Riverine Flooding and Landfalling Tropical Cyclones Over China

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Abstract Riverine flooding associated with landfalling tropical cyclones (TCs) in the western North Pacific basin is responsible for some of the most severe socioeconomic losses in East Asian countries. However, little is known about the spatial and temporal patterns of TC flooding and its climate controls, which constrain the predictive understandings of flood risk in this highly populated region. We provide a climatological characterization of TC flooding over China based on an exceptional network of stream gauging stations across the entire country. The most extreme floods in central and northeastern China are associated with TCs despite infrequent TC visits in these regions. Temporal variations in TC flooding demonstrate a mixture of controls tied to surface temperature anomalies in the northern hemisphere. The established links between TC flooding and climate controls present a potentially predictive tool of TC flood risk over China and other East Asian countries under future climate conditions.

Plain Language Summary Riverine flooding associated with landfalling tropical cyclones is responsible for some of the most severe socioeconomic losses all around the globe. This is a particularly critical issue for East Asian countries that lie on the margin of western North Pacific, the most active ocean in generating tropical cyclones. In this study, we investigate spatial and temporal variations of riverine flooding triggered by landfalling tropical cyclones across China. Our results show that the most extreme floods in central and northeastern China are associated with tropical cyclones, even though very few tropical cyclones affect this area. Surface temperature anomalies in both the Pacific and Atlantic regions determine the number of generated tropical cyclones, spatial pattern of tracks, and moisture transport. These combined effects, which can be well depicted using selected climate indices that represent large-scale variability of the Earth’s system, lead to temporal variations in the total number of flood peaks triggered by landfalling tropical cyclones across China. We establish relationships between these climate indices and the number of flood peaks induced by tropical cyclones over China and its subregions. These relationships can be used to project flood risk associated with these storms for other East Asian countries under a future climate.

1. Introduction

Typhoon Nina (1975) was responsible for the August 1975 flood over central China, one of the most destructive floods in world history (National Oceanic and Atmospheric Administration, 2007). Torrential rainfall and flooding resulted in 26,000 direct fatalities and approximately 100,000 additional fatalities from famine and disease. The August 1975 flood plays an important role in shaping the envelop curve of flood peaks over China and the world (e.g., Costa, 1987). Tropical storm Bilis (2006) is another one of those “poster-children” storms illustrating that riverine flooding associated with landfalling tropical cyclones (TCs) can pose as severe of a threat as other well-known TC-related coastal hazards (e.g., storm surge and strong wind; Rappaport, 2014). Despite its significance, little is known about the spatial and temporal variability of TC-induced riverine flooding across China. This is a particularly critical issue as China is located on the margin of the western North Pacific (WNP) basin and experiences some of the most severe impacts from landfalling TCs in the world (e.g., Peduzzi et al., 2012).
There is a vast body of literature focused on various aspects of TCs (e.g., genesis, intensity, and tracks) in the WNP basin (e.g., Chen et al., 2011; Colbert et al., 2015; Kossin et al., 2016; Wu et al., 2014). Previous studies highlight a decreasing trend in TC frequency (e.g., Hu et al., 2018; Zhang, Wu, & Zou, 2018) and a poleward migration of TC tracks in the WNP basin (Altman et al., 2018; Liang et al., 2017; Song & Klotzbach, 2018). In addition, there is evidence for an increasing trend in TC intensity and duration in the past decades (e.g., Emanuel, 2005; Li et al., 2017; Mei & Xie, 2016; Tu et al., 2018). TC activity in the WNP basin shows strong modulation by large-scale climate patterns, such as El Niño-Southern Oscillation (ENSO; e.g., Liu, 2019; Patricola et al., 2018; Zhao & Wang, 2019; Camargo & Sobel, 2005; Chan, 2000; Zhan et al., 2017; Wang & Chan, 2002). However, quantifying the impacts of changes in TC activity on riverine flooding remains elusive. This is mainly due to the fact that flood processes reflect complex interplays of space-time rainfall variability and watershed properties (e.g., Smith et al., 2005; Woods & Sivapalan, 1999). In addition, extreme rainfall from landfalling TCs is tied to complex interactions of TC circulations with synoptic weather systems (e.g., midlatitude trough, Atallah & Bosart, 2003; Liu & Smith, 2016, Evans et al., 2017) and regional topography (e.g., Houze, 2012; Khouakhi et al., 2017). TC-induced riverine flooding (in terms of magnitude and frequency) depends on both TC activity (e.g., track and location) and their interactions with physiographic and synoptic environments (Gao et al., 2009; Shu et al., 2018; Yu et al., 2017; Zhang, Vecchi et al., 2018) and merits additional investigation.

