The Impact of Tropical Cyclones on Extreme Precipitation over Coastal and Inland Areas of China and Its Association to ENSO

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ABSTRACT

The coastal part of China and its surrounding regions are dominated by a highly dense population and highly developed economy. Extreme precipitation events (EPEs) cause a lot of damage and hence changes in these events and their causes have been drawing considerable attention. This study investigated EPEs resulting from western North Pacific (WNP) tropical cyclones (TCs) and their potential link to El Niño–Southern Oscillation (ENSO), using TC track data, daily precipitation data from 2313 stations for 1951–2014, and the NCAR–NCEP reanalysis dataset. Two types of EPEs were considered: EPEs within 500 km from the TC center, and those caused by mesoscale and synoptic systems, referred to as predecessor rain events (PREs), beyond 1000 km from the TC center. Results indicated significant impacts of TCs on EPEs along the coastal areas, and discernable effects in inland areas of China. However, the effect of TCs on EPEs tended to be modulated by ENSO. During neutral years, inland areas of China are more affected by TC-induced extreme precipitation than during El Niño or La Niña years, with the highest density of TC tracks and larger-than-average numbers of tropical storms, typhoons, and landfalling TCs. During the El Niño phase, the central and eastern equatorial Pacific was characterized by higher sea surface temperature (SST), greater low-level vorticity (1000 hPa) and upper-level divergence (250 hPa), and stronger prevailing westerlies, which combined to trigger the movement of mean genesis to the eastern and southeastern WNP, resulting in fewer TCs passing through the Chinese territory.

1. Introduction

Tropical cyclones (TCs) and TC-induced storm surge, heavy precipitation, and flooding caused enormous losses of life and economic damage worldwide (Lin et al. 2015; Yan et al. 2016). In the backdrop of warming climate, the intensity of nonextreme TCs and the frequency of the most intense TCs are expected to increase, based on the results of theoretical analyses and mathematical models (e.g., Knutson et al. 2010; Bindoff et al. 2013; Christensen et al. 2013). Considering future economic development and population growth in urban
areas, the increasing frequency of higher-intensity TCs is expected to cause greater risk of hazard and damage in urbanized areas (Webster et al. 2005; Mendelsohn et al. 2012; Xu et al. 2014). TCs are usually associated with weather extremes, such as strong wind and heavy precipitation. However, the most serious TC-induced damages are caused by heavy precipitation–induced sudden excessive runoff and consequent flash flooding (Jonkman et al. 2009). Therefore, statistical relations between TCs and extreme precipitation, as well as the physical dynamics and mechanisms, have received much attention (e.g., Konrad and Perry 2010; Kunkel et al. 2010; Gu et al. 2017a,b; Zhang et al. 2017).

Studies on relations between TCs and extreme precipitation at global and regional scales have focused on the impact of TCs on extreme precipitation mainly along coastal areas (Knight and Davis 2009; Chang et al. 2012; Lavender and Abb 2013; Villarini and Denniston 2016; Khouakhi et al. 2017). Quantifying the contribution of TCs to extreme rainfall, Khouakhi et al. (2017) concluded that TCs contributed to about 35%–50% of precipitation changes in coastal areas worldwide. Increasing frequency of floods has also been observed in inland regions (e.g., >1000 km from the center of a TC), and these floods were believed to be triggered by a mesoscale and sub-synoptic system of predecessor rain events (PREs), which is different from extreme precipitation induced by the TC itself (Cote 2007; Wang et al. 2009; Bosart et al. 2012). Such inland floods can lead to severe damage and fatalities, such as occurred with Hurricanes Irene in 2011, Isaac in 2012, and Sandy in 2012 in the United States (Villarini et al. 2011; Mendelsohn et al. 2012; Peduzzi et al. 2012). However, there is limited literature addressing the impact of PRE-related extreme precipitation events on inland flooding (Rowe and Villarini 2013).

