This region is characterized with complex terrain, i.e., Taihang and Qinling Mountains. Interactions of tropical cyclones with regional topography can significantly enhance rainfall intensity through orographic lifting, as demonstrated by Typhoon Nina (1975). For instance, historical records of extreme rainfall (e.g., three-day rainfall accumulation exceeding 1000 mm) from Typhoon Nina (1975) were observed in the windward topographic region (Yang et al., 2017). The other 6 tropical cyclones are categorized into the second group (Figure 11). A common feature for the tropical cyclones in the second group is extratropical transition process during the life cycle of the storms. Annual flood peaks are frequently observed after the extratropical transition process (see the curvatures of tropical cyclone tracks in the latitudes around 30° in Figure 11), and are frequently observed in northern China. Except Typhoon Herb (1996), 4 of the top 5 largest number of annual flood peaks are caused by tropical cyclones with extratropical transition.

There is no strong preference for the spatial distribution of annual flood peaks with respect to storm tracks (i.e., left or right of the track), even though the records floods caused by tropical cyclones tend to be frequently observed in the left-front quadrant (typically the down-shear side) of the circulations. This is related to the preferable distribution of extreme tropical cyclone rainfall, due to enhanced moisture convergence and updraft on the down-shear side of the circulation (e.g., Atallah et al., 2007; Shu et al., 2018).

5 Summary and Conclusions

In this study, we examine flood peak distributions over China based on 1120 stream gauging stations with continuous records of annual maximum instantaneous discharge for more than 50 years. The principal findings of this study can be summarized as follows.

(1) There are 38% and 35% stations exhibiting significant change points in mean and in variance, respectively. Change points tend to occur during the period 1980-2000, and show strong a spatial concentration in the lower Yellow River, upper Huaihe River, the entire Haihe River, upper Yangtze and Pearl River basins. Hydrological regimes in these regions demonstrate intensive anthropogenic influences, for instance, large hydro-power generation dams, cascade constructions of small-capacity reservoirs, transboundary water-transfer projects, soil-water conservation projects, urbanization. There is a weak signal of climate impacts on the abrupt changes in annual flood series across China. Abrupt change is the dominant mode of violation of the stationary assumption for annual flood peaks over China.

(2) Approximately 6% stations (69 in total) show significant linear trends in the annual flood peak series. Those stations with significant trends are uniformly distributed across the country, with 62 of them exhibiting significantly decreasing trends. The decreasing trends of flood peak magnitude in northern China may be at least partially tied to changes in extreme rainfall. Disconnections between changes in annual rainfall extremes and annual maximum floods are identified in southern China, and highlight complex flood-generation processes across China. The dominance of decreasing trends in annual flood peak series indicates weakening tendencies of severe flood hazards (i.e., annual maximum floods) over China, even though flood-affected area and economic damages are on the rise in recent decades (Kundzewicz et al., 2019). Future studies need to further examine changes in flood frequency for a complete assessment on flood hazards (based on peaks-over-threshold flood series, similarly see, e.g., Mallakpour and Villarini, 2015).

(3) We fit GEV distribution for the stationary time series of annual flood peaks, and examined the dependence of its parameters on drainage area. We find that the location and scale parameters are linearly scaled with drainage area in a log-log domain. There is only a weak tendency for the shape parameters to decrease as a function of drainage area. Our results highlight scale-independent properties of upper tails of flood peaks. The relationships between GEV parameters and drainage area show strong spatial splits between northern and southern China, indicating space-time rainfall organization as an important player in determining the upper-tail properties of flood peak distributions over China. Procedures for regional flood frequency analysis should explicitly address the spatial splits through considering spatial heterogeneity in flood hydroclimatology.

(4) Flood-generation systems over China show a mixture of monsoon, tropical cyclones, and extratropical systems. Tropical cyclone plays an important role in characterizing spatial-temporal variability of flood peaks and the upper-tail properties of flood peak distributions over China. More than 50% of the annual flood peaks in the southeastern coast are caused by tropical

cyclones. The percentage progressively decreases when we move further inland and to higher latitudes. Tropical cyclones lead to heavier tails of flood peak distributions (with larger shape parameters of the GEV distribution) in northern China. Those regions are characterized with record floods frequently associated with tropical cyclones, despite that tropical cyclone visits relatively infrequently compared to the southern China. Record floods in southern China are more frequently associated with monsoon-related extreme rainfall rather than landfalling tropical cyclones. We highlight the importance of considering the mixture of flood-generation mechanisms in flood frequency analyses especially in northern China. Contrasting roles of tropical cyclones in flood peak distributions highlight the necessity of tailored procedures for flood-control practices and flood hazard assessment across China. For instance, landfalling tropical cyclones can be good candidates for PMP/PMF designs for drainage basins in northern rather than southern China.

(5) Tropical cyclone plays an important role in most severe flood hazards in the history of China. There are 9 tropical cyclones that produced more than 100 annual flood peaks over China, contributing to approximately 50% of total annual flood peaks caused by all historical tropical cyclones. The large number of annual flood peaks is associated with extended spatial coverages of extreme rainfall after the storms going through the processes of extratropical transition. An additional feature for severe flood hazards is tied to favorable synoptic set-up for persistent moisture transport after the storm making landfall, as demonstrated by Typhoon Herb (1996), Typhoon Andy (1982), and Typhoon Nina (1975). Interaction of tropical cyclone with regional topography is a key element for most extreme floods in central China (mainly the middle/lower Yellow River basin and upper Huaihe River basin). Annual flood peaks caused by tropical cyclones do not show strong spatial preferences with respect to the tracks, even though the record floods tend to be frequently observed in the left-front quadrant of the circulation. Hydrometeorological analyses can provide improved physical characterization on severe flood hazards associated with landfalling tropical cyclones (see e.g., Yang et al., 2017).