The overarching goal of the present study is to develop a predictive understanding of riverine flooding associated with landfalling TCs over China, given the existing knowledge about TC activity in the WNP basin. Understanding the nexus between large-scale weather phenomena (e.g., TC) and regional-scale flood response is an important research topic in hydrologic sciences. This emerges to a critical question, as evidence pointing to an increased flood hazards associated with TCs (e.g., Knutson et al., 2010). To the best of our knowledge, this has not been explicitly addressed in literature. Our analysis is based on an exceptional network of stream gauging stations across China with records of annual maximum floods during the period 1965–2017. An important theme of our study is the role of large-scale climate controls in TC flooding in the WNP basin. Instead of testing the validity of specific climate modes (such as ENSO), we expand the “pool” of candidates and construct the interannual variability of TC flooding based on a combination of indices that demonstrate multiple climate controls. Our results, in alignment with the analysis of Villarini et al. (2014) and Aryal et al. (2018) for the North Atlantic basin, can advance our understandings of the links between TC flooding and large-scale climate variability. We also expect to shed light on spatial and temporal patterns of TC flooding across China and provide tools for projecting TC flood risk across different subregions of the country under future climate conditions.

2. Data and Methods

There are 1,620 stream gauging stations across China, each having records of annual maximum peak discharge for at least 30 years during the period 1965–2017 (see supporting information for details). The data set is used to investigate the spatial patterns of TC flooding over China. Four subregions across China are selected, that is, southeastern coast, middle Yangtze River basin, central China, and northeastern China (Figure S1). Climatological TC activity and flood hydroclimatology show small heterogeneities within the four subregions (see details in section 3).

We associate an annual flood peak of a given stream gauging station with a particular TC if the circulation center is within 500 km of the station during a time window of 2 days prior to or a week after the timing of flood peak (e.g., Hart & Evans, 2000; Villarini et al., 2014; Villarini & Smith, 2010). Composite analysis based on satellite retrievals of TC rainfall further justifies the choice of 500 km as a suitable spatial threshold (figure not shown). We use the notion of flood ratio, that is, the magnitude of flood peak associated with TCs divided by the sample 10-year flood (i.e., the 90th percentile of the entire annual flood peak series) for a given station, to provide a regional perspective of TC flooding (e.g., Smith et al., 2018). TC tracks are obtained from the International Best Track Archive for Climate Stewardship (IBTrACS), with records of the location (i.e., latitude and longitude) of the center of circulation at 6-hr intervals for each recorded TC in the WNP basin.

We select 21 climate indices to constitute the initial “pool” that describes large-scale weather phenomena (Table S1). All of the indices are key indicators of temporal variation of the Earth’s climate system, with some having been identified with strong influences on TC activities in other basins (e.g., ONI in Atlantic basin,
Mixed annual flood ratios larger than 1, that is, southeastern coast, central China, and northeastern China. For central and northeastern China, the maximum TC flood peaks are associated with landfalling TCs despite infrequent occurrences compared to the southeastern coast. For most of the inland regions, less than 10% of the annual flood peaks are associated with landfalling TCs. This is mainly tied to the small TC frequencies in the vicinity of the stream gauging station. Typhoon Tim (1994), Typhoon Freda (1984), and Typhoon Herb (1996) produced the three largest counts of annual flood peaks over China (Table S2). Typhoon Herb and Typhoon Tim are also among the costliest TCs during the period 1983–2006 over China (Zhang et al., 2009). The ten largest TCs in terms of counts of annual flood peaks contribute to 15% of the total TC flood peaks over China during the period 1965–2017.

We divide the total number of annual TC flood peaks by the total TC occurrences to highlight the probability for a given stream gauging station with its annual flood peaks induced by TCs (Figure 1c). Central and northeastern China stand out with a noticeably high probability for TCs to produce the largest annual flood peak, indicating that a TC will most likely lead to the largest flood peak for the year as long as it can “survive” into inland region after landfall. The low probability in the southeastern coast is primarily due to the disproportionately large number of TC occurrences relative to the total number of years.

