**Impact of tropical cyclones on flood risk in southeastern China:
spatial patterns, causes and implications**

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Impact of tropical cyclones on flood risk in southeastern China: spatial patterns, causes and implications

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ABSTRACT: Using flood peaks data from 62 hydrological stations covering a period of 1951-2014 and tropical cyclone (TC) tracks, floods due to TCs were differentiated and relations between occurrences of floods and TCs were investigated. Then, the impact of TCs on the flood magnitude and frequency was evaluated. Results indicated that there was more than one external influencing factor for flood occurrences, i.e. convective precipitation and TC-related heavy precipitation. In general, the landed TC events have a crucial influence on the occurrence of floods in eastern and western parts of Guangdong province. The mountainous topography limits the northward propagation of TC events and hence limits their impact on the

occurrence of floods in the northern part. More than 60% of the largest 10 hazardous floods in the northern and eastern parts were attributed to TCs and hence they significantly modified the probability distributions of flood peaks, increasing the location and scale parameters of the generalized extreme value (GEV) probability distribution model. Therefore, development of measures for mitigation of coastal flooding would need to consider the occurrences of TCs.

Key words: Flood peaks; Tropical cyclone; Influencing factors; Generalized Extreme Value probability distribution; Coastal regions

1. Introduction

Coastal regions of the globe are usually urbanized with denser population and better developed economy (Mori and Takemi, 2016), but these regions are also highly susceptible to natural hazards, such as storm surge and coastal flooding. Tropical cyclones (TCs) are one of the major causes of hazardous hydrological and/or weather extremes in the coastal regions of the world (Hopley and Harvey, 1976; Webster et al., 2005; Igeta et al., 2007; Pielke et al., 2008). These extreme events include floods, landslides, damaging winds, high waves, and storm surges. Intense TCs can cause devastation (Mori and Takemi, 2016) and have therefore aroused worldwide concern (Eliot and Pattiaratchi, 2010). With growing population and infrastructure facilities, coastal urban regions are becoming more vulnerable and are being increasingly threatened by TCs. Seto (2011) projected that in the next few decades, most

population increase will take place in the exposed deltas, near estuaries, coastal zones and coastal cities of Asia (and Africa) due to better employment and education opportunities. With increasing urban population and greater financial capital invested in the flood prone coastal zones (Chan et al., 2014), socio-economic trends would amplify the possible consequences of future floods.

Coastal regions in Asia, especially in vulnerable deltas and coastal cities, are home to more than half of the Asian population (Chan et al., 2014). More than 325 million inhabitants are living in the coastal low-lying flood prone areas in East Asia alone (McGranahan et al. 2007). Many of these coastal regions are predicted to be vulnerable due to climate change (e.g. sea-level rise), with millions of people and their economic assets being vulnerable to floods and storms (Ward et al. 2011; Walsh et al., 2012; Chan et al., 2014). Considering the case of China, an agricultural country with the largest population of the world, its coastal regions are mostly economically developed, densely populated, and are frequently hit by landfalling tropical cyclones (TCs). Southeastern China, such as Guangdong province (Zhang et al., 2011a), is a particular case. Guangdong province has a large number of megacities and is major part of the Pearl River Delta. Flash floods, mountainous floods, and water logging are some of the natural disasters that occur in the province (Zhang et al. 2011a). Some of these disasters are mainly the consequences of typhoons or TCs. Statistically speaking, an average of 9 TCs make a landfall in China every year (Yin et al., 2010). When TCs make a landfall in these areas, they cause strong winds, torrential rains, and tidal surges, resulting in serious losses of life and property (Zhou et al., 2004). It is

therefore important to evaluate the impacts of TCs on flood risk in coastal regions, such as Guangdong province.