Landfalling TCs are capable of transporting abundant water vapor and thus help provide favorable conditions for the occurrence of extreme precipitation (Smith et al. 2011). In many cases, the precipitation shield induced by TCs is asymmetric due to the interaction with mid-latitude disturbances or fronts. It is therefore logical to examine precipitation over stations within the cloud shield from satellite imagery one by one, but defining the TC-induced precipitation shield in this way is inconvenient for climate research over a multiyear period (e.g., Larson et al. 2005; Ren et al. 2007). Therefore, definitions of TCs based on a circle with an effective radius have been widely accepted (e.g., Chen et al. 2010;
Jiang and Zipser 2010; Lee et al. 2010; Li et al. 2015). The effective radius can range from 250 to 1000 km (Hasegawa 2005; Chen et al. 2010; Li et al. 2015), but recent studies have reached a consensus that the optimal radius is 500 km (e.g., Jiang and Zipser 2010; Lee et al. 2010; Smith et al. 2011; Khouakhi et al. 2017; Gu et al. 2017a,b). However, the 500-km effective radius of TCs only considers the main precipitation shield; PREs, usually 1000 km away from the center of the landfalling TCs, are thus not taken into account (Cote 2007; Wang et al. 2009; Bosart et al. 2012; Rowe and Villarini 2013). It should be noted that only a proportion of TCs can produce PREs. For example, only 47 PREs were documented in 21 TCs in the Atlantic, Caribbean, and Gulf of Mexico basins from 1998 to 2006 (Cote 2007). Because PREs can often result in significant inland flooding, more and more recent studies have started to investigate their relations (e.g., Galarneau et al. 2010; Rowe and Villarini 2013).

Although studies have tried to investigate the relationship between TCs and large-scale climate oscillations (Villarini et al. 2012; Klotzbach and Blake 2013; Yan et al. 2016), the connection between the magnitude and frequency of TC-induced extreme precipitation and large-scale climate controls has not been addressed. Yan et al. (2016) showed that changes in power dissipation and TC frequency were sensitive to the variation in sea surface temperature (SST), especially in the Pacific. Hence, examining the influence of SST anomalies on TC-induced extreme precipitation magnitude and frequency is critical for TC prediction.

The western North Pacific (WNP) generates most TCs, and these TCs tend to be the strongest (Peduzzi et al. 2012). China, located in the western WNP, is especially vulnerable to landfalling TCs from the WNP (Zhang et al. 2009). This study attempts to investigate extreme precipitation changes in relation to WNP TCs by highlighting the landward and coastal regions of China where TCs are dominant drivers for the occurrence of extreme precipitation with consideration of both the main precipitation shield of TCs and the PREs. It is now acknowledged that El Niño–Southern Oscillation (ENSO) strongly impacts WNP TCs (Camargo and Sobel 2005; Klotzbach and Blake 2013; Corporal-Lodango et al. 2016; Khouakhi et al. 2017). Therefore, the influence of ENSO on the relation between magnitude and frequency of extreme precipitation and TCs was also evaluated (e.g., Yonekura and Hall 2011; Klotzbach and Blake 2013; Colbert et al. 2015).

The major objectives of this study therefore were 1) to determine extreme precipitation events due to TCs; 2) to quantify the relation between extreme precipitation, TCs (intensity and tracks), and ENSO; and 3) to probe into the causes behind the relation from the perspective of large-scale environmental variables (e.g., SST, vorticity, divergence, and wind). The main goal of our study is to quantify relations between extreme precipitation, TCs, and ENSO. Here we will provide a consistent long-term
analysis of the character of TC-induced extreme precipitation, and provide insight into the spatial changes in TC-induced extreme precipitation as the storms move inland. In addition, we will also highlight the regional differences of TC-induced extreme precipitation during the different ESNO phases and try to explain the possible reasons. To achieve this main goal, the first work is to determine TC-induced extreme precipitation. Results of this study will help clarify causes of extreme precipitation events in China and extreme precipitation variation in both space and time in a warming climate.

2. Data

a. Precipitation and TC track data

In situ precipitation observations from 2474 stations across China were collected from the China Meteorological Information Center (e.g., Ma et al. 2015). A total of 2313 stations with at least 35 years of observations and less than 1% missing values were analyzed. Locations of stations and information on precipitation records are shown in Fig. 1a. The missing values of precipitation for 1–2 days were filled by the average precipitation of the neighboring days. Consecutive days with missing data were interpolated by the long-term average of the same days of other years. For the objectives of this study, the gap-fill method did not significantly affect the final results. A similar method had been used by Zhang et al. (2011) to fill daily missing precipitation values.