The largest flood peak by Typhoon Herb (1996) and Typhoon Andy (1982) is approximately 9 times as large as the sample 10-year flood (Figure 1d and Table S2). There are nine and seven stations with flood ratios larger than 3 for Typhoon Nina (1975) and Andy (1982), respectively, and these two TCs also produce the largest annual flood peaks. Typhoon Andy and Typhoon Herb produced the three largest counts of annual flood peaks over China (Table S2). Typhoon Herb and Typhoon Tim are also among the costliest TCs during the period 1983–2006 over China (Zhang et al., 2009). The ten largest TCs in terms of counts of annual flood peaks contribute to 15% of the total TC flood peaks over China during the period 1965–2017.

Spatial variations of flood ratios highlight contrasting roles of landfalling TCs in flood hazards as well as mixed flood-generating mechanisms across China. Due to the high TC frequency, the entire records of annual flood peaks are dominated by TCs in the southeastern coast. Extreme floods (i.e., with recurrence intervals exceeding 10 years) in the middle Yangtze River basin are less likely associated with landfalling TCs, but flooding in this basin is dominated by other mechanisms, for example, East Asia summer monsoon (e.g., Ding & Zhang, 2009). By contrast, the upper-tail properties of the flood peak distributions in central and northeastern China are determined by TCs despite infrequent occurrences compared to the southeastern coast. Our results are consistent with Yang et al. (2019), who showed that TCs are responsible for a
The majority of record floods (i.e., the largest flood peak for the entire records of a station) in central and northeastern China.

Extreme TC flooding in central and northeastern China can be partially tied to the synchronous seasonality of rainfall and TC frequency (Figures 2c and 2d). For instance, the peak probability density of TC frequency exceeds 1.5 during late July and early August in central China, with the peak timing less-than-one-week lag behind the rainfall peak. The situation is the same for northeastern China but with a flattened probability density function of TC frequency (Figure 2d). The “Late-July-Early-August” rainfall peak over central and northeastern China.

Figure 1. Maps show (a) TC frequency; (b) percentage of annual flood peaks associated with TCs; (c) probability of annual flood peaks induced by TCs, that is, ratio between (b) and (a); and (d) maximum flood ratio (i.e., annual flood peak magnitude by TCs divided by the 10-year flood for a given station during the period 1965–2017). The dashed black line in (d) indicates the divide of the second and third grand staircases over China. Results are based on the network of stream gauging stations and are interpolated using the inverse distance weighting method. Black boxes in (d) outline four subregions over China, and from south to north, they are southeastern coast, middle Yangtze River basin, Central China, and northeastern China.
northeastern China is closely tied to the propagation of monsoon (e.g., Ding & Chan, 2005; Ding & Zhang, 2009). Most watersheds in central and northeastern China are close to saturation during this time of the year. Passages of TCs during this season of the year will most likely lead to extreme floods in these regions.

Extreme floods in central and northeastern China can also be tied to the role of the interactions of TC circulation with complex terrain and midlatitude synoptic systems (e.g., upper-level trough) in producing record-breaking rainfall. The maximum 6-hr rainfall accumulation from Typhoon Nina (1975) is 830 mm (the current world record), and there are eight rain gauges with 3-day rainfall accumulation exceeding 1,000 mm during this storm. Those rainfall extremes are located in the windward slope of the mountains (see Yang et al., 2017, for details). A notable feature of large flood ratios (i.e., larger than 3) is that they are all distributed along the divide of the second and third Grand Staircase over China (Figure 1d). The interaction of TCs with midlatitude systems also provides a favorable environment for TCs transitioning to extratropical cyclones, a key element in producing extreme rainfall in midlatitude regions (e.g., Atallah & Bosart, 2003).

The unsynchronized seasonality of rainfall and TC frequency, that is, 2-month lag in the middle Yangtze River basin enable saturated watersheds to be depleted before the passage of these storms and thus may lead to less severe floods (Figure 2b). A notable exception is Tropical storm Bilis (2006) that made landfall in early July (with the probability density of 0.3; Figure 2b), only 2 weeks after the climatological rainfall peak. Bilis led to severe flooding in the middle Yangtze River basin with the maximum flood ratio equal to 8.4. It is the only flood ratio larger than 5 in southern China (i.e., south of Yangtze River) during the entire historical record.