Attribution analysis on the nonstationarities of annual flood peaks across China point to mixed controls of human activities, external climate factors (i.e., extreme rainfall), and changes in soil moisture on flood hydrology. The homogeneity of flood population for flood frequency analysis needs to be carefully revisited in a changing environment. This is especially proposed by England et al. (2018) in Hydrology Subcommittee Bulletin 17C as an imminent need to "define flood potentials for watersheds altered by urbanization, wildfires, deforestation, and by reservoirs". Innovative approaches that explicitly address the nonstationarities should be embraced for flood frequency analysis across China, for instance, process-based approaches that rely on physically-based hydrological modelling which can represent the processes of nonstationarities in flood series (see e.g., Wright et al., 2014; Yu et al., 2018), statistical modelling approaches that mathematically parametrize the role of human regulations in flood series based on the framework of probability theory (Salas et al., 2018; Serago and Vogel, 2018; Gao et al., 2019; Dong et al., 2019; Barth et al., 2019). These approaches should be especially in great needs for northern China that exhibits an overwhelming portion of stations with nonstationarities in flood series.

Our results highlight the important role of landfalling tropical cyclones in determining the upper tails of flood peak distributions across China, especially the northern China and the southeastern coast. Previous studies show strong teleconnections between tropical cyclone activity in the western North Pacific basin and large-scale climate variability, e.g., the El Niño-Southern Oscillation (e.g., Chan and Shi, 1996; Chan, 2000), Madden-Julian Oscillation (e.g., Kim et al., 2008). Statistical models that adopt varying parameters on time or other predictors (such as, large-scale climate indices) can provide predictive tools of understanding future changes in flood hazards associated with landfalling tropical cyclones (e.g., Zhang et al., 2018c). Future studies need to zoom into watershed scales, and explore physical connections between extreme flood processes and key tropical cyclone features (e.g., space-time structures of tropical cyclone rainfall, tropical cyclone intensity), to provide additional insights into flood hazard associated with landfalling tropical cyclones.

A unique feature of our study is a nation-wide assessment of flood hazard based on an unprecedented network of stream gauging stations across China. Comprehensive analysis based on the exceptional dataset over China, together with studies by Villarini et al. (2009) and Burn and Whitfield (2018) in North America, Blöschl et al. (2017, 2019) in European countries, among others, promotes improved understandings on flood hydrology and hydroclimatology under a changing environment from a global perspective. A future endeavor will further exploit the dataset through developing a data archive of key hydrological indices that is accessible to worldwide research community.

Data availability. The data used in this research are collected from distributed hydrological offices of major river basins over China. The dataset is unavailable to access due to licensing issues at the moment.

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Table 1. Summary of tropical cyclones that produced more than 100 annual flood peaks over China. All the stations that are located within the 500 km buffer zone of each tropical cyclone track are counted. The “storm type" column shows whether the tropical cyclone experienced extratropical transition (ET) or not (TS).

Rank	Storm name	Total No. of storm-affected stations	Total No. of annual flood peaks	No. of record floods	Storm type
1	Herb (1996)	465	167	4	TS
2	Wendy (1963)	622	159	6	ET
3	Tim (1994)	591	156	2	ET
4	Freda (1984)	634	144	2	ET
5	Doris (1961)	836	119	2	ET
6	Winnie (1997)	482	114	0	ET
7	Andy (1982)	375	111	10	TS
8	Russ (1994)	330	104	1	ET
9	Nina (1975)	441	102	24	TS