Survey of literature shows that previous researches mainly focused on the impact of TCs on extreme precipitation (e.g. Ren et al., 2006). Yin et al. (2010) examined the extent to which TCs are responsible for heavy rainy days (precipitation > 100 mm/d) in coastal Fujian Province. Breña-Naranjo et al. (2015) evaluated the rainfall contribution of tropical depressions, storms and hurricanes across Mexico from 1998 to 2013 using the satellite-derived precipitation dataset TMPA 3B42. Chen et al. (2010) investigated both the synoptic and mesoscale processes responsible for causing heavy rainfall events which produced up to 379.5 mm over southwestern Taiwan on 7 June 2003. Urbanization of coastal regions over the globe and related TC-induced flood risks have aroused increasing concern (Zhang et al., 2008; Muis et al., 2015). Although southeastern China, including Guangdong province, has numerous megacities, such as Hong Kong and Guangzhou, whose economies are highly developed, limited researches have been reported concerning tropical cyclones and flood risk. Yang et al. (2015) investigated climate change trends, impacts on flood events, flood vulnerability and risk, and response strategies in the Pearl River Delta (PRD), a rapidly urbanizing coastal area in southeastern China. However, the study by Yang et al. (2015) was done based on a reanalysis dataset and model projections with results from the literature. No reports are available addressing the impact of TCs on hydrological extremes, based on observed hydrological datasets in southeastern China.

It is widely accepted that evaluation of flood risk and related drivers is crucial for effective risk management (Muis et al., 2015). Further, quantifying the contribution of tropical cyclones to the terrestrial water cycle can help determine the benefits and hazards caused by TCs (e.g. Huang et al., 2011). Therefore, the central issues of this study are (1) “mixtures” of flood peak distributions, (2) regional characteristics of flood magnitudes influenced by TCs, and (3) parameter characteristics of flood peak distributions related to TCs. This study attempted to relate floods to TCs in the coastal region of southeastern China by taking Guangdong province as a case study, evaluate the potential effect of TCs on flood risk. Results of this study would be helpful for mitigation of flood hazards in southeastern China.

2. Study region and data

Guangdong province, involving the Pearl River Delta (PRD) and the lower Pearl River basin, is a highly developed region in China (Fig. 1). The PRD has been the fastest developing region in China since the adoption of so-called “reform and open door” policy in the late 1970s, with a highly dense agglomeration of over 100 towns and cities (Fig. 1). On less than 0.5% of the country’s territory, PRD produces about 20% of the national GDP, attracts about 30% of Foreign Direct Investment, and contributes about 40% of export (therefore, PRD is called the “World Factory”) (Zhang et al. 2011a). Guangdong province is located in the way where northwest Pacific subtropical cyclones enter and/or departs from the mainland of Asia with the coastline (except islands) of about 3368 km. Guangdong province is topographically

high in north, northwest and northeast parts and is topographically lower in the central and south parts. Precipitation events generally last 2-3 days and even 7-8 days with the largest amount of 100-800 mm. Therefore, the TC-induced rainstorms can easily trigger the occurrence of flash floods and mountainous floods. Hence, evaluation of flood risk under the impact of TCs is crucial for management of flood risk and mitigation of food hazards.

The flood event was defined as the annual maximum daily discharge which is consistent with previous studies (e.g. Zhang et al., 2015a, 2015b; Villarini et al., 2011a). The annual maximum daily discharge with unit of m^3/s was used as the flood peak series. Flood peak data were obtained from the Hydrological Bureau of Guangdong province which firmly controls the quality of data before release (Zhang et al., 2012; Ying, 2014). We calculated the maximum, 90th, 50th and 10th of flood peaks in each station (Fig. 2). There is an obviously spatial heterogeneity for the magnitudes of flood peaks across Guangdong province. The maximum magnitude of flood peaks at most of the stations ranges from 1000 to 5000 m^3/s . The stations with the highest magnitudes of flood peaks mainly located in the northern and northeastern Guangdong province.

