Trends in Landfalling Tropical Cyclone–Induced Precipitation over China

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ABSTRACT

In this study, trends in landfalling tropical cyclone (TC)-induced precipitation over China during 1980–2017 and the involved possible mechanisms are analyzed. Consistent with previous studies, it is found that the total annual TC precipitation shows a distinct spatial distribution with a significant increasing trend in southeastern China but a decreasing trend in southern China. This characteristic is found to be related to the increase in both the annual TC precipitation frequency and the precipitation intensity per TC over southeastern China but to the decrease in the annual TC precipitation frequency over southern China. A noticeable northward shift of total landfalling TC-induced annual precipitation has been identified. It is shown that the precipitation induced by strong TCs (STCs) significantly increased in southern China, whereas that induced by weak TCs (WTCs) increased in southeastern China, with the latter dominating the northward shift of total landfalling TC-induced precipitation over mainland China. The increasing trend of STC-induced precipitation in southern China is found to be closely related to sufficient water vapor supply and the increase in average duration and intensity of STCs after landfall. The increasing trend of WTC-induced precipitation in southeastern China is related to the northward shift of the average landfalling position of WTCs and changes in the environmental conditions that are more favorable for TC maintenance and precipitation.

1. Introduction

In response to global warming, precipitation has shown significant regional dependent trends in the globe. For more than half of the global land, an increasing probability of intense precipitation events has been documented by Groisman et al. (2005). A number of weather systems can produce intensive precipitation over land. The tropical cyclone (TC) is one of them. A strong TC can produce torrential rainfall, leading to floods and landslides after their landfall, which could cause loss of life and severe damage of properties (Karl and Easterling 1999; Zhang et al. 2009). Many studies have shown an increasing trend in the destructiveness of TCs due to the increasing trend in TC intensity and lifetime from observations and climate model simulations (Knutson and Tuleya 2004; Emanuel 2005; Webster et al. 2005; Klotzbach 2006; Knutson et al. 2007; L. Liu et al. 2010; Park et al. 2014; L. Zhang et al. 2016; Liu et al. 2020). Some studies have also shown that a positive relationship exists between TC-induced rainfall rate and TC intensity (Rodgers et al. 2001; Lonfat et al. 2004; Jiang 2012; Yu et al. 2017; L. Liu et al. 2019). Other studies have reported significant contributions by landfalling TCs to both the annual total precipitation and extreme precipitation events in the United States (Knight and Davis 2009; Shepherd et al. 2007; Kunkel et al. 2010).

East Asia is one of the regions that suffer the most severe damages from landfalling TCs. Several studies have investigated the changes in spatial distribution and variability of heavy rainfall induced by landfalling TCs (Ren et al. 2006, 2007; Kim et al. 2006; Wu et al. 2007; Ying 2011a,b; Zhang et al. 2013). Kim et al. (2006) found an abrupt increase in heavy rainfall (≥100 mm day^{-1}) related to TCs over the Korean peninsula during August–September after the late 1970s. Ren et al. (2006, 2007) investigated TC precipitation over China and...
found a significant downward trend in annual TC precipitation volume. Wu et al. (2007) studied the effect of TCs on the total and extreme TC precipitation in Hainan Island and found that both the number of TCs affecting Hainan Island and the TC-induced precipitation and its contribution to the total precipitation decreased. However, both the total amount of precipitation from the extreme rainfall events and the number of extreme heavy precipitation days affected by TCs increased significantly. On average, both the number of extreme rainfall days and the precipitation amount induced by each TC also increased significantly over Hainan Island. Based on a quantile regression analysis of station data, Ying et al. (2011a) estimated the TC-induced precipitation trends over mainland China and found that although the landfalling TC frequency decreased over China, especially over South China, both precipitation per TC and maximum hourly precipitation induced by a TC increased significantly at stations in the southeast coastal region. They also found that the location of significant precipitation trends was related to mountains and coastline in southeastern China. However, in another study, Ying et al. (2011b) found that there were insignificant trends in extreme TC rainfall, such as the maximum TC precipitation and the maximum hourly precipitation over China during 1955–2006.