The starting and ending times of daily precipitation dataset were from 1951 to 2014 (Fig. 2). Precipitation data from more than 2000 stations were available for 1960–2014 (Fig. 2a), and the lengths of daily precipitation data from more than 1500 stations ranged from 55 to 60 years (Fig. 2b). Although different record lengths of daily precipitation data may lead to varying degrees of precision of statistical estimators, the lengths of precipitation data from most of the stations were long enough to ensure the accuracy and representativeness of analysis.

The TC data used in this paper were obtained from the Shanghai Typhoon Institute (STI) of the China Meteorological Administration (http://tcdata.typhoon.org.cn/). The best-track data for each TC at 6-h time intervals for 1949 to the present were also collected, including the latitude–longitude position, the maximum sustained surface wind speed (WND), and the minimum central pressure. A TC with a wind speed of 10.8–17.1 m s\(^{-1}\) is classified as a tropical depression (TD), while for tropical storm (TS) and typhoon (TY) status, the wind speed is 17.2–32.6 m s\(^{-1}\) and larger than 32.6 m s\(^{-1}\).
respectively. The quality of TC tracks has been controlled using the method of Ying et al. (2014). The topography data and population density data, obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn), were used to estimate changes in the risk of TC-induced extreme precipitation (Figs. 1b,c).

b. ENSO phases and NCAR–NCEP reanalysis data

ENSO phases were derived from SST anomalies in the region 5°N–5°S, 170°–120°W (i.e., Niño-3.4), which is also the most important region for WNP TC activities (Camargo and Sobel 2005). Monthly ENSO data were obtained from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA). To determine the ENSO phase in a specific WNP TC season (July–October; Lee et al. 2010), the entire 64-yr period from 1951 to 2014 was subdivided into three categories: 1) El Niño years, when the average of Niño-3.4 index values in the TC season was larger than 0.5; 2) neutral years, when the average ranged from −0.5 to 0.5; and 3) La Niña years, when the average was smaller than −0.5. The classification of ENSO phases is given in Table 1 (Lyon and Camargo 2009). The values of geopotential height, wind, divergence, SST anomalies, and precipitable water (PW) were provided by the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis. The NCEP–NCAR reanalysis project uses a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present. A large subset of this data is available from the Physical Sciences Division (PSD) in its original 4 times daily format and as daily averages with 2.5° × 2.5° spatial resolution. Subdaily and monthly data of geopotential height, wind, divergence, SST anomalies, and PW can be obtained from Earth System Research Laboratory.

c. Linkages between extreme precipitation and TCs

To evaluate the influence of TCs on the magnitude and frequency of extreme precipitation, annual maximum (AM) and peak-over-threshold (POT) sampling methods were used to define the magnitude of extreme precipitation as the annual maximum daily precipitation and the frequency of extreme precipitation as the number of days exceeding a threshold (i.e., the 95th percentile of nonzero rainfall events) of every year, respectively (Khouakhi et al. 2017). The following criteria were used to identify whether a daily precipitation was induced by TCs: the center of circulation of storm was located within a 500-km radius from the rain gauge during the time window of ±1 day (Knight and Davis 2009). The spatial distribution of the number of TCs passing within 500 km from a given precipitation station was consistent with previous studies (Fig. 1d; Chen et al. 2011).

Extreme precipitation with a 10-yr return period (i.e., extreme precipitation was expected to occur, on average, once every 10 years) was calculated by the 90th percentile of annual maximum daily precipitation. Similar to the flood ratio defined by Czajkowski et al. (2013), the extreme precipitation ratio (EPR) was defined as the ratio of the magnitude of TC-induced extreme precipitation to that of 10-yr return period extreme precipitation. Because of the large differences in the absolute magnitudes of extreme precipitation in different regions, EPR was used to normalize the TC-induced extreme precipitation in order to obtain a regional view. An EPR larger (smaller) than 1 indicated a degree of TC-induced extreme precipitation larger (smaller) than the 10-yr extreme precipitation.