The longest flood peak series was 64 years and the smallest was 16 years. Flood peak data from 44 gaging stations were longer than or equal to 50 years in length (Fig. 3). These data have a few missing values which were processed as follows: the missing values of 1–2 flood peaks were replaced by the average value of neighboring flood peaks; adequate consecutive days with missing data were filled by the long-term

average of flood peaks of other years. A similar gap fill method has also been used by Zhang et al. (2011b). Data of TCs in terms of location and intensity were collected from Shanghai Typhoon Institute (STI) of China Meteorological Administration, China. The temporal resolution of the TC data was 6 hours (Ying et al., 2014). The quality of TC tracks has been controlled by Ying et al. (2014).

3. Methodology

3.1 Identification of TC-induced flood events

Identification of TC-induced flood events is needed for evaluating the potential impacts of TCs on flood occurrences and flood risk. The key to differentiate the TC-induced floods from other flood regimes is the temporal relation between TCs and flood events. Based on a study by Villarini et al. (2014), flood events can be taken as those induced by TCs when the following two conditions are satisfied: (1) the stations with the occurrence of flood events are within 500 km from the center of TC; and (2) the occurrence time of peak flood is 2 days before and/or 7 days after the occurrence time of a TC. This study followed these criteria for differentiating TC-induced floods.

3.2 Generalized Extreme Value (GEV) Probability Distribution

The GEV distribution has been widely used for analyzing hydrometeorological extremes (e.g. Gu et al., 2016a; El Adlouni et al., 2007) and has three parameters which are the location μ , the scale, α ($\alpha > 0$), and the shape, κ . The cumulative

density function (cdf) of a random variable y drawn from a GEV distribution is given as (Cannon, 2010):

$$F(y; \mu, \alpha, \kappa) = \exp \left[- \left\{ 1 - \kappa \frac{y - \mu}{\alpha} \right\}^{1/\kappa} \right], \quad \kappa \neq 0, \quad 1 - \kappa \frac{y - \mu}{\alpha} > 0$$

$$F(y; \mu, \alpha, \kappa) = \exp \left[- \exp \left\{ 1 - \frac{y - \mu}{\alpha} \right\} \right], \quad \kappa = 0$$
(1)

For small samples, the maximum likelihood (ML) estimates of parameters are usually unstable when compared to the moments method due to the generation of physically unrealistic κ values (Coles and Dixon, 1999; Martins and Stedinger, 2000; Cannon, 2010). Martins and Stedinger (2000) developed the Generalized Maximum Likelihood (GML) estimator with a more restrictive penalty (or prior distribution) on κ and the shape parameter was limited to the range of $-0.5 \leq \kappa \leq 0.5$.

4. Results

4.1 Composite causes of floods

Guangdong province is climatically warm and humid. Rainstorms are the major cause of flood hazards. Generally, rainstorms in the Guangdong province are driven by western wind weather systems and tropical weather systems. Two rainfall or flood seasons were identified, i.e. March-June, the first flood season (FFS) and July-September, the second flooding season (SFS). TCs can bring abundant water vapor, with strong convergent air circulation and intense uplift of air mass, triggering the occurrence of rainstorms. Based on the time when flood peak occurs and relation between the occurrence of floods and TC, floods events were categorized into three

types: floods during FFS, or simply FFS floods; floods during SFS, or simply SFS floods, and TC-induced floods.

Firstly, we analyzed the influence of TCs on precipitation extremes across the Guangdong province (Fig. 4). Daily precipitation data at 30 stations covering a period of 1951-2014 were obtained from National Climate Center (NCC) of China Meteorological Administration (CMA) (Gu et al., 2016b). Both annual maximum (AM) and peak-over-threshold (POT) methods were used to obtain the extreme precipitation events. For AM sampling, we computed the annual maximum daily rainfall for every year. For POT sampling, 95th percentile of the distribution of the non-zero precipitation series was selected as the threshold value at each station, and we computed the extreme precipitation events that exceed the threshold value. The choice of a 95th is consistent with previous studies (e.g. Villarini et al., 2011b, 2013). The extreme precipitation events were considered to be TC-induced events if the circulation center of the storm is located within a 500 km radius from the rain gauge during a time window of ± 1 day (Gu et al., 2016b; Khouakhi et al., 2016).