Zhang et al. (2013) further investigated the landfalling TC precipitation features over mainland China and the contribution of TC rainfall to changes in the precipitation climate and the average rainfall per TC in the peak TC season (July–September) during 1965–2009. They found that the TC rainfall accounted for more than 10% of the summer rainfall in South and Southeast China, even more than 40% along the southeast coastline, and the average rainfall per TC significantly increased in Southeast China south of the Yangtze River and east of 110°E, which was consistent with the results of Ying et al. (2011a). Zhang et al. (2013) also found that the increasing trends in the average rainfall per TC were not accompanied by enhanced TC intensity, nor did they result from the slowdown of TC movement. Instead, they argued that the increasing trends in the average rainfall per TC in China might be associated with changes in the East Asian summer monsoon activity through modulating the moisture transport and other synoptic forcing conditions.

Although previous studies have revealed many characteristics of TC-induced precipitation over mainland China, including the long-term increasing trend in the average rainfall per TC, the detailed spatial patterns and the contributions by different category TCs have not been examined, and the involved factors responsible for the observed trends have not been well understood. In this study, we explore the spatial distribution of trend in landfalling TC-induced precipitation over mainland China and the involved possible mechanisms. The rest of the paper is organized as follows. Section 2 describes the data and analysis methods. The temporal and spatial characteristics of trends in the observed landfalling TC precipitation over mainland China are presented in section 3. Section 4 examines the trend characteristics of TC precipitation in different categories and the involved possible mechanisms. The primary findings are summarized in the last section.

2. Data and analysis methods

The best-track TC dataset used in this study is acquired from the Shanghai Typhoon Institute of China Meteorological Administration (STI/CMA), which includes latitude and longitude of the TC center, TC intensity in terms of the maximum sustained 10-m wind speed, and central sea level pressure at 6-h intervals. TCs, including tropical depressions (TD), that made landfall over mainland China, including Hainan Island, during 1980–2017 are included in our analyses. In this study, the STI/CMA best-track dataset is used as the primary TC data because relatively more observational data were available over mainland China when the postseason TC analysis was conducted to generate the best-track TC data. Actually, the annual postseason analysis of TC data is performed by STI/CMA to reduce uncertainties and improve the accuracy using all available data, including station observations, ship weather reports, automatic surface observations, synoptic charts, radiosonde data, aircraft reconnaissance, satellite, coastal radar observations, and the real-time TC warming advice from various agencies (Ying et al. 2014). Note that TCs whose centers remained offshore and did not make landfall over mainland China were not considered in our analyses.

The daily precipitation dataset used in this study is obtained from STI/CMA as well. Previous studies simply defined the TC precipitation as precipitation within a radius of 550 km from the center of a TC (Englehart and Douglas 2001) or 500 km from the center of a TC (Dare et al. 2012; Zhang et al. 2019). In this study, the objective synoptic analysis technique (OSAT) developed by Ren et al. (2006, 2007) is adopted to isolate the TC-induced rainfall from the total daily precipitation; a similar technique was also used in Zhang et al. (2013). TC precipitation can result from the TC eyewall and spiral rainbands, or from the interactions between the TC circulation and other local weather systems. TC rainbands are generally asymmetric about the TC center. Therefore, the simple circle method is not good enough. The OSAT method imitates the process by which a weather forecaster manually analyzes a synoptic map.
There are two primary steps: first, separating the daily precipitation into several independent rainbands, and second, according to the distance function between the TC center and the distribution of the rainbands, distinguishing which rainbands are related to the TC. The details of the method can be found in Ren et al. (2006, 2007). Note that because having too few stations with precipitation is not representative, the only cases that are considered in our analyses are those for which there were more than 30 stations at which daily precipitation was observed in a TC day. The TC precipitation is determined when the TC’s rainbands are over mainland China, including Hainan Island, even if the center of the TC was still over the ocean but made landfall later.