### 3.2. Role of Climate Controls in Total Occurrences of TC Flood Peaks

We examine the temporal variations of the total number of TC-induced annual flood peaks based on a subset stations over China. The 348 stations have complete records during the period 1965–2017. There are 753 flood peaks (i.e., 2.5 annual peaks per station) for the top 10 years with the largest number of TC-induced
annual flood peaks (i.e., positive anomaly), contrasting to 217 flood peaks (i.e., 0.7 annual peak per station) for the 10 years on the lower end of the spectrum (i.e., negative anomaly; see Table S3 for details). Composite tracks for TCs during the positive anomaly years are characterized by two dominant paths: a westward-moving route that crosses the northern portion of the South China Sea and southern Taiwan and one path showing recurved routes around 125°E along the coast toward the Korean peninsula. TCs
during the negative anomaly years are mainly clustered in the northern portion of the South China Sea (Figures 3a and 3d). Contrasting TC tracks lead to distinct spatial patterns of riverine flooding across China. We see overwhelmingly more flood peaks with flood ratios larger than 1 during the positive anomaly years than the negative anomaly years. The contrast is even more striking for northeastern China, due to the re-curvature of TC tracks during the positive anomaly years (Figure 3a). The impacts of TCs during the negative anomaly years are confined to southeastern China (Figures 3a and 3d).

The years with the top 10 largest number of TC-induced annual flood peaks (hereafter positive anomaly years) are characterized by surface temperature below the climatological mean (i.e., multiyear average) over land in the northern hemisphere and sea surface temperature above the climatological mean in a large portion of the WNP basin (Figure 3b), while the reverse is true for the negative anomaly years (Figure 3e). Above-average temperature in the waters of the WNP basin as identified in the positive anomaly years provide abundant moisture supply and convective energy for TCs. Stepwise regression analysis further confirms the analysis of climatological background for the “end-member” years of the total number of TC-induced annual flood peaks. The six strongest explanatory climate indices, that is, Pacific North American (PNA) Index, East Atlantic pattern, Tropical Northern Atlantic Index, Western Pacific Index, Tropical Southern Atlantic Index, and Arctic Oscillation, explain 49% of the variance of the total number of TC-induced annual flood peaks (Figure S2).

Anomalies in surface temperature through perturbed atmospheric circulation (as represented by air pressure and wind fields) influence TC activities (including genesis and tracks) and moisture transport. A notable feature is the anticyclonic (cyclonic) pattern of integrated moisture flux during the positive anomaly (negative anomaly) years (Figures 3c and 3f). This is tied to the impact of temperature anomalies in tropical Pacific and Atlantic on the Walker circulation (Hu et al., 2018; Kosaka & Xie, 2013). Enhanced Atlantic SST suppresses TC genesis through intensified vertical wind shear in the WNP basin (Zhang et al., 2018b) and thus decrease the number of TC-induced annual flood peaks over China. In addition, the cyclonic pattern during the negative anomaly years indicates enhanced Western Pacific Subtropical High (WPSH). TCs in the WNP basin generally take the routes along the southwestern flank of WPSH. Enhanced WPSH constrains TC tracks to low latitudes, which is not favorable for moisture transport from the Pacific toward mainland China. There is a narrow belt of enhanced moisture transport in the western tropical Pacific, possibly associated with the southwestern extension of WPSH during the negative anomaly years (Figure 3f). Another feature is related to the “dipole-like” pattern of pressure anomalies between Aleutian Islands and the vicinity of Hawaii (i.e., definition of PNA). The jet stream along 40°N in northern Pacific (known as East Asian subtropical jet stream) is weakened during the negative phase of PNA (Figure 3c). Previous studies show that weakened East Asian subtropical jet stream corresponds to high TC frequency in the WNP basin (e.g., Chen et al., 2019; Hu et al., 2019). PNA is the only climate index that exists among the top 6 strongest explanatory variables for both the entire country and four subregions (Table 1). In addition to PNA, indices related to ENSO, such as NINO3, NINO4, ONI, SOI, and MEI, are also selected indicating the significant controls of temperature anomalies in the waters of tropical Pacific in TC-induced riverine flooding across China.