Guangdong province is the region frequently hit by TCs with abundant water vapor which usually caused occurrences of extreme precipitation (Ying et al., 2011). Under the influence of TCs, duration of extreme precipitation was prompt and the TC-induced moisture propagation and disturbance energy would collide with mid-latitude circulation, which can benefit the occurrence of extreme precipitation. The fraction of AMs associated with TCs is large in the southwest and northeast parts of the Guangdong province, with values ranging from 30% to more than 70%

at precipitation stations along the coast of southwestern Guangdong (Fig. 4a). Our results are in line with those from previous studies (e.g. Gu et al., 2016b; Khouakhi et al., 2016). Though the contributions of POTs induced by TCs are lower than AMs, the fraction is still more than 30% (Fig. 4b). In addition, the fraction is obviously lower in northern Guangdong than southwestern and northeastern Guangdong both for AMs and POTs (Fig. 4).

While there are many studies examining the TC-induced extreme precipitation across China (Lee et al., 2010; Ying et al., 2011; Chen et al., 2011), the little attention that inland TC-induced flooding has received has generally focused on case studies of specific events or over a specific area. Moreover, though extreme precipitation events are an important role in flood generation, and there are many other crucial factors also influencing floods such as land use/land cover and antecedent soil moisture condition. Therefore, it is insufficient to allow direct inference of flooding just using extreme precipitation events. That is why we related climatology and flooding to TCs.

Fig. 5 illustrates the spatial distribution of percentage of the above-mentioned three types of floods to the total number of flood events in the study region. It can be seen from Fig. 5a that TC-induced floods were observed mainly in the southwest and northeast parts of the Guangdong province. The TC-induced floods of these two regions accounted for more than 40% and even more than 60% of the total number of floods. The largest contributions of TC-induced flood events are found in areas that experience the largest fraction of TC-induced extreme precipitation events (Figs.

4, 5). Evidently the decreasing percentage, below 30%, of TC-induced floods to total floods can be detected in the southwest and northeast to north parts of the study region (Fig. 5a). It can be seen from Fig. 1a that topographical features of the southwestern and northeastern Guangdong province are dominated by mountainous terrain which greatly weakens the strength of TCs and also impedes the northward propagation of TCs. Fig. 5b shows that flood events occurred mainly during FFS. More than 52% stations were characterized by floods that occurred during FFS and most of these stations were observed in central and northern parts of Guangdong province. Stations located at northern parts of Guangdong province were dominated mainly by floods that occurred during FFS. Comparatively fewer floods can be identified during SFS and only two stations, accounting for 4.5% of the total stations, were dominated by 30-40% of the floods that occurred during SFS (Fig. 5c).

There is striking spatial heterogeneity in the frequency of extreme precipitation events and flood peaks caused by TCs (Figs. 4, 5). The percentage of TC-induced flood peaks has an abrupt decrease moving from southwest and northeast parts to north parts of Guangdong province. This feature of regional percentage of TC-induced flood peaks is possibly linked to orographic effect, which has been reported by previous studies (Villarini and Smith, 2010; Ying et al., 2011). The main topography in northern Guangdong is undulating mountain from small to large with maximum elevation of 1848m (Figs. 1a, 6a). Ying et al. (2011) pointed out that the influence of mountains on circulation may contribute to the spatial pattern of trends in influence of TC activity. In addition, there is indeed an abrupt decrease in the total

numbers of passing TCs, the maximum strength of passing TCs and the maximum 2-min mean maximum sustained wind (MSW, m/s) near the TC center moving from southwestern and northeastern to northern Guangdong (Fig. 6b, c, d). The changes in TC characteristics are consistent with the spatial distribution of percentage of TC-induced flood peaks. Wen and Song (2006) also attributed the decreasing percentage in northern Guangdong to blocking and weakening effect of mountains.