The European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data at the horizontal resolution of 0.75° × 0.75° (Dee et al. 2011) are used to examine changes in large-scale environmental conditions responsible for the observed changes in the precipitation characteristics of landfalling TCs over mainland China. The sea surface temperature (SST) data are obtained from NOAA’s Optimum Interpolation Sea Surface temperature (OISST), which provide a series of global analysis products including the daily SST at the resolution of 0.25° × 0.25°. The soil moisture is obtained from the NOAA Gridded Climate Dataset, which has a horizontal resolution of 0.5° × 0.5°.

3. Characteristics of landfalling TC precipitation

Figure 1a shows the spatial distribution of the average annual precipitation induced by landfalling TCs over mainland China during 1980–2017. Consistent with previous studies (Ren et al. 2006; Zhang et al. 2013), large TC precipitation is mainly located in the southern and southeastern China, including Guangxi, Guangdong, and Fujian provinces, and Hainan Island. The time series of total annual TC precipitation over mainland China as a whole presents a slightly decreasing linear trend (Fig. 1b), which is consistent with the results of Ren et al. (2006), who found that the total volume of landfalling TC precipitation over China was slightly decreasing. However, the trend of the annual landfalling TC precipitation over mainland China shows a distinct spatial distribution (Fig. 1c). The annual TC precipitation increased significantly over southeastern China and decreased notably over southern China, including Hainan Island (Fig. 1c). Comparing Figs. 1a and 1c, we can see that the maximum increasing trend in the annual TC precipitation occurs in the northern area and the maximum decreasing trend occurs in the southern area of the large precipitation region, indicating a northward shift in landfalling TC-induced precipitation over mainland China during the study period. The frequency of landfalling TCs shows a significant decreasing trend (Fig. 1d); that is, the number of TCs making landfall over mainland China decreased in recent decades. Further, we calculated the frequency of landfalling TCs in the southern area and southeastern area (with 24°N as the dividing line; Figs. 1e and 1f). The results show that the landfalling TC frequency in the southeastern area was stable, while the frequency in the southern area experienced a significant decreasing trend during recent decades. Therefore, the decrease in total landfalling TC frequency over mainland China was contributed primarily by the decrease in frequency in the southern area. This suggests that the total annual precipitation decrease could be primarily due to the significant decrease in landfalling TCs over mainland China, especially in southern China.

Figure 2 shows the time series and trend in the average precipitation per landfalling TC. There is a significant increasing linear trend of the average precipitation per landfalling TC over mainland China as a whole (Fig. 2a) with statistical significance over the 95% confidence level. This means that the precipitation intensity per landfalling TC increased significantly during 1980–2017, especially in the southeastern coastal region over mainland China (Fig. 2b). However, over Hainan Island, the precipitation per landfalling TC shows a significant decreasing trend. We also analyzed the trend of the TC precipitation per landfalling TC per day, which shows a significant increasing trend over mainland China as a whole as well (Fig. 3a). The trend also displays a spatial distribution with the largest increasing trend in the southeastern coastal area (Fig. 3b), which contributes to the increase in the average precipitation per landfalling TC in the region (Fig. 2b). The trend in annual TC rainfall days (frequency) shows a clear transition near 24°–25°N—namely, an increasing trend over southeastern China and a decreasing trend over southern China (Fig. 3c). Therefore, both the annual precipitation frequency and the average precipitation per TC per day increased over southeastern China, leading to the large increasing trend in total TC precipitation over southeastern China (Fig. 1c). The decreasing trend in the frequency of landfalling TCs (Fig. 1d) offsets the increasing trend of the average precipitation per TC per day over southern China (Fig. 3a). This leads to the decreasing trend in the total TC precipitation over southern China as seen in Fig. 1c. Wu et al. (2005) found a considerable decreasing trend of TCs in the South China Sea, leading to fewer rainfall days of landfalling TCs in the southern coastal area over mainland China. In addition, the decreasing trends in both the average precipitation per TC per day (Fig. 3b) and the annual frequency of TC precipitation days (Fig. 3c) give
FIG. 1. (a) Spatial distribution of the landfalling TC-induced annual precipitation averaged during 1980–2017 over China (mm yr$^{-1}$). (b) Time series and trend of the landfalling TC-induced total annual precipitation averaged over China during 1980–2017 (mm yr$^{-1}$). (c) Spatial distribution of trends in the landfalling TC-induced annual precipitation over China during 1980–2017 (mm yr$^{-1}$). Also shown are time series and trend of the landfalling TC frequency over (d) China mainland, (e) the southern area, and (f) the southeastern area during 1980–2017. The dashed, solid, and blue curves in (b), (d), (e), and (f) indicate the raw data, 5-yr running mean, and the corresponding linear trends, respectively. Regions with trends that are significant over 95% confidence level are shown with dots in (c).
rise to a significant decrease in the total TC precipitation over Hainan Island (Fig. 1c). This is consistent with the results of Wu et al. (2007), who found that the number of TCs impacting Hainan Island significantly decreased.