3. Results and discussion

a. Influence of TCs on extreme precipitation in inland areas

During 1951–2014, China—especially southeastern China, the area most affected by TCs—was hit by more than 500 TCs (Fig. 1d). Several to dozens of TCs moved
deep inland (Fig. 1d). Among the TCs moving deep inland, four TCs were selected to display the EPR maps by interpolating the values among precipitation stations using the inverse distance weighting method (Fig. 3). The reasons why these four TCs were selected were that 1) all of these TCs moved deep inland with very strong TC strength, which effectively showed the influence of TCs on inland extreme precipitation, and 2) these four TCs had different landfalling locations and moving tracks (TY Nina and TY Tim moved northward after landing, and TY Rana and TS Bilis moved downward after landing), demonstrating the influence of TCs on extreme precipitation in different regions.

Large areas in the path of these TCs were identified with EPRs larger than 1, indicating that these TCs-induced extreme precipitation events were larger than the corresponding 10-yr extreme precipitation. However, the largest EPRs were not found in coastal areas but inland provinces (Fig. 3), which was not expected. Maps of this kind provided key information essential to highlight the prevalence of TC-induced extreme precipitation away from coastal areas. Taking TY Nina as an example, the EPRs in both HeN (Henan) and HB (Hubei) provinces (Fig. 1c) were the largest, suggesting the two inland provinces suffered from severe flooding caused by Nina (Fig. 3a). Observations also showed that the flooding caused by Nina indeed led to hundreds of thousands of casualties in HeN province (Ding 2015).

Beside the direct influence of TCs on inland extreme precipitation, heavy precipitation was produced by a TC over a long distance (i.e., PREs). Cote (2007) first defined the term predecessor rain event to describe mesoscale and subsynoptic-scale regions of high-impact heavy rainfall that occur well in advance of recurving tropical cyclones over the eastern third of the United States. He defined a PRE as a coherent region of heavy

FIG. 5. The 250-hPa geopotential height (solid gray to black contours; units: m), 850-hPa wind (black arrows), and precipitable water (PW) (colored regions) at (a) 0000 LT 12 Jul, (b) 1200 LT 12 Jul, (c) 0000 LT 13 Jul, and (d) 1200 LT 13 Jul 1994 when TC Tim moved toward inland.
rainfall, with rainfall rates exceeding 100 mm in 24 h, that was positioned poleward and was separate from the main rain shield associated with the TC. TY Tim (1994) and TY Herb (1996) were selected as examples to show the distantly located heavy precipitation (Fig. 4). For TY Tim, the total accumulated precipitation for 24 h on 13 July 1994 showed an anticyclonically curved swath of heavy precipitation over northeast China consisting of one “precipitation corridor” (Fig. 4a). For TY Herb, there were two regions with total accumulated precipitation for 24 h on 4 August 1996 of more than 100 mm, of which one was located in HB province and the other was northward far away from the center of Herb (Fig. 4b). Overall, the heavy rainfall produced by the two TCs was higher than 100 mm in 24 h and positioned poleward and separated from the main rain shield associated with the two TCs; this is agreement with the definition of Cote (2007).

An important aspect of a PRE is that the deep tropical moisture, typically manifested as total column precipitable water (PW) values greater than 50 mm, originally associated with the TC must be advected poleward into the PRE region (Galarneau et al. 2010). The large-scale flow evolution associated with the development of the two TCs in 24 h provided a favorable environment for the poleward transport of tropical moisture (Figs. 5 and 6). For TY Tim, at 0000 local time (LT; UTC + 8) 12 July, a 850-hPa cyclonic circulation center was located in eastern China, with an accompanying 250-hPa trough crossing northern China, which brought abundant moisture from the South China Sea to eastern China (PW > 60 mm) (Fig. 5a). At 1200 LT 12 July and 0000 LT 13 July, the 850-hPa cyclonic circulation center moved northward and the accompanying 250-hPa trough stretched southward, which facilitated the transport of tropical moisture toward northern China with PW more than 60 mm in a wider range of area.
At 1200 LT 13 July, although the 850-hPa cyclonic circulation disappeared, the warm moisture from the South China Sea encountering the cold moisture from north produced a PRE represented by moist air (PW > 50 mm) in northeast China (Fig. 5d).