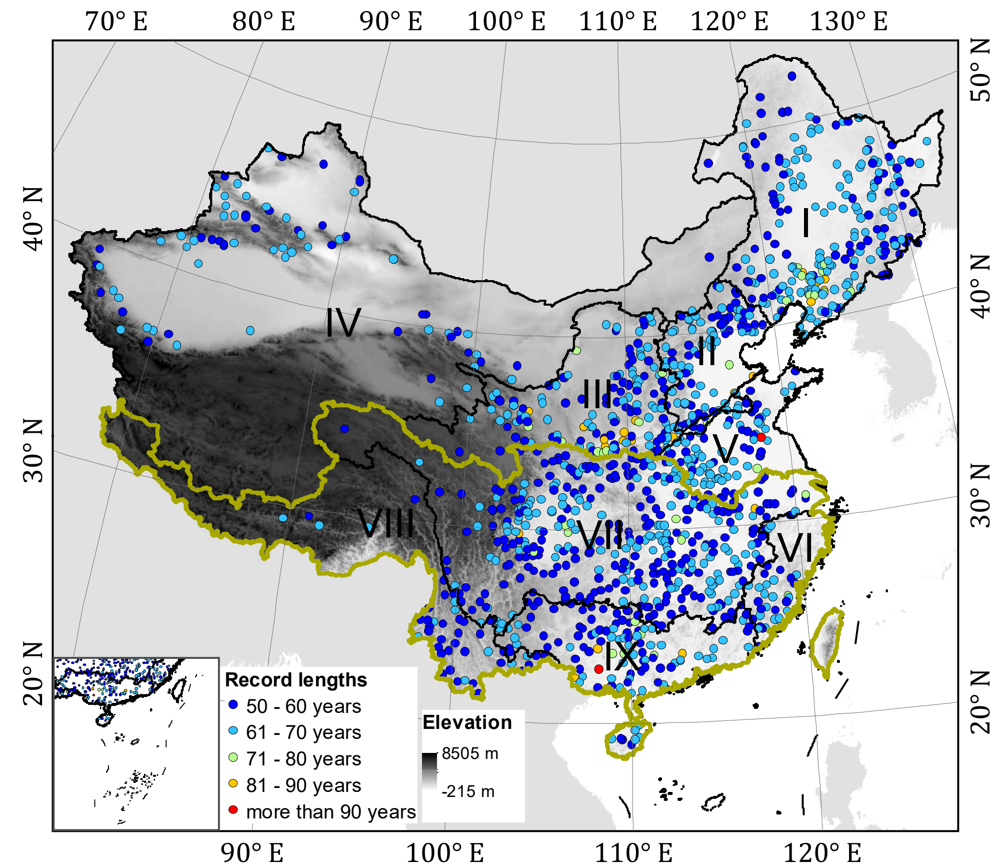

Figure 1. Overview of the stream gauging stations with record lengths of more than 50 years over China (1120 gauges in total). Scatter shading represents the record length (in years) for each station. The grey shading represents topography, while the black lines represent the first-level hydrologic units. The Roman numerals highlight the nine major hydrologic units in China: I-Northeastern river basins, II-Haihe River basin, III-Yellow River Basin, IV-Northwestern river basins, V-Huaihe River basin, VI-Southeastern river basins, VII-Yangtze River basin, VIII-Southwestern river basin, and IX-Pearl River basin. Olive line shows the boundary of river basins in southern China (VI-IX), with the rest of the river basins in northern China (I-V).

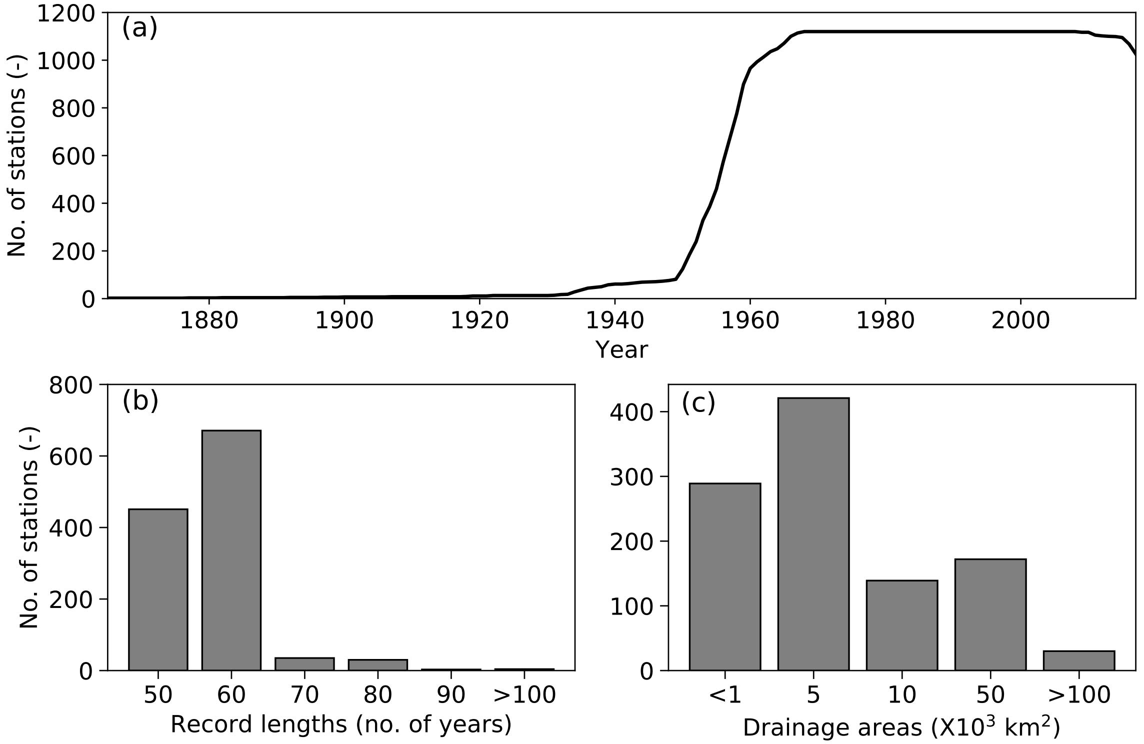

Figure 2. (a) Time series of total number of available stations (with record lengths of more than 50 years) for each year. Histograms of all the 1120 stream gauging stations sorted by (b) record lengths and (c) drainage areas.