4. Characteristics of strong and weak TC precipitation

We further classify landfalling TCs into strong TCs (STCs; with sustained maximum wind speed $\geq 32$ m s$^{-1}$, including typhoons, severe typhoons, and super-typhoons) and weak TCs (WTCs; with sustained maximum wind speed $< 32$ m s$^{-1}$, including tropical storms, severe tropical storms, and tropical depressions) at landfall. The TDs are included here because, on one hand, TDs in the STI/CMA best-track dataset were, to some extent, reliable based on the description of the STI/CMA best-track data as mentioned in section 2; on the other hand, the precipitation induced by TDs could be very large when they interacted with some favorable weather systems. Thus, the precipitation induced by TDs is also important. The spatial distributions of precipitation induced by STCs and WTCs are shown in Figs. 4a and 4b, respectively. Precipitation induced by STCs is large in the southern coastal area, such as Guangxi, Guangdong, and Hainan provinces (Fig. 4a), and slightly south of the maximum in the total TC precipitation shown in Fig. 1a. Precipitation induced by WTCs is generally large in the southern and southeastern coastal area, including eastern Guangdong and Fujian provinces (Fig. 4b) and is to the northeast of that induced by STCs. Note that precipitation induced by WTCs is generally weaker than that induced by STCs.

Since the spatial distributions of STC and WTC precipitation are different, it is interesting to examine the spatial pattern of their respective trends in the study period. Figure 5 presents the time series and the trends of average precipitation per STC and average precipitation per WTC, respectively, during 1980–2017. Consistent with the average precipitation per TC (Fig. 2a), STC precipitation also shows a significant increasing trend with statistical significance over 95% confidence level (Fig. 5a), indicating that precipitation induced by a STC increased in the study period. The trends in STC precipitation are positive over mainland China but negative over Hainan Island (Fig. 5b). The most significant increase in STC precipitation occurs in the southern coastal area (mainly in Guangdong and Guangxi provinces), namely the region with the maximum rainfall per STC shown in Fig. 4a. This indicates that the precipitation induced by STCs significantly increased over mainland China, especially in the southern coastal area, but decreased over Hainan Island.

The average precipitation per WTC shows no significant trend over mainland China (Fig. 5c). This is primarily due to the cancellation of the decreasing trend in the southern coastal area and the increasing trend in the southeastern coastal area of mainland China (Fig. 5d). It is interesting to note that significant increasing trends primarily occurred in Fujian and Zhejiang provinces, north of the peak WTC precipitation (Fig. 4b). This means that WTC-induced precipitation shifted northward in the study period, resulting in an increase in WTC.
precipitation in the southeastern coastal area and a decrease in the southern coastal area (Fig. 5d). This is in sharp contrast to the STC-induced precipitation, which shows that the maximum increasing trend almost in the region coincided with peak STC precipitation. This indicates that the northward shift of total landfalling TC precipitation over mainland China (Fig. 1c) is mainly contributed by the northward shift of WTC-induced precipitation.