The percentages of stations with flood events that occurred during FFS and SFS and the floods due to TCs were analyzed to determine the annual variation of floods due to different influencing factors (Fig. 7). In general, floods occurring in Guangdong province were mainly influenced by TCs and westerly system-related rainstorms and they occurred mainly during FFS. Floods that occurred during SFS were found at below 20% of the total stations (Fig. 5c). It can be seen from Fig. 7a that TC-induced floods were subject to annual and inter-annual variability with discernible temporal clustering property. During the early 1960s, 1970s, early and late 1980s, and also during some specific years of the early 2010s, floods at more than 80% of the total stations were attributed to TCs. However, below 10% of the total stations were characterized by floods resulting from TCs during some specific years, such as 1955, 1971, 1985, 1997 and 2002. TCs occurred intermittently and were concentrated during specific time intervals (Rowe and Villarini, 2013) and this may be the reason why TC-induced floods were subject to annual variability. Flood frequency changes due to TCs should be the cause of considerable concern for flood mitigation in southeastern China. However, no significant trends were detected in the

percentage of stations with TC-induced floods (Fig. 7a). In addition, floods that occurred mainly during FFS were also subject to large annual variability. However, larger annual variability can still be observed for the percentage of stations with TC-induced floods (Figs. 7a and 7b). Larger variability of TC-induced floods should be of great importance to mitigation of flood hazards in southeastern China and also in coastal regions over the globe, which has the potential to enhance the sensitivity of water resources systems to TCs. Fig. 7c shows that relatively rare floods occurred during SFS. However, the percentage of stations with floods during SFS had a slightly increasing tendency, particularly in the early 1980s. However, the percentage of stations with floods during SFS was decreasing after the mid-1990s.

4.2 Impacts of TCs on flood magnitude

Due to different influencing factors causing floods, flood magnitude changes are subject to spatial variability. With the aim to characterize the spatial pattern of magnitudes of floods due to TCs, the first step was to eliminate the impact of drainage area on the flood magnitude, because floods in larger river basins are generally characterized by larger magnitudes than those in smaller river basins. In this study, the flood ratio, defined as the ratio between the flood peak magnitude caused by a TC and the at-site expected 10 year flood peak magnitude, was used to standardize the TC-induced flood magnitude (Rowe and Villarini, 2013). The “expected 10 year” represents the flood peak that is expected to occur, on average, once every 10 years. The flood ratio of > 1 indicates TC-induced flood magnitude is

larger than 10 year flood and vice versa. The 10 year return period was computed based on the GEV distribution and the goodness-of-fit was tested by the K-S D statistic value (Fig. 8). It can be observed from Fig. 8 that the K-S D statistic values at almost all stations, except two stations, were lower than the 0.05 significance level. Hence, it can be said that the GEV model performed satisfactorily in modelling the flood magnitude series in southeastern China and can be used to quantify the return periods of a flood magnitude.

It should be emphasized that eastern and western parts of Guangdong province are heavily influenced by TCs in terms of flood occurrences (Fig. 5). Four typical years were chosen as case studies, i.e. 1971, 1985, 1995 and 2006, when Guangdong province was heavily impacted by TCs (Fig. 7a), to demonstrate the impact of TCs on the flood magnitude. During 1971, TC Lucy landed in the Pearl River Delta and traversed through the western part of the province (Fig. 9a). During 1985, however, TCs Hal and Winona landed in eastern and western parts, respectively, and both traversed through the northern part (Fig. 9b). During 1995, TCs Helen and Iving landed in eastern and western parts, and during 2006 TC Kaemi traversed through northern boundary of the province. It can be seen from Fig. 9 that due to impact of TCs, the flood magnitude in the eastern and western parts was relatively large. However, the flood magnitude in the northern part was smaller due to the blocking effect of mountains (Figs. 9a, b, c). Some TCs, such as Kaemi, which traversed besides northern boundary of the Guangdong province triggered the occurrence of floods with magnitudes larger than the 10-year flood, about 1.4-1.7 times larger than

the 10-year flood (Fig. 9d). These results clearly corroborated the significant impact of TCs on the flood magnitude in southeastern China and the Guangdong province.