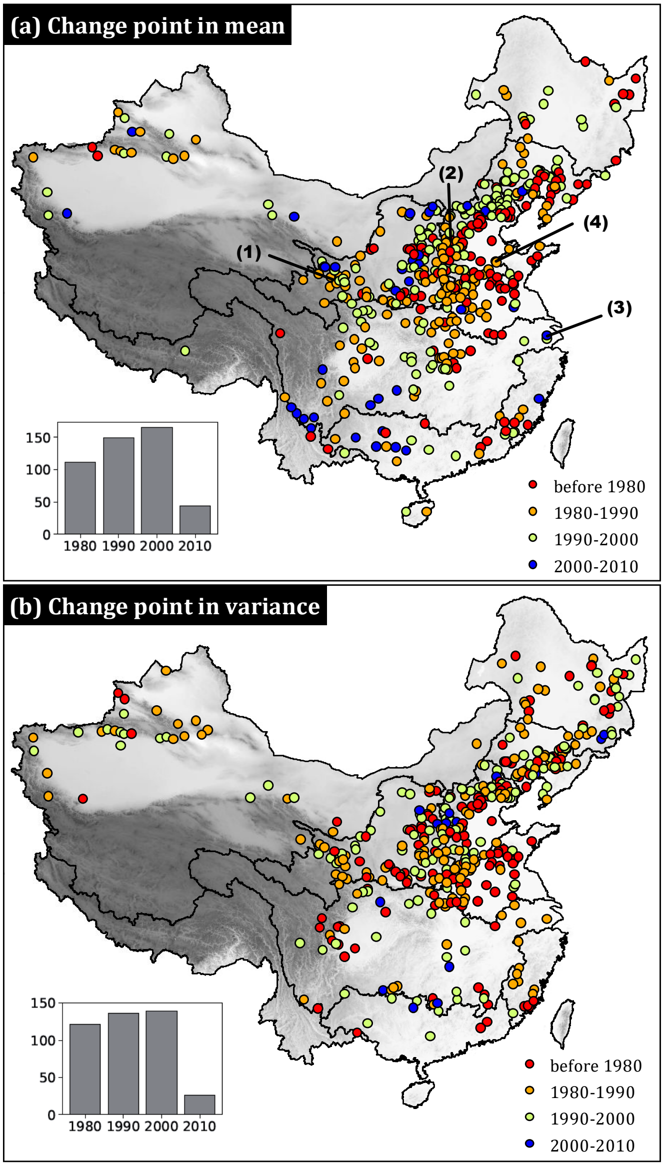

Figure 3. Change points in (a) mean and (b) variance. Color represents the year of change-point occurrence. The insert plot shows the histogram of the years of change-point occurrence (y-axis represents the number of change points, while x-axis represents the ending year of a 10-year period, e.g., 1990 actually means 1980-1990). Only stations with results being statistically significant (at the level of 5%) are shown.

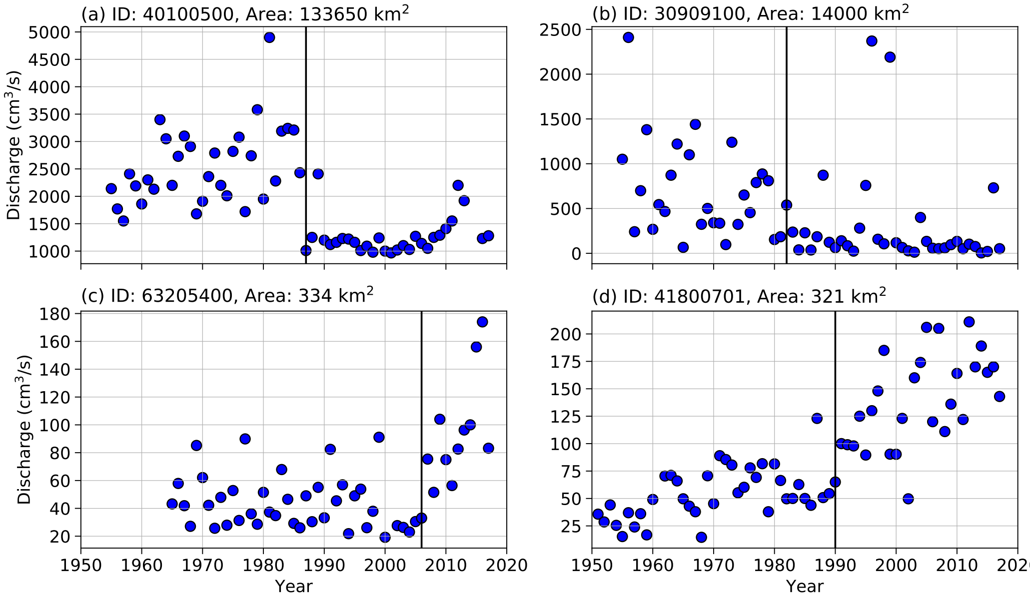

Figure 4. Time series of annual flood peaks for four stream gauging stations with strong human interventions: (a) large hydroelectric dams (upper Yellow River, ID: 40100500), (b) a cascade of small reservoirs (upper Haihe River, ID: 30909100), (c) urbanization (a tributary in the lower Yangtze River, ID: 63205400), and (d) transboundary water-transfer project (a tributary in the lower Yellow River, ID: 41800701). Locations of the four stations are represented by the numbers in brackets in Figure 3, with (1) to (4) corresponding to (a) to (d), respectively. Black lines indicate the year of occurrence for change point in mean. Results are based on the Pettitt's test. Only stations with Pettitt's test being statistically significant (at the level of 5%) are shown.

