

Changes in Tropical Cyclone Rainfall in China

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Abstract

The torrential-rainfall-associated tropical cyclone (TC) activity often causes flood disasters in China. Moreover, studies suggest that TC-related rainfall rates are likely to increase in a warmer climate. Using daily precipitation observations at 514 meteorological stations during 1965–2009, this study investigates the primary features of TC rainfall in China, with a particular focus on the contribution of TC rainfall to the changes in the precipitation climate and the average rainfall per TC.

TC rainfall mainly affected eastern and southeastern China, accounting for more than 10% of the summer rainfall in South and Southeast China. TC rainfall trended upward in the lower reach of the Yangtze River and Southeast China, contributing to the “wetting in the south and drying in the north” pattern by enhancing the rainfall in Southeast China. This study suggests that the average rainfall per TC has significantly increased in Southeast China during 1965–2009. In the peak season (July–September), all significant changes are upward trends that occur south of the Yangtze River east of 110°E. This study finds that the increasing rainfall per TC was not accompanied with the enhanced TC intensity. In addition, no significant trend can be found in the translation speed of TCs that affected China during 1965–2009, suggesting that the increasing TC rainfall per TC in China was not due to the slowdown of TC movement.

Keywords tropical cyclone torrential rainfall; trend; monsoon

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1. Introduction

Among the natural hazards in China, tropical cyclones (TCs) cause significant property damage and life loss, leading to 505 deaths and 37 billion Chinese yuan (approximately 0.4% of the annual gross

domestic product) in direct economic loss per year during 1984–2008 (Zhang et al. 2011). TC disasters in China are mainly associated with torrential rainfall, which often causes floods, landslides, and mudslides. Rainfall records in most of the coastal provinces in China were related to TC activity (Tao 1980). For example, the 100-h rainfall associated with Typhoon Morakot (2009) exceeded 2000 mm at many rain gauge stations in Southern Taiwan. The resulting landslide buried the whole Xiaolin village and killed approximately 600 people in this village alone (Hong et al. 2010). Morakot set up a new rainfall record and was regarded as the most severe typhoon disaster in Taiwan. It is obviously important to improve our understanding on TC rainfall.

TC precipitation is closely associated with the interaction of TC circulation and large-scale environmental flow (Jones 1995, 2000a, b; Wang and Holland 1996a, b, c; Bender 1997; Frank and Ritchie 1999, 2001; Corbosiero and Molinari 2002; and Reasor et al. 2004), and changes in TC intensity and environmental flows tend to alter TC precipitation. Regional model simulations of TCs in a warmer climate show that TC-related rainfall rates are likely to increase (Knutson and Tuleya 1999; Knutson et al. 2010). Although many studies show widespread increases in heavy precipitation events (e.g., 95th percentile) over the past several decades even in places where total amounts have decreased, these studies did not distinguish TC rainfall from that associated with other weather systems (IPCC 2007). Following an early study by Cry (1967), several recent studies investigated TC contribution to the annual total and extreme precipitation in the United States (Knight and Davis 2007, 2009; Nogueira and Keim 2010, 2011) and in China (Ren et al. 2006; Wu et al. 2007; Cheng et al. 2007). These studies did not address possible rainfall changes for an average TC. So far, the TC rainfall rate change has not been well understood in existing observational studies (Knutson et al. 2010).

Recently, Chinese meteorologists found that summer precipitation increased in the mid-lower reach of Yangtze River, but it decreased in northern China over the past 50 years (Hu et al. 2003; Yu et al. 2004; Wang and Zhou 2005; Wang and Ding 2006). The precipitation trend pattern of wetting in the south and drying in the north was attributed to the effect of increase in human-made black carbon (Menon et al. 2002), while Yu et al. (2004) argued that it might be linked to the stratosphere temperature changes and the interaction between the troposphere and stratosphere. While the mechanisms associated with the precipita-

tion trends have been investigated extensively, it is unclear how TC activity contributed to the precipitation change, especially in southern China, where TC activity plays an important role in the summer precipitation (Ren et al. 2007).