To understand the possible mechanisms responsible for the overall increasing trend in STC precipitation, we examined the large-scale environmental conditions and their corresponding trends. It is found that in addition to some other favorable dynamic and thermodynamic conditions (not shown), the atmospheric moisture supply seems to play a key role in enhancing STC precipitation. Figures 6a and 6b display the average water vapor and vapor flux vertically integrated between 1000 and 700 hPa and their trends during 1980–2017. The southern coastal area of mainland China, where large STC precipitation occurred (Fig. 4a), is perennially covered by high low-level water vapor content and large moisture flux convergence between the southwesterly flow with high moisture content from the Bay of Bengal and southeasterly flow with plenty of water vapor from the western North Pacific. The area is very conducive to precipitation induced by STCs. The water vapor in this area increased significantly in the study period (Fig. 6b), which favored the increase in STC-induced precipitation. In addition, an increasing trend in divergence in the upper troposphere occurred in the southern area and neighboring seas (Fig. 6c) and an increasing trend in ascending motion (Fig. 6d) appeared at
500 hPa. Both are conducive to the maintenance of TC intensity and thus contribute to the decrease in overland intensity weakening rate and the increase in mean overland duration of landfalling TCs (e.g., Park et al. 2011). Meanwhile, both the landfall intensity (Fig. 6e) and duration after landfall (Fig. 6f) of STCs increased noticeably, with statistical significance over the 90% confidence level. This is also conducive to increasing precipitation of STCs. Previous studies have suggested that there was some relationship between TC-induced rainfall rate and TC intensity (Rodgers et al. 2001; Lonfat et al. 2004; Jiang 2012; Yu et al. 2017; M. Liu et al. 2019). Yu et al. (2017) analyzed the rainfall distribution in TCs making landfall over mainland China and revealed that, on average, axisymmetric rainfall was closely related to TC intensity. Stronger TCs produce more averaged total rainfall, larger averaged rain areas, and higher averaged rain rates. M. Liu et al. (2019) also showed that TCs with high intensity tended to produce high rainfall rates, especially toward the storm center. Therefore, the sufficient water vapor supply and the increase in both duration after landfall and the increase in storm intensity at landfall are all responsible for the increasing trend in STC precipitation in the southern coastal area of mainland China except over Hainan Island.

The northward shift of WTC precipitation is mainly due to the northward shift of mean landfalling location of WTCs (Fig. 7a) and changes in favorable environmental conditions, including surface conditions and low-level vertical wind shear. The average landfalling latitude of WTCs shows a clear increasing trend (Fig. 7a) with statistical significance over 90% confidence level. The average landfalling latitude increased from about 22°N to about 24°N in the study period. In addition to the northward shift of the average landfalling location, the average intensity of landfalling WTCs also shows a significant increasing trend in the study period (Fig. 7b). Therefore, no matter whether they were STCs or WTCs, the intensity of TCs at landfall over mainland China increased significantly in recent decades. This increasing trend is consistent with the significant warming trend in SST in the coastal oceans near East Asia, particularly offshore of mainland China (Fig. 7c). The near-surface air temperature (Fig. 7d) and soil moisture (Fig. 7e) also show increasing trends, particularly in the southeastern coastal area of mainland China, providing more favorable thermodynamic conditions to slow down the weakening of TCs after landfall. Previous studies have demonstrated that the soil moisture and temperature are critical for TC maintenance and TC precipitation over land (Tuleya and Kurita 1978; Tuleya et al. 1984; Tuleya 1994; Shen et al. 2002; Zhang et al. 2011; L. Liu et al. 2019). As shown in Tuleya (1994), warm land surface and high soil moisture are favorable for surface enthalpy flux and thus may slow down the weakening of a TC after landfall. Zhang et al. (2011) conducted several sensitivity numerical experiments and found that both the latent and sensible heat flux sustained the landfalling TCs and maintained the spiral structure of rainbands.