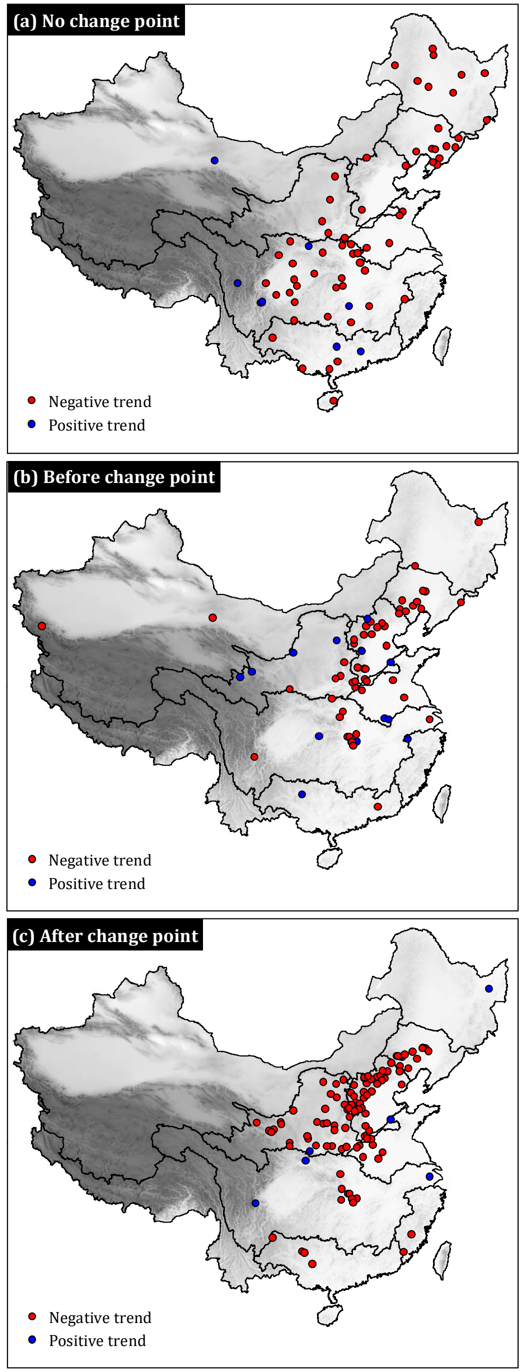

Figure 5. Mann-Kendall test results for stations (a) without change point in mean and (b,c) with change point in mean. Results are statistically significant at the level of 5%. Different number of data points between (b) and (c) are associated with (1) insufficient record lengths for sub-groups before or after change points, (2) linear trends for either sub-group being not statistically significant.

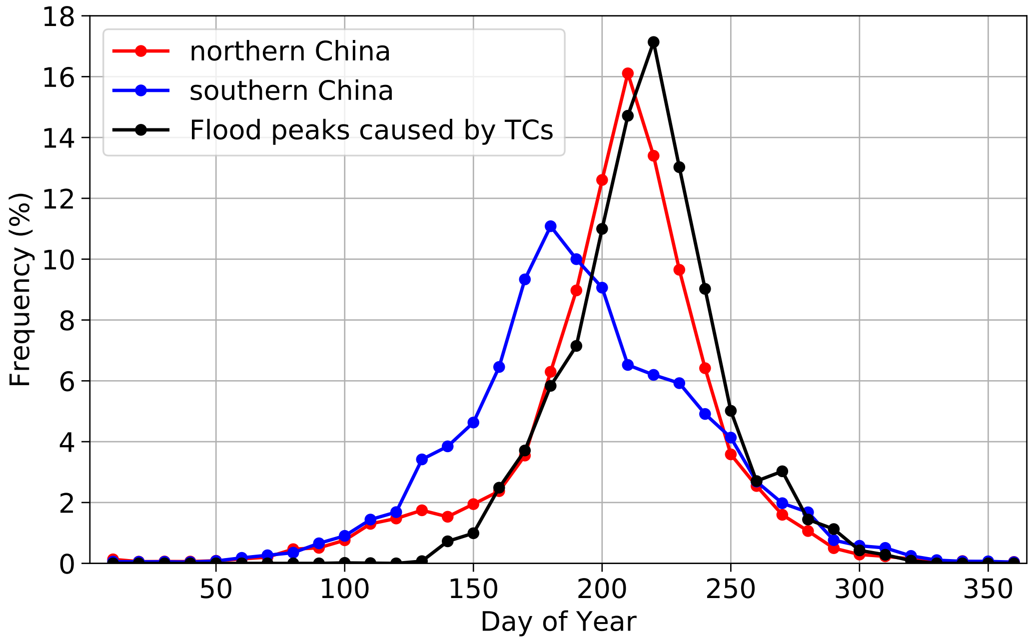

Figure 6. Seasonality of annual maximum flood peaks for northern China (red), southern China (blue), and annual flood peaks caused by tropical cyclones (black).