Generally, extreme flood events with considerably large flood magnitudes, causing high mortality and/or massive loss of property, are the cause of considerable concern, whereas flood events that have minor or moderate impacts are usually ignored. Hence, the TC-induced floods with maximum flood ratio and 90% percentile of flood ratios were analyzed (Fig. 10) in order to characterize their spatial patterns. It can be observed from Fig. 10a that the maximum flood peaks of TC-induced flood events at most of the stations across Guangdong province were larger than that of 10 year flood event. Stations with a flood ratio of > 1.3 were found mainly in the eastern and western parts of the province and in the northern part of northern Guangdong province. However, stations with a flood ratio of < 1.0 were found mainly in the northeast parts of the western Guangdong province and also central and south parts of the northern Guangdong province. Figs. 1a and 10a combine to show that mountainous regions were dominated by hydrological stations with > 1 and even > 1.3 flood ratio, and hence high risk of mountainous floods or flash floods can be expected, particularly during the TC periods. In addition, high altitude around the Pearl River Delta and low-lying terrain across the Pearl River Delta tend to trigger flood inundation during the TC periods because of flash floods. This is why the TC-induced high flood ratio along the western, northern and northeastern parts of the province should arouse considerable concern for mitigation of flood hazards, particularly hazardous floods. Fig. 10 indicates similar spatial

patterns of 90% (percentile) of flood ratio when compared to those of the maximum flood ratio, which further corroborates widespread impacts of TC on floods across the province.

4.3 Impacts of TC events on probability distribution of peak flood flow

The generation mechanisms of floods are related to complicated topographical features, different landing points of TC events. Also, there are different flood types because of various external influencing factors such as convective rainfall as a result of strong convection moisture current (e.g. Fig. 5). Therefore, regionalization of the Guangdong province was done, based on the topography and different causes of flood events, i.e. region I (eastern Guangdong province), region II (northern Guangdong province) and region III (western Guangdong province) (Fig. 11). Regionalization can help to clarify different influencing factors behind flood events and also the effect of TCs on flood peaks.

Larger flood peaks can have more impacts on the parameters of probability distributions. Hence, this study analyzed percentages of ten largest flood events in terms of magnitude due to the impact of TCs (Fig. 11). It can be observed from Fig. 11 that spatial patterns of the largest 10 flood events matched well those of floods induced by the TC events (Figs. 5, 11), implying significant impacts of TCs on large floods. Specifically, the TC-induced largest 10 flood events accounted for more than 60% of the total flood events observed in the eastern and western Guangdong province; this result is in agreement with those shown in Fig. 5. The largest 10 floods

in the northern Guangdong province occurred mainly during FFS, and less than 30% of the largest 10 floods can be attributed to TCs. Less than 20% of the largest 10 flood events occurred during SFS. Flood events in the northern Guangdong province were mainly due to rainstorms and the flood magnitudes due to TC events were relatively lower and showed minor impacts on the probability distributions. However, floods in the eastern and western Guangdong province were mainly due to TCs and large flood magnitudes had considerable impacts on the probability distributions. Therefore, magnitude of floods in the eastern and western Guangdong province should attach considerable importance to TCs. Also, floods caused by heavy precipitation and/or TCs are common along the coastal regions of the globe (e.g. Eliot and Pattiaratchi, 2010). Hence, the relation between heavy precipitation and TCs in the coastal regions and coastal cities have aroused widespread attention (Yin et al., 2010; Huang et al., 2011; Breña-Naranjo et al., 2015).