Using daily precipitation observations at 514 meteorological stations during 1965–2009, we investigate the primary features of TC rainfall in China. In particular, this study focuses on 1) how much TC-related rainfall contributed to the so-called “wetting in the south and drying in the north” pattern in China and 2) how the average rainfall per TC changed during 1965–2009. The rest of the paper is organized as follows. The data and the analysis method are first described in Section 2; changes in TC rainfall in China and its contribution to the summer rainfall trend pattern are examined in Section 3. In Section 4, we examine the changes in the average rainfall per TC, followed by a summary in Section 5.

2. Data and methodology

The daily precipitation observations covering mainland China and Hainan Island are obtained from the data sharing system of the China Meteorological Administration (it does not cover Taiwan Island). Considering the gradual establishment of the meteorological stations during 1951–1960 in China and the advent of routine monitoring of TC activity since the mid-1960s, our analysis is limited to 1965–2009. After eliminating stations that had more than 10% missing data each year, we selected 514 stations for this study; their geophysical locations are shown in Fig. 1a. The station density is quite varied, and there are relatively more stations in southern and southeastern China. This region is highly populated and relatively developed in economy, coinciding with the primary areas affected by TCs. TC data are obtained from the Shanghai Typhoon Institute of China Meteorological Administration (STI/CMA) and the Joint Typhoon Warning Center (JTWC), including the TC location and intensity in the western North Pacific basin (western North Pacific and South China Sea) at 6-h intervals. Considering that relatively more observational data were available for TCs over land, the STI dataset is applied to partition TC rainfall from the station observation. Although the maximum wind speeds recorded by JTWC and STI are averaged over 1-min and 2-min periods, respectively, TCs in this study are referred to those that directly cause rainfall over mainland China and Hainan Island with maximum sustained winds of at least 17.2 m s^{-1} . Note that Ren et al. (2006) and Cheng et al. (2007) also included tropical

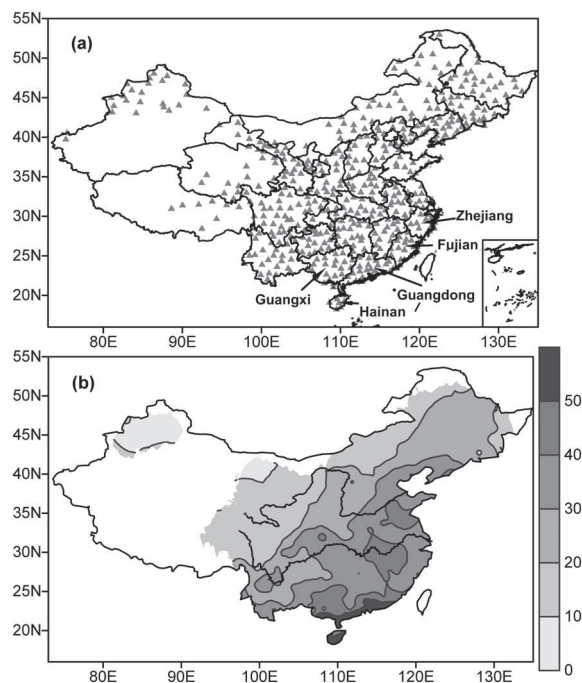


Fig. 1. (a) Spatial distribution of the selected rain gauge stations in mainland China and Hainan Island and (b) thresholds (mm) for the 95th percentile of daily extreme rainfall.

depressions with maximum sustained winds of less than 17.2 m s^{-1} .