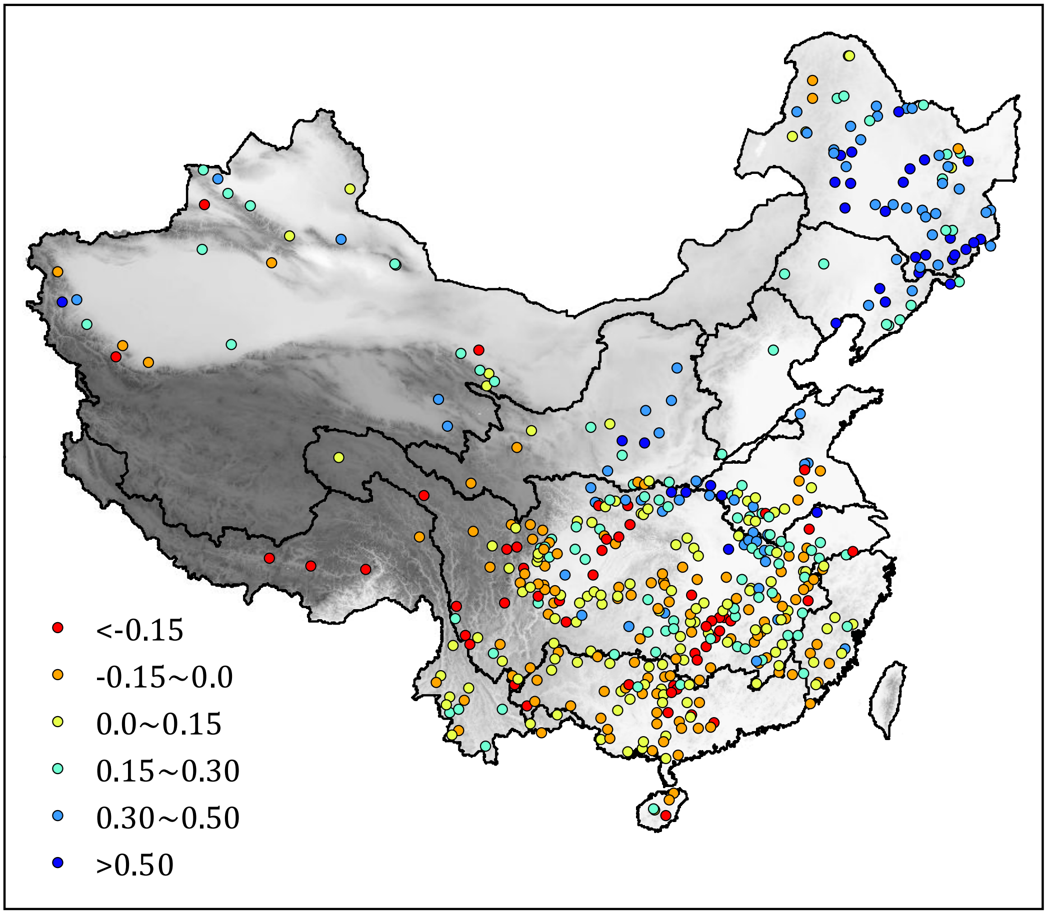

Figure 7. Map of the GEV shape parameters for the stationary time series of annual flood peaks.

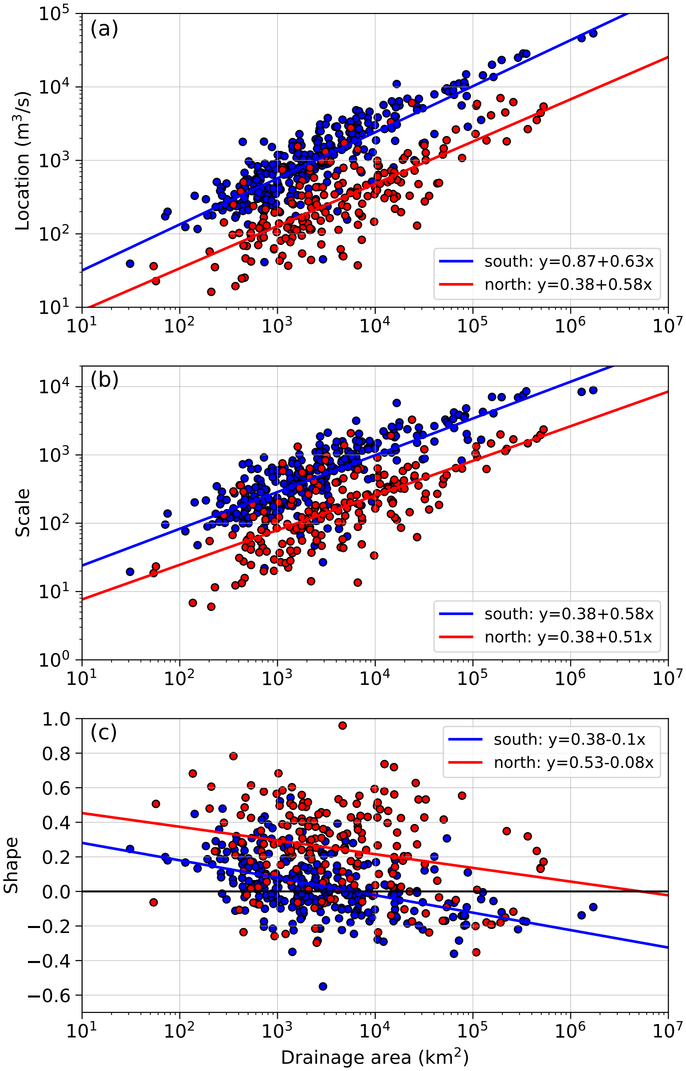

Figure 8. Scatterplots of GEV parameters (a) location, (b) scale, and (c) shape, as a function of drainage areas. Blue (red) scatters represent stations over south (north) China.