Similarly, for TY Herb, an 850-hPa cyclonic circulation center was located in eastern China bringing tropical moisture from the WNP to central China (PW > 60 mm) (Fig. 6a). Then, with the cyclonic circulation disappearing, the 250-hPa ridge across China and an axis of high PW values (>50 mm) that extended from the South China Sea to central China was the moisture source for extreme precipitation in central and northern China (Figs. 6b–d). The processes of moisture translation clearly showed how TCs enhanced remote precipitation (Wang et al. 2009).

**b. Characteristics of magnitude and frequency of TC-induced extreme precipitation**

By exploring the associations between the magnitude and frequency of extreme precipitation over the past 64 years, we were able to provide a climatological view of the areas that had been most affected by the TCs (Figs. 7, 8, and 9). A majority of China was detected with the magnitude of extreme precipitation exceeding the 10-yr extreme precipitation (Fig. 7a). These areas almost covered all areas of eastern China with high population density (Figs. 1c and 7a), which was in line with the results of previous studies (e.g., Ying et al. 2011). The undulating mountains represent a natural divide (Fig. 1b) and shield the western part of the domain. Among these areas with EPRs larger than 1, the coastal areas were as expected, consistent with previous studies (Ren et al. 2006, 2007; Ying et al. 2011), but large areas located in inland provinces were different from previous studies (Ren et al. 2006, 2007; Ying et al. 2011).

Compared with the magnitude of TC-induced extreme precipitation, the spatial distribution of extreme precipitation days associated with TCs (i.e., frequency) followed as expected with a decrease from southeast to northwest China (Fig. 8). This feature was in agreement with the spatial distribution of the number of TCs passing within 500 km from a given precipitation station (Fig. 1d), and in line with previous studies (e.g., Chen et al. 2011). When we focused on the ratios between extreme precipitation days associated with TCs and total extreme precipitation days for every year, similar spatial distributions between EPRs and the ratios were also found (Figs. 7 and 9). Although absolute extreme precipitation days associated with TCs were larger in coastal areas than inland areas, the ratios in inland areas were as almost the same as those in coastal areas (Figs. 8 and 9).
suggesting that the frequency of extreme precipitation in inland areas in particular years was induced by TCs in large part. It should be also noted that the spatial distributions of EPRs (Fig. 7), frequency (Fig. 8), and ratios (Fig. 9) in different percentiles (i.e., maximum, 97.5th, 95th, and 90th) were consistent, suggesting that these above features were not related to a single event but were more persistent (Figs. 7–9).

c. Influence of ENSO on magnitude and frequency of TC-induced extreme precipitation

After examining the impact of TCs, we analyzed the influence of ENSO on the magnitude and frequency of TC-induced extreme precipitation (Figs. 10 and 11). Larger EPRs associated with TCs tended to occur during the neutral phase of ENSO (Fig. 10). In addition, EPR values exceeding 10-yr extreme precipitation during both El Niño and La Niña phases of the ENSO mainly concentrated along the coast of China, while the spatial distribution of the EPR values of larger than 1 extended inland (Fig. 10).

The frequency of TC-induced extreme precipitation during both El Niño and La Niña phases of ENSO decreased from the coast to inland suddenly, whereas the decrease was gentler during the neutral phase (Figs. 11a–c). Higher frequency of TC-induced extreme precipitation also tended to occur during the neutral phase with concentration on the southeast coast (Fig. 11b). Turning our attention to the proportion between TC extreme precipitation days and total extreme precipitation days, the proportion with higher values also tended to occur during the neutral phase (Fig. 11e). Moreover, the proportion with higher values extended inland during the neutral phase in comparison with that during the El Niño and La Niña phases (Figs. 11d–f). These results suggested that the largest threat posed by TCs in terms of extreme precipitation was generally during the neutral phase of ENSO.

The landfalling TC tracks during the El Niño and La Niña phases as well as the total numbers of past TCs seemed to be similar, which may be the reason for the spatial distributions of TC-induced extreme precipitation being analogous (Fig. 12). The TC tracks during the neutral phase were the densest, compared with other phases (Fig. 12). In addition, there were more straight-moving tracks entering inland and recurring tracks extending farther northeast and reaching higher latitudes during the neutral phase, which provided beneficial conditions to produce TC-induced extreme precipitation in inland areas.