It is necessary to distinguish TC rainfall from other weather systems in this study. Englehart and Douglas (2001) defined TC rainfall as the rainfall within a radius of 550 km from TC centers when they explored the role of tropical storms over the eastern North Pacific in the rainfall climatology of western Mexico. Cheng et al. (2007) took the TC rainfall data from the STI/CMA dataset, in which the TC rainfall was subjectively identified on the basis of weather maps. In this study, the objective synoptic analysis technique (OSAT) is adopted to isolate the TC-related rainfall from the total daily precipitation (Ren et al. 2006; Ren et al. 2007). The TC rainfall can result from the convective activity associated with the eye wall and spiral rainbands, as well as from the interaction between the TC circulation and other weather systems. The TC rainfall is generally asymmetric with respect to the TC center, especially when TCs affect China. The OSAT approach imitates the manual analysis taken by an operational weather forecaster. First, on the basis of the spatial structure of the observed station precipita-

tion, all precipitation observations are grouped into several rainbelts. Given the distances between the TC center and a rainbelt's weighted-precipitation center, one can identify whether the station precipitation is TC rainfall by comparing these distances with the specified TC maximum size (d_1) and minimum size (d_0), which vary with TC intensity. The typical values for d_0 and d_1 are 500 km, which is the maximum distance between a TC center and the associated squall lines, and 1100 km, which is usually the maximum radius for a TC, respectively.

Figure 2 shows an example of the identified stations with the rainfall related to Typhoon Matsa (2005). As the TC center was located to the north of Taiwan Island over the East China Sea on 5 August, 2005, the TC rainfall is mainly identified in eastern China (Fig. 2a). When the TC made landfall in Zhejiang Province on 6 August, the rainfall area extended further northward up (Figs. 2b and 2c). The non-TC rainfall west of 110°E was relatively small and separated by a nonrainfall zone on 5–6 August. The identified TC rainfall area is consistent with the visible satellite image shown in Fig. 2c. In the approach, at maximum, a rainbelt associated with a TC can extend 1100 km away from the TC center (Ren et al. 2007). This example shows that the OSAT can effectively isolate TC rainfall.

In this study, an extreme rainfall event at a station is defined on the basis of the daily rainfall (TC and non-TC rainfall combined) that exceeds the 95th percentile of all nonmissing and nonzero observations at the station during 1965–2009. This method is similar to that in previous studies (e.g., Manton et al. 2001; Wang and Zhou 2005). Figure 1b shows the spatial distribution of the resulting thresholds for extreme rainfall events at each station. The threshold generally decreases with increasing latitude. The thresholds above 50 mm day^{-1} occur only in the coastal region of south China and Hainan Island. The thresholds above 30 mm day^{-1} cover the entire reach of the Yangtze River, the east reach of the Yellow River, and southern part of northeastern China.

To examine the changes in precipitation in this study, a 95% confidence level is adopted for all significant tests with the Mann–Kendall method, and the autocorrelation in the data is checked for the effective sample size (Kundzewicz and Robson 2000; Yue and Wang 2004).