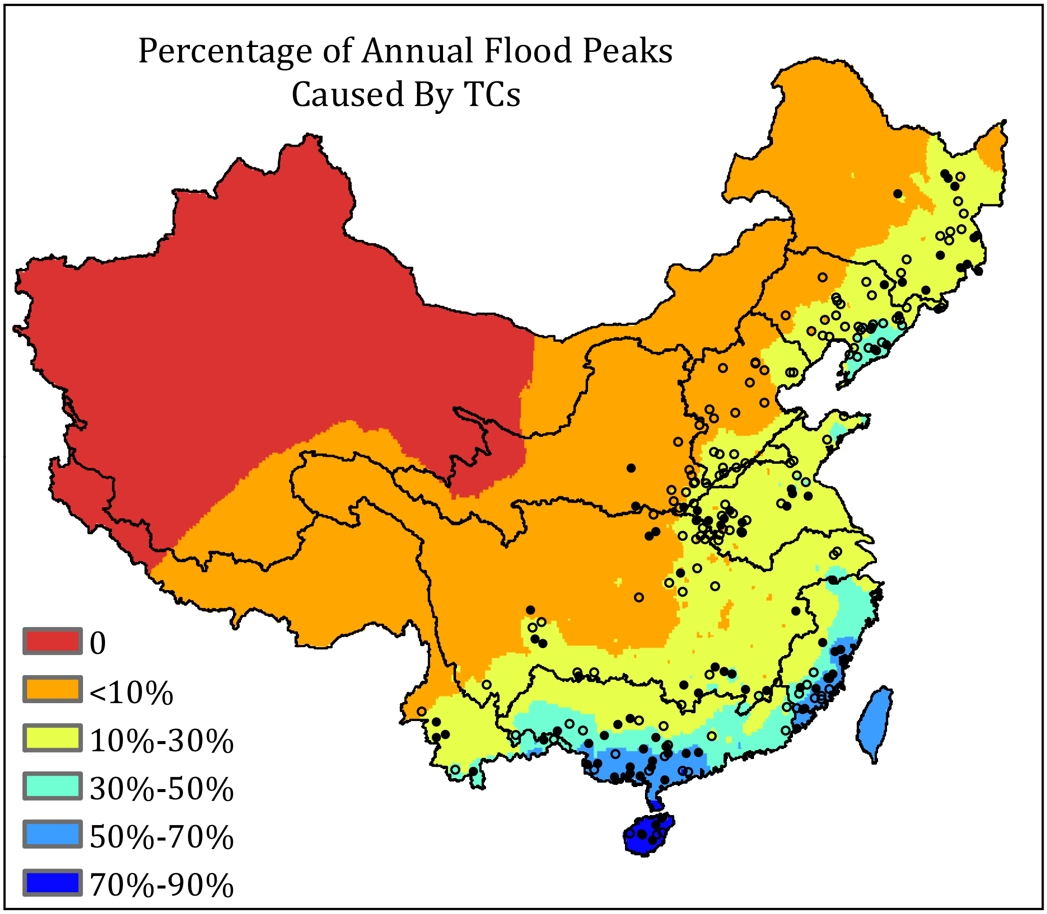

Figure 9. Percentage of annual flood peaks that are caused by tropical cyclones. The black dots and circles represent the stations with record floods caused by tropical cyclones. The black dots further highlight stations with stationary time series of annual flood peaks.