FIG. 8. As in Fig. 7, but for the extreme precipitation days associated with TCs. Extreme precipitation days were defined as the number of days exceeding a selected threshold value (i.e., 95th percentile of the nonzero rainfall values) counted for every year.
Furthermore, the frequency of all TCs and landfalling TCs classified by three TC intensities (i.e., TD, TS, and TY) during the three phases is shown in Fig. 13. To provide a representative set of TC frequency, the time series of TC count was standardized by subtracting the long-term mean and then dividing the difference by the standard deviation \[ \frac{(x_i - \mu)}{\sigma}, \] where \( x_i \) was the count of TC in year \( i \), \( \mu \) was the long-term mean, and \( \sigma \) was the

![Fig. 9](image_url)

**Fig. 9.** As in Fig. 7, but for the ratios between extreme precipitation days associated with TCs and total extreme precipitation days for every year.

![Fig. 10](image_url)

**Fig. 10.** The (top) maximum and (bottom) mean EPRs associated TCs on the (left) El Niño, (center) neutral, and (right) La Niña phase of ENSO.
standard deviation]. For all the TCs, TDs and TSs exceeded the average during the La Niña phase, and TYs with the largest strength of TC intensity tended to occur during the El Niño phase. Previous studies also revealed that TCs were more intense in the El Niño phase than in the La Niña phase (e.g., Chia and Ropelewski 2002; Klotzbach and Blake 2013). However, above-average numbers of TSs, TYs, and all TCs occurred during the neutral phase. Moreover, for landfall TCs, there were more TCs with TS, TD, and TY intensities during the neutral phase, whereas fewer TCs with all three TC intensities occurred during both El Niño and La Niña phases. That may be another reason why TC-induced extreme precipitation tended to occur during the neutral phase.

Finally, we discuss the plausible physical mechanisms responsible for the relationship between TCs and ENSO by analyzing the differences of large-scale environmental variables, such as SST, vorticity, divergence, and zonal wind, during different ENSO phases (Fig. 14). The SST in the WNP had a diverse behavior during the three ENSO phases (Figs. 14a–c), which played a significant role in accounting for the difference in the TC numbers in China (Yan et al. 2016). SSTs were more pronounced with higher values during El Niño than during both the neutral and La Niña phases over the central and eastern equatorial Pacific (Figs. 14a,c). This implies that the displacement of mean genesis location of TCs tended toward the east and southeast in El Niño years, leading to fewer TCs in China (Chan 2000). Compared with the negative SST difference over WNP between neutral and La Niña phases, the positive SST difference was more pronounced over the central equatorial Pacific, indicating that SST in that region was much warmer during the neutral phase than during the La Niña phase (Fig. 14b). This conformed to the broader region of TC formation (Mendelsohn et al. 2012).

Another driver of the TC genesis was the Southeast Asian monsoon trough (Huangfu et al. 2017). The flow intensification on either side of the monsoon trough benefitted the TC genesis with increasing low-level vorticity (Frank 1987). The 1000-hPa vorticity was stronger over the central and eastern equatorial Pacific that also showed higher SSTs during the El Niño phase than during both neutral and La Niña phases (Figs. 14d,f), which also provided a favorable environment for TC genesis eastward. When comparing the vorticity between neutral and La Niña phases, a stronger vorticity was found in most regions of WNP during the neutral phase than during the La Niña phase (Fig. 14e). The vorticity at 1000 hPa during neutral years is stronger than in the La Niña phase in most parts of WNP (Fig. 14e), suggesting that stronger low-level vorticity is prevalent over most areas in neutral years with enhancing TC genesis. The upper-level divergence continued to deepen to benefit surface low pressure area development (Corporal-Lodango et al. 2016). Relative to neutral and La Niña phases, stronger 250-hPa divergence was observed over the central and eastern equatorial Pacific during the El Niño phase (Figs. 14g,i). The central and eastern equatorial Pacific, with stronger divergence, was the area with stronger vorticity and higher
SSTs in El Niño years, showing that TC genesis locations moved into the eastern Pacific. Most regions of WNP had stronger divergence in neutral years than La Niña years, enhancing the surface low pressure area development (Corporal-Lodangeo et al. 2016; Fig. 14h). Regions with higher upper-level divergence values are conducive for TC development, justifying the higher frequency of TCs in neutral phases relative to La Niña phases; this is in agreement with the areas of stronger low-level vorticity (Figs. 14e,h). Additionally, analysis of low-level zonal winds helped detect bursts of westerly winds associated with the TC genesis over WNP (Figs. 14j–l). Compared with neutral and La Niña phases, westerlies were prevalent over the central and eastern equatorial Pacific during the El Niño phase, which pushed the warm pool eastward and thereby displaced the mean genesis locations eastward (Figs. 14j–l). Although strong easterly winds can be detected in the central equatorial Pacific, consistent with the preferred regions of TC genesis in both neutral and La Niña phases (Figs. 14k,l), the central equatorial Pacific has warmer SST during the neutral phase than La Niña phase (Fig. 14b). Compared with La Niña phase, easterlies burst during the neutral phase and push warmer SSTs westward, which is beneficial for TC genesis westward.