3. Changes in TC rainfall and its contribution to the summer precipitation trends

First, we examine the climatology of TC rainfall in

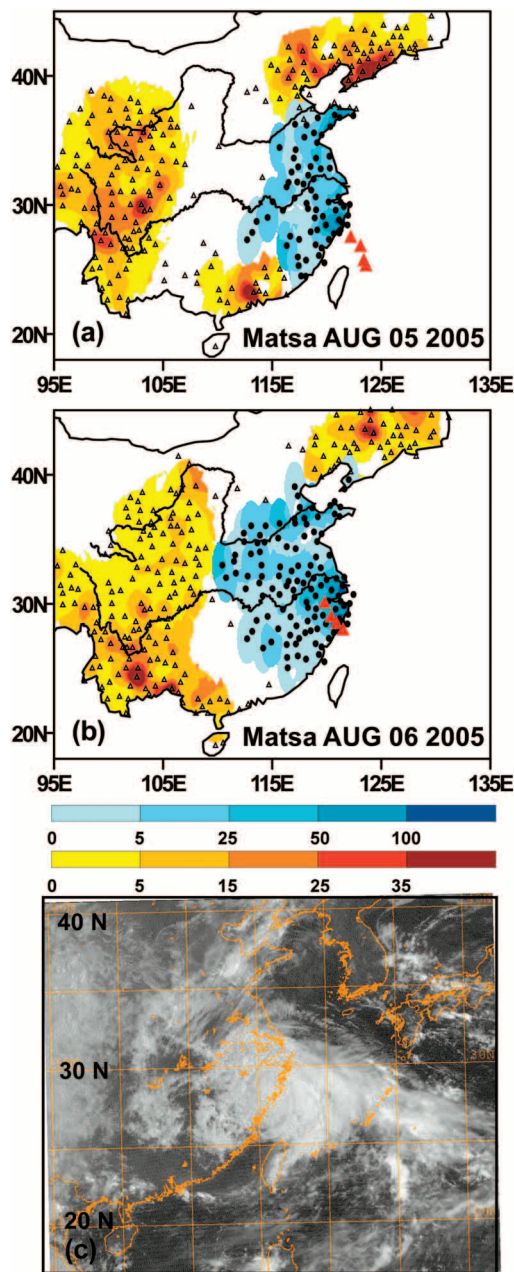


Fig. 2. Identified rain gauge stations with TC (cool colors) and non-TC (warm colors) precipitation (mm) for Typhoon Matsa (2005) on (a) 5 August and (b) 6 August. The visible GOES-9 satellite image is also shown in (c) when the TC made landfall on 6 August. Red triangles indicate TC centers at 18, 00, 06, and 12 UTC and black dots and triangles indicate stations with TC and non-TC precipitation, respectively.

China. Figure 3 shows the spatial distribution of the annual TC rainfall, which is compared to the annual non-TC rainfall during 1965–2009. This figure shows that TCs mainly affected eastern and northeastern China in terms of rainfall. The annual TC rainfall generally decreases northwestward. The TC rainfall above 50 mm per year occurs south of the Yangtze River. In the coastal provinces of southern and southeastern China, the TC rainfall exceeds 100 mm per year (Fig. 3a), while the non-TC rainfall exceeds 1000 mm per year (Fig. 3b). In the southern coastal areas (Guangdong Province and Hainan Island), the TC rainfall is generally more than 300 mm per year. The spatial distribution of the annual TC rainfall is similar to that in Ren et al. (2007) and Cheng et al. (2007), although both studies also included rainfall related to tropical depressions.

In the southeastern coastal areas, TC rainfall contributes more than 10% of the annual rainfall (Fig. 3c), and it becomes more important during the typhoon peak season (July–September) since TCs mainly affect the areas in summer. TC rainfall contributes more than 20% of the summer rainfall in the coastal provinces of southern and southeastern China, where the TC rainfall exceeds 300 mm per year (Fig. 3d). It should be mentioned that the TC contribution can be more than 40% along the coastline. These results are also generally consistent with that in Ren et al. (2007), Cheng et al. (2007), and Hsu et al. (2008). It is suggested that changes in TC rainfall should be considered when the rainfall changes in southern and southeastern China are discussed.

Ren et al. (2007) and Cheng et al. (2007) calculated the trends in the annual TC rainfall at each station and found the decreasing trend at most stations during 1957–2004 and 1960–2003, respectively. Our calculation based on the data during 1965–2009 generally agrees with these two studies (Fig. 4). The annual TC rainfall trended downward mainly west of 115°E, including Guangdong, Hainan, and Guangxi Provinces, while the increasing trends occurred in the eastern coastal areas of Southeast, East, and Northeast China with a few stations along the southeastern coast that are statistically significant.

Using the JTWC best track data from 1965 to 2003, Wu et al. (2005) showed that subtropical East Asia experienced increasing typhoon influence over the four decades due to the westward shift of the two prevailing TC tracks over the western North Pacific, whereas the typhoon influence over the South China Sea decreased considerably. Using a trajectory model, they found that the long-term shifts in the typhoon