In addition, the low-level vertical wind shear between 850 and 1000 hPa shows a significant decreasing trend over southeastern China (Fig. 7f), which provides a favorable dynamical environmental condition conducive to TC intensification and maintenance. Note that the deep-layer vertical wind shear between 850 and 200 hPa was also analyzed and the results showed a decreasing trend to the north of approximately 33°N over mainland China, but the trend in the region affected by landfalling TCs was not statistically significant (figure not shown). Wang et al. (2015) compared the correlation between TC intensity change and vertical wind shear in various vertical layers over the WNP. They found that the low-level shear
between 850 (or 700) and 1000 hPa was more destructive to TCs than the commonly used deep-layer vertical wind shear between 200 and 850 hPa in the active typhoon season over the WNP. As a result, the combination of the northward shift of the average landfalling position of WTCs and the more favorable dynamic and thermodynamic conditions led to the increasing WTC-induced precipitation in the southeastern coastal area of mainland China. This also explains why the increasing trend of WTC precipitation occurred north of the maximum WTC precipitation and the dominant contribution by WTCs to the northward shift of the total landfalling TC precipitation.

5. Conclusions

In this study, the daily TC precipitation dataset produced using the OSAT method (Ren et al. 2006, 2007) and the best-track TC data obtained from STI/CMA are used to explore the characteristics of the landfalling TC-induced precipitation and the precipitation per landfalling TC after landfall over China during 1980–2017. The total annual TC precipitation over China as a whole shows a decreasing trend primarily due to the decreasing trend in the frequency of landfalling TCs during 1980–2017, which is consistent with the results of Ren et al. (2006). It is found that the total annual TC precipitation shows a distinct spatial distribution with a significant increasing trend in southeastern China but a decreasing trend in southern China. This increasing to the north and decreasing to the south are found to be related to the increase in both the annual TC precipitation frequency (annual average TC precipitation days) and the average precipitation per TC per day, over southeastern China, and to the decrease in the annual TC precipitation.
FIG. 6. Spatial distributions of (a) water vapor mixing ratio (shading; kg kg$^{-1}$) and vapor flux (vectors; kg m kg$^{-1}$ s$^{-1}$) integrated from 1000 to 700 hPa, (b) trends in water vapor mixing ratio (shading; 10$^{-2}$ g kg$^{-1}$ yr$^{-1}$) integrated from 1000 to 700 hPa, (c) upper-tropospheric divergence (10$^{-6}$ m$^{-1}$ s$^{-1}$ yr$^{-1}$) at 200 hPa, and (d) vertical motion at 500 hPa (Pa s$^{-1}$ yr$^{-1}$) during 1980–2017. Also shown are time series and trends of (e) averaged landfalling intensity (m s$^{-1}$) and (f) duration after landfall (h) of STCs over China during 1980–2017. Regions with trends that are significant over 90% confidence level are shown with dots in (b)–(d). The dashed, solid, and blue curves in (e) and (f) indicate the raw data, the 5-yr running mean, and the corresponding linear trend, respectively.
FIG. 7. Time series and trends of (a) averaged landfalling latitude (°N) and (b) averaged landfalling intensity (m s\(^{-1}\)) of WTCs over China during 1980–2017; spatial distributions of trends in (c) SST (K yr\(^{-1}\)), (d) air temperature at 950 hPa (K yr\(^{-1}\)), (e) soil moisture (g kg\(^{-1}\) yr\(^{-1}\)), and (f) vertical wind shear between 1000 and 850 hPa (m s\(^{-1}\) yr\(^{-1}\)) during 1980–2017. The dashed, solid, and blue curves in (a) and (b) indicate the raw data, the 5-yr running mean, and the corresponding linear trend, respectively. Regions with trends that are significant over 90% confidence level are shown with dots in (c)–(f).
frequency over southern China. In addition, a northward shift in precipitation induced by landfalling TCs over mainland China during recent decades has been identified.