The probability distribution of flood peaks shows the critical statistical properties of floods which can be further interpreted by the distribution parameters (Fig. 12). It can be seen from Fig. 12 that the location, scale and shape parameters of flood peaks are within large ranges of 0-1400 for location parameter, and of 0-900 for scale parameter, implying significant temporal variability of flood peaks. Besides, comparison between distribution parameters indicates that distribution parameters, i.e. location, scale and shape, of flood peaks not by TC events and those of the entire flood peak series followed the dashed line for region II, showing not the dominant role of TC events in influencing peak flow changes in region II, i.e. northern

Guangdong province. However, scattering patterns of distribution parameters can be observed for regions I and III, i.e. western and eastern Guangdong province, indicating that TCs exerted critical impacts on flood peak variations in regions I and III. Larger variability of flood peak accentuated the fragility and vulnerability of water supply systems. Meanwhile, TCs greatly impacted flood peaks in regions I and III; this finding is important for water resources management in these two regions and also for mitigation of altered extreme hydrological processes in a changing environment.

5. Discussion

Impacts of TCs on heavy precipitation and floods have been widely investigated in coastal regions (Eliot and Pattiaratchi, 2010; Chen et al., 2010; Huang et al., 2011; Chan et al., 2014; Breña-Naranjo et al., 2015). Southeastern China, encompassing the Guangdong province which is a case study in this paper, is economically developed, has dense population, and is highly sensitive to coastal floods, rainstorms and water levels, and hence coastal flooding, heavy rainfall, and water levels of the Pearl River Delta have attracted increasing concern (Zhang et al., 2008; Zhang et al., 2012; Yang et al., 2015). This study analyzed potential impacts of TCs on flooding in terms of flood magnitude and frequency. However, TC-induced floods and the degrees of related hazards are closely related to both convective rainstorms and TC-induced heavy precipitation as well as human activities, such as building of

hydraulic infrastructure facilities and urbanization (Zhou et al., 2012; Muis et al., 2015). The flood ratio in the eastern and western Guangdong province is larger than 1 and is far larger than the 10 year flood event (Fig. 7). TC-induced heavy precipitation is the cause of the larger-than-1 flood ratio in the eastern and western Guangdong province. Moreover, the western and eastern Guangdong province underwent fast and heavy urbanization (Fig. 1b) which caused increased runoff coefficient due to urbanization-induced increased impervious ground surface (Yang et al., 2013; Huong and Pathirana, 2013; Muis et al., 2015), and hence amplified flood magnitude and intensity. Yang et al. (2013) argued that increased flood magnitude was due to urbanization when compared to natural river basins. Since Guangdong province is dominated by the Pearl River Delta with numerous megacities with dense population density and is economically developed (Fig. 1), river channels within the province are highly channelized with levees. Therefore, flooding is easily amplified with increased magnitude and intensifies flood hazard. Increased vulnerability of coastal regions of the province to flood hazard and TC-induced heavy precipitation should cause considerable concern.

In this study, the GEV distribution without considering the effect of nonstationarity on flood peaks was employed. Indeed, many researchers have developed nonstationary methods to quantify return periods (Adlouni et al., 2007; Machado et al., 2015). However, the introduction of covariate variables due to the necessity of evaluating the changing magnitude of floods with the same return period sometimes causes uncertainty in the estimated flood magnitude (Adlouni et al., 2007;

Machado et al., 2015). In this study, the nonstationarity of flood peaks was not statistically significant and the length of peak flood flow series was 64 years, being statistically long enough. In this case, consideration of possible nonstationarity in peak flood flow was not necessary in a mathematical sense (Koutsoyiannis, 2006). Statistical test results justified the application of GEV model in modelling peak flood flows. The novelty of this study is that it sheds new light on the relation between peak flood flow and TCs in terms of flood magnitude and frequency in both space and time. Moreover, the impact of TCs on statistical properties, such as probability distribution of flood peaks, was analyzed, providing a relatively complete picture of the impact of TCs on flooding in the coastal regions. This study bridges the knowledge gap between TC behavior and coastal flooding in terms of magnitude and frequency, flood magnitude and its probability distribution, and has the potential to provide a theoretical framework for similar researches in the coastal regions of the globe.