### Table 1

| Regions                  | Number of stations | Climate indices |
|--------------------------|--------------------|-----------------|
|                         |                    | 1   2   3   4   5   6 |
| Entire country           | 348                | PNA EA TNA WP TSA AO |
| Southeastern coast       | 26                 | PNA WP NINO3 TSA EA PDO |
| Middle Yangtze River basin | 37               | EN/NP PNA NINO4 SCAND ONI SOI |
| Central China            | 13                 | PNA WHWP PDO NP EN/NP NINO3 |
| Northeastern China       | 9                  | EN/NP SOI MEI ONI PNA PDO |

Note: The results are based on stepwise regression (using the adjusted $R^2$ metric).
Abbreviations: AO, Arctic Oscillation; EA, East Atlantic pattern; NP, North Pacific pattern; PNA, Pacific North American Index; TNA, Tropical Northern Atlantic Index; TSA, Tropical Southern Atlantic Index.
We further examine the individual role of PNA and ENSO (using the ONI index) in TC flooding over China and its subregions, to highlight dominant controls of large-scale climate mode in TC flood risk for east Asian countries. Both climate indices are negatively correlated with TC flood frequency over China. For instance, the total number of TC-induced annual flood peaks during the negative phase of each climate pattern is approximately 1.5 times as large as that during the positive phase over the entire country (Table S4). The role of two climate indices in TC flood frequency varies among the four subregions. The PNA anomaly is strongly correlated with TC flood frequency in southeastern coast and central China, while they only show weak impacts in the middle Yangtze River basin and northeastern China. There are 46 TC-induced annual flood peaks over central China during the negative phase of PNA anomaly, which is 4 times as many as that during its positive phase. The anomaly of ENSO, however, only shows strong correlation with TC flood frequency in the southeastern coast of China.

The negative phase of PNA anomaly also tends to produce larger flood ratios (i.e., with more flood ratios larger than 1) than its positive phase (Figure 4). The spatial contrast of flood ratios between two phases is quite apparent in central and northeastern China where we observe several stations with maximum flood ratios approaching 2. Spatial patterns of flood ratios are, however, comparable between the negative and positive phase of the ENSO anomaly.

**Figure 4.** Dependence of TC flood peak magnitude on two climate indices, PNA (left column) and ENSO (right column), during their positive phase (first row) and negative phase (second row), respectively. Color represents maximum TC flood ratio values for each phase. The third row shows histograms of flood ratios for two phases (pink for positive phase and green for negative phase) of each climate index. The solid lines represent fitted probability density functions based on the Rayleigh distribution, while the dashed lines highlight mean values. We use the nonparametric Kolmogorov-Smirnov (K-S) test to determine if the distributions between two phases differ significantly (with p values shown in the plots).
positive phases of the ENSO anomaly. Statistical distributions of flood ratios also show no significant differences between two phases of ENSO anomaly, while the contrary is true for PNA (Figures 4c and 4f). Our results highlight intricated nexus between climate modes and TC flooding in the WNP basin. Despite previously established connections between ENSO and TC activities (e.g., genesis and frequency) in the WNP basin, we emphasize that flood risk over China induced by landfalling TCs is actually controlled by combined roles of multiple climate modes (such as PNA), with ENSO alone actually playing a secondary role.

3.3. Temporal Variations in the Total Occurrences of TC Flood Peaks for each Subregion

Total TC occurrences in the WNP basin are significantly decreasing during the period 1965–2017, with an estimated trend of −3.5 per decade (p < 0.01, Figure 5a). We further show spatial variations in the trends of TC occurrences, to shed light on the shifting patterns of TCs in the WNP basin. The entire basin is overwhelmed by grid boxes with reduced TC occurrences, especially in the regions with most frequent TC occurrences (Figure 5b). The maximum change rate is −1 per decade. However, if we restrict attention to coastal regions in higher latitudes (i.e., north of 25°N), we observe weak tendencies of increasing TC occurrences. Our results are consistent with previous studies that show a noticeable poleward migration of TCs in the WNP basin in the past decades (e.g., Liang et al., 2017).