4. Conclusions

We evaluated the magnitude and frequency of TC-induced extreme precipitation over China, and their
relation with ENSO. The EPRs described as the ratios between the magnitude of TC-induced extreme precipitation and 10-yr extreme precipitation were used to determine the characteristics of TC-induced extreme precipitation at the regional scale. Four particular TCs moving deep into inland areas caused greater extreme precipitation with respect to 10-yr extreme precipitation in inland areas than coastal areas. Beside the direct influence of TCs on inland extreme precipitation by the main precipitation shield, a TC also can bring about extreme precipitation in inland areas far away from the cyclone by remote moisture transport (Wang et al. 2009). The EPRs of all the TC-induced extreme precipitation agree with the results of the particular TCs, and emphasize that TCs are responsible for both magnitude and frequency of extreme precipitation not only in coastal areas but also in inland areas. Different from previous studies, which only revealed the contributions of TCs to extreme precipitation in areas near the landfall location, our results suggest that TCs are also an important factor for extreme precipitation in farther inland areas.

The relationship between magnitude and frequency of TC-induced extreme precipitation and ENSO indicated the importance of ENSO. Most of the TC-induced extreme precipitation with larger magnitude in inland areas tends to occur during the neutral phase of ENSO, whereas larger TC-induced extreme precipitation during El Niño and La Niña phases mainly concentrate on coastal areas. The frequency of TC-induced extreme precipitation follows an expected spatial distribution decreasing from southeast to northwest. The proportion of TC-induced extreme precipitation days to total extreme precipitation days in inland areas tends to be higher during the neutral phase than during the El Niño and La Niña phases.

ENSO plays an important role in TC tracks, intensity, and genesis, thereby affecting the relation between extreme precipitation and TCs (Chan 2000; Klotzbach and Blake 2013). Compared to other phases, the density of TC tracks is higher and the number of TCs that move inland with recurring tracks extending farther northeast and higher latitudes is the most during the neutral phase. Additionally, the neutral phase shows an association with above-average TCs of TS and TY intensities for all of TCs and landfall TCs. The large-scale environment variables, such as SST, vorticity, divergence, and zonal wind, modulate the TC development and preferred areas of TC genesis (e.g., Tippett et al. 2011). During El Niño, higher SSTs, greater vorticity and divergence, and stronger prevalent westerlies over the central and...
eastern equatorial Pacific provide an advantage of displacement of the mean genesis location in El Niño years to the east/southeast in the WNP, causing fewer TCs to pass through China.

Results of this study demonstrate that WNP TCs are responsible for heavy extreme precipitation over large parts of China including both coastal and inland areas, which was not known before. Because the influence of TCs on inland extreme precipitation is much larger than expected, further studies on future changes of TCs and inland extreme precipitation are needed.

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REFERENCES


Hasegawa, A., 2005: Tropical cyclone and heavy precipitation over the western North Pacific in present and doubled CO2 climates simulated by the CCSRS/NIES/FRCGC T106 AGCM. Second Int. Workshop on the Kyosei Project, Center for Climate System Research, Kona, HI.