We have further classified landfalling TCs into STCs and WTCs to examine the differences in their precipitation characteristics over mainland China. Some interesting new findings include a noticeable northward shift in the average landfalling location of WTCs and their associated precipitation, and an overall increasing trend in landfalling intensity of both STCs and WTCs. It is shown that the precipitation induced by STCs mainly concentrated in the southern coastal area, slightly south of the maximum total TC precipitation, while the precipitation induced by WTCs is mainly located in the southeastern coastal area over mainland China, coinciding with the region of total TC precipitation. Moreover, the STC precipitation shows an increasing trend in most regions with large STC precipitation over mainland China, especially in southern China. The location of WTC-induced precipitation is east and north of that of STC-induced precipitation and shows a decreasing trend in the southern coastal area and an increasing trend in the southeastern coastal area of mainland China. The most significant increasing trend occurred north of the peak precipitation area induced by WTCs, indicating a noticeable northward shift of the WTC-induced precipitation in the study period. These results demonstrate that the northward shift of total landfalling TC precipitation is mainly contributed by the WTC precipitation primarily due to the northward shift of landfalling location of WTCs.

Results from further analyses indicate that both the intensity at landfall and the duration after landfall of STCs increased noticeably. The region of STC precipitation is perennially located in the convergence zone with high humidity in the lower troposphere. Water vapor in the area increased significantly in the study period, providing more water vapor supply for TC intensification/maintenance and precipitation. In contrast, WTCs show a significant increasing trend in their average landfall latitude, leading to a northward shift of WTC-induced precipitation. Moreover, the increasing intensity of WTCs at landfall and the increasing SST in the coastal oceans, the increase in land surface soil moisture and temperature, and the decrease in low-level vertical wind shear over southeastern and eastern China provide more favorable dynamic and thermodynamic conditions for WTCs to survive longer after landfall, leading to the increase in WTC precipitation.

Note that there was a remarkable decreasing trend in landfalling TC-induced precipitation over Hainan Island, regardless of STCs or WTCs. We found that this is mainly due to the significant decreasing trend in both the average precipitation per TC and the annual frequency of TC precipitation days over the past decades. Wu et al. (2007) found that the number of TCs impacting Hainan Island significantly decreased. Therefore, the decreasing trend in landfalling induced precipitation over Hainan Island is most likely a result of the decreasing landfalling TC frequency. In addition, the decreasing trend in the average precipitation per TC over Hainan Island might be partially due to the decrease in TC intensity at landfall and unfavorable environmental conditions. For example, Wang et al. (2013) found that due to the increase in the tropical Indian Ocean SST, the lower-level anomalous anticyclone occurred over South China Sea, which was unfavorable for TC genesis and intensification over the South China Sea. This is evident by a trend of decreasing ascending motion in the western South China Sea seen in Fig. 6d. Nevertheless, because of the small area of the island and the sensitive regional climate patterns over Hainan Island, a more detailed analysis on the possible mechanism responsible for the observed decreasing trend of landfalling TC-induced precipitation over Hainan Island is reserved for a future study.

Note that this study has focused on the analysis of long-term trends in the observed precipitation induced by landfalling TCs over mainland China based on data between 1980 and 2017. Because the limited period was analyzed due to TC precipitation data quality, the northward shift in TC precipitation could be partly contributed by the decadal/interdecadal variations, which need further investigations. However, a recent study by Liu et al. (2020) pointed out that the landfalling TC activity over mainland China seems not to be significantly modulated by the decadal/interdecadal variations because several interdecadal shifts identified in other climate parameters did not appear in landfalling TC characteristics over mainland China. Nevertheless, results from this study imply an increasing stress of potential landfalling TC-induced precipitation in the populated southeastern coastal region of mainland China if the trend continues in the near future.

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