Even though TC occurrences in WNP basin are significantly decreasing, the three subregions of China (i.e., northeastern China, central China, and southeastern coast) only show modest decreases in the total number

Figure 5. (a) Time series of total TC frequency in the WNP basin during the period 1965–2017. Shade indicates the 95% confidence bounds. The estimated trend and p values are shown in the plots. (b) Map of climatological mean TC frequency in the WNP basin (number per year, black contours) and its change rate within grid box of 2.5° by 2.5° during the period 1965–2017. Change rates are estimated based on Poisson regression, with the black cross symbols representing statistical significance at the level of 5%. Black boxes outline four subregions over China.
of TC-induced annual flood peaks during the past decades (Figure 6); only central China region has a trend that is statistically significant ($p < 0.05$). In sharp contrast, the middle Yangtze River basin shows a significant increasing trend in the occurrence of annual flood peaks induced by TCs ($p < 0.05$, Figure 6b). Inconsistent changes between TC frequency and number of TC-induced annual flood peak further highlight the importance of analyzing flood response to TC storms rather than projecting TC flood risk through changes in TC activities alone (e.g., frequency and genesis).

The interannual variability of the total number of annual flood peaks over the four subregions during the period 1965–2005 can be well reconstructed based on the selected six strongest explanatory climate indices through multiple regression (explainable variance ranging from 18% to 48%, Figure 6). High consistencies

![Image of Figure 6](https://example.com/f6.png)

**Figure 6.** Temporal variations in the total number of TC-induced annual flood peaks over (a) southeastern coast, (b) the middle Yangtze River basin, (c) Central China, and (d) northeastern China. The black lines indicate observed series of total number of annual flood peaks, while the red solid lines represent reconstructed time series using selected climate indices via multiple regression during the period 1965–2005. The red dashed lines represent predicted values during the period 2005–2017 based on the established multiple regression models. The insert black numbers are coefficients of determination ($R^2$) between the observed and reconstructed time series. The correlation coefficients ($R$) and $p$ values between predicted and observed series are labeled for the four subregions, with the exception of Central China (no annual flood peaks associated with TCs during the validation period). The dashed black line represents the estimated tendencies based on Poisson regression (the 95% confidence bounds are shaded in gray). The $p$ values for the estimated trend of each region are 0.37 for the southeastern coast; 0.02 for the middle Yangtze River basin; 0.58 for Central China; and 0.43 for northeastern China.
between the predicted and observed counts of annual flood peaks during 2005–2017 further enhance the reliability of the established multiple regression models. Inferior performances of the models in central and northeastern China are possibly tied to the fact that most TC flood peaks are associated with re-curved TC tracks (Figure S3). The existing pool of climate indices is unable to represent the variability of baroclinic environment in midlatitude regions and interactions with regional topography (e.g., Keller et al., 2019), both of which are critical for extreme rainfall and flooding in these regions.

4. Conclusions

In this study, we provide a climatological characterization of TC flooding based on an exceptional network of stream gauging stations over China. We identify contrasting roles of TCs in controlling the upper-tail properties of flood peak distributions over different subregions of China. Central and northeastern China stand out with high probabilities of extreme floods associated with TCs, even though these storms are not very frequent here. This is tied to the synchronized seasonality of rainfall and TC frequency as well as active interactions between storms and ambient environments (e.g., upper-level trough and complex terrains) in midlatitude regions. This is in contrast with the public perception that TC-related hazards are tightly concentrated along the coasts, even though Typhoon Nina (1975) and Bilis (2006) raised alarms for riverine flooding. Our results provide the foundation for better designs of flood-control infrastructures and flood risk assessment associated with landfalling TCs in inland China.

TC flood risk (as represented by the total number of TC-induced annual flood peaks over different regions) demonstrates a combination of climate controls as represented by temperature anomalies in central tropical Pacific, western north Pacific, and north Atlantic. The combination of climate controls reveals its role in riverine flooding through perturbations on TC frequency, tracks, and moisture transport during the monsoon season. The established links between selected climate indices and TC flooding provide useful tools for projecting the flood risk associated with landfalling TCs in the WNP basin and will be a focus of future studies. Our results highlight the necessity of improved mitigation and adaptation strategies for TC-related flood hazards over China as well as other countries in East Asia, as the evidence point to changing spatial patterns of TC occurrences and growing influences of TCs in East Asia (Wu et al., 2005). Model projections also show quite robust increases in TC rainfall under the context of climate change (e.g., Knutson et al., 2010; Patricola & Wehner, 2018; Liu et al., 2018). Future studies need to zoom into watershed scales and explore physical connections between extreme flood response and responsible TC features (e.g., space-time rainfall variability).

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