6. Conclusions

Impacts of TCs on coastal flooding in southeastern China were investigated, using well-collected hydrological data. Flood peaks data were collected from 62 stations, and the TC dataset in terms of location and intensity were collected from Shanghai Typhoon Institute (STI) of China Meteorological Administration. TC-induced flood events in terms of frequency and magnitude, and the impacts of TCs on the probability distribution floods were analyzed. The following conclusions

were obtained:

(1) Southeastern China, encompassing Guangdong province used as a case study, is topographically high in west, north and southeast parts of the province and has a low-lying terrain in the south and central part parts. Hence, Guangdong province, as a coastal region, is very sensitive to flood hazards and flood inundation, since this region is heavily populated with numerous megacities.

(2) Flooding is caused by more than one external factor, such as TC-induced rainstorms and convective heavy rainstorms. However, TC-induced heavy rains play the key role in the occurrence of flooding in terms of frequency and magnitude. In addition, TC-induced floods are subject to specific and discernible spatial patterns. TC-induced floods are observed mainly in eastern and western Guangdong province. Mitigation of flood hazards in these two regions should attach more importance to TCs, particularly the prediction of TCs with warning systems. Moreover, flood peak changes are seasonal: peak flood flow events in Guangdong province occur mainly during FFS and relatively rare flood events can be observed during SFS; this finding provides information for the control of TC-induced flood hazards.

(3) Hazardous flood events in eastern and western Guangdong province are attributed mainly to TCs. The mountainous topography of the province prevents the northward propagation of TCs. Therefore, TCs landing in eastern and western Guangdong province have limited impacts on flooding in northern Guangdong province, and this point interprets the rare occurrence of TC-induced floods in the

northern Guangdong province. Therefore, flash floods due to convective heavy rains should arouse considerable concern for flood control.

(4) In eastern and western Guangdong province, more than 60% of the largest 10 flood events are attributed to TCs and hence TCs can modify the probability distribution of flood peak with an increase in the location and scale parameters of the GEV model. That is, TCs can greatly amplify hazardous floods with respect to magnitude and variability, which undoubtedly enhance the intensity and frequency of flood hazards. Hence, TCs under warming climate should be attached critical importance for flood hazards in coastal regions and particularly for those regions over the globe that are hit frequently by TCs.

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Fig. 1 Location of hydrological stations (a), spatial pattern of land use and land cover (b), Gross Domestic Product (c) and population (d) across Guangdong province.

Fig. 2 Maps for (a) maximum, (b) 90th, (c) 50th and (d) 10th of flood peaks across Guangdong province. The unit of flood peaks is m^3/s .

Fig. 3 Information of hydrological dataset used in the study.

Fig. 4 Spatial distribution of percentage of tropical cyclone-induced extreme precipitation events

Fig. 5 Spatial distribution of percentage of tropical cyclone-induced flood events and floods that occurred during the first and second flood seasons.

Fig. 6 Maps for (a) topography, (b) the total numbers of passing TCs, (c) the maximum strength of passing TCs, and (d) the maximum 2-min mean maximum sustained wind (MSW, m/s) near the TC center. The years of TCs range from 1951-2014. The strength classes are 1-6, according to the “Chinese National Standard for Grade of Tropical Cyclones”, which was put in practice since 15 June 2006. Class 1 indicates tropical depression, while class 6 indicates super typhoon.

Fig. 7 Percentage of stations with tropical cyclone-induced flood events and floods that occurred during the first and second flood seasons.

Fig. 8 K-S statistic D values for goodness-of-fit test of the GEV distribution of peak flood series across the Guangdong province.

Fig. 9 Spatial distribution of flood ratio of tropical cyclone-induced floods during specific years across the Guangdong province.

Fig. 10 Percentage of tropical cyclone-induced maximum flood ratio and 90th percentile of the flood ratio across Guangdong province.

Fig. 11 Spatial distribution of percentage of TC-induced 10 largest flooding events and floods that occurred during the first and second flood seasons.

Fig. 12 Impacts of tropical cyclone on the location, scale and shape parameters of the GEV distribution for peak flood series across Guangdong province.