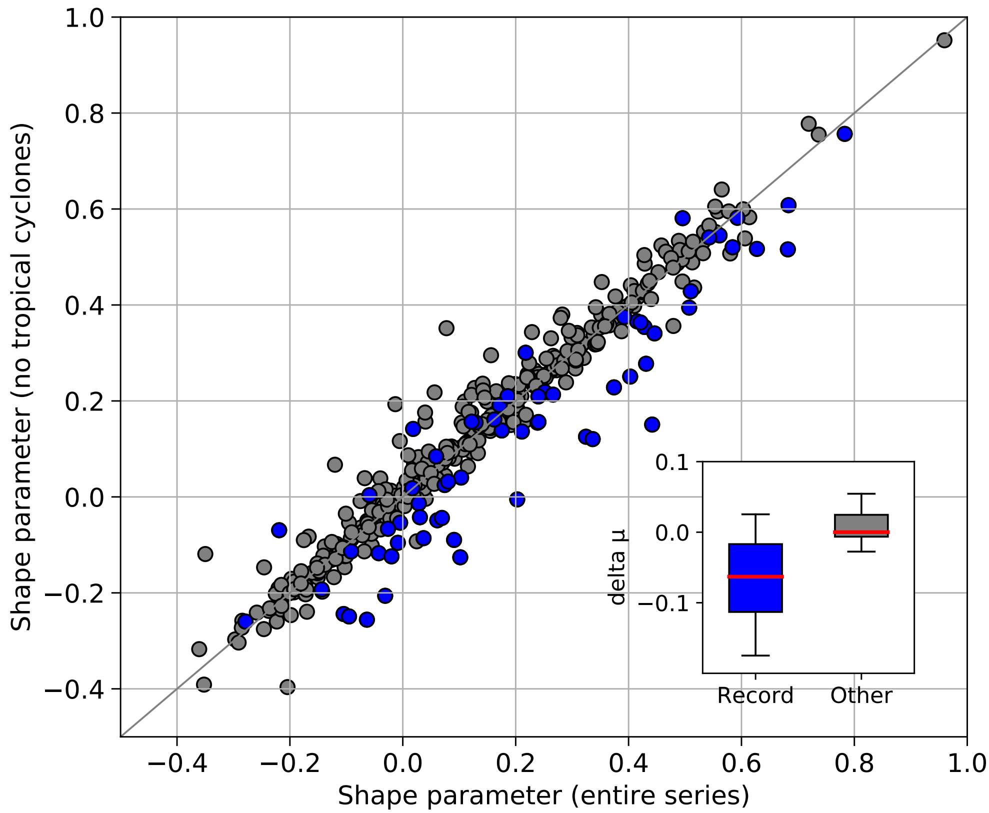

Figure 10. Scatterplot of the shape parameters for the entire series versus the series with annual flood peaks caused by tropical cyclones removed. Blue dots highlight the stations with record floods that are caused by tropical cyclones (see Figure 1 for locations). The insert boxplot shows the differences of shape parameter (series with TC flood peaks removed minus the entire series) for stations with (blue) and without (grey) TC-induced record floods.

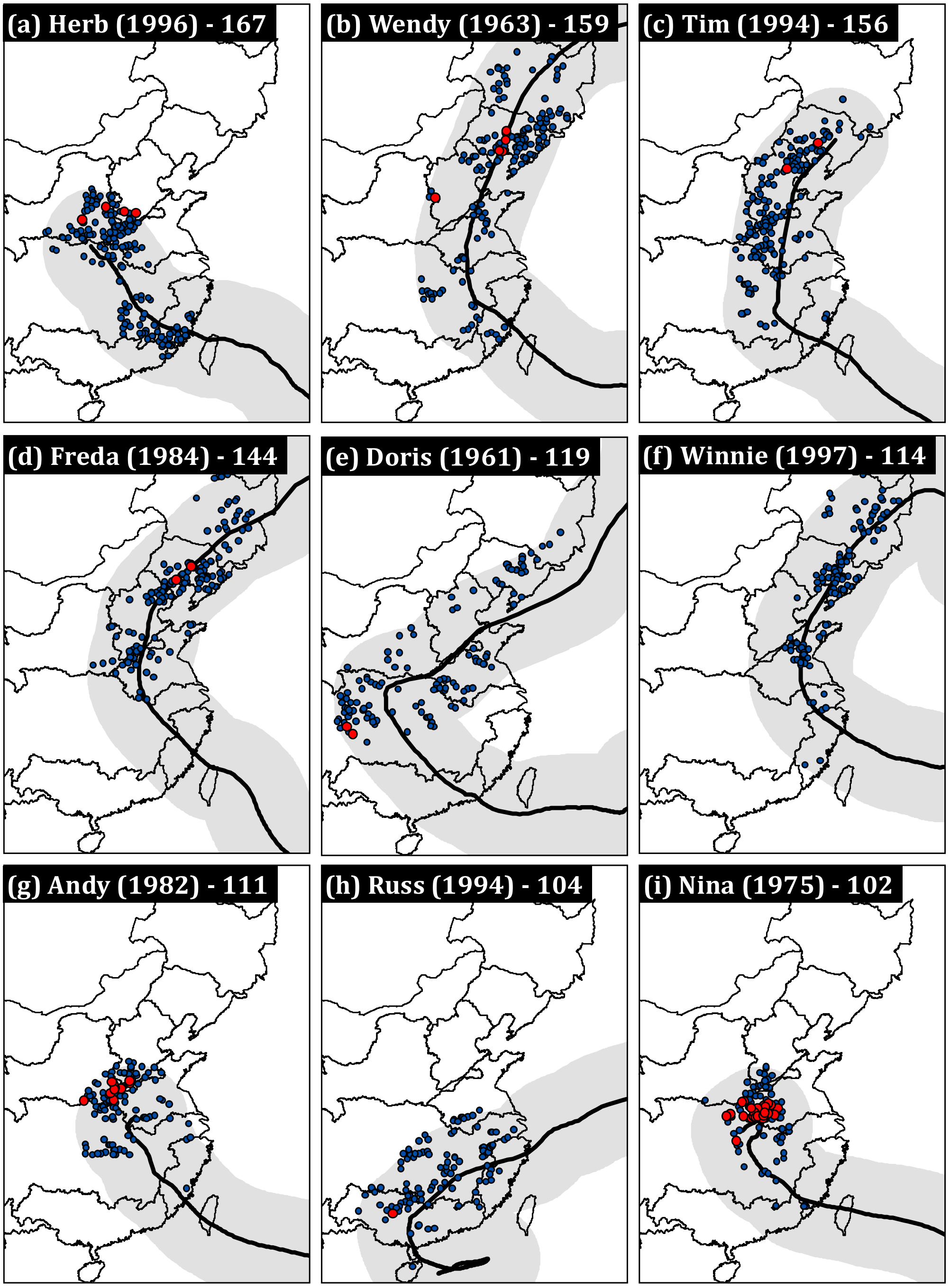

Figure 11. Tropical cyclones that produced more than 100 annual flood peaks (blue dots) over China. Red dots highlight that the annual flood peak is also the record flood of the station. Dark black line shows tropical cyclone track. Grey shading represents 500 km buffer zone of each track. See Table 1 for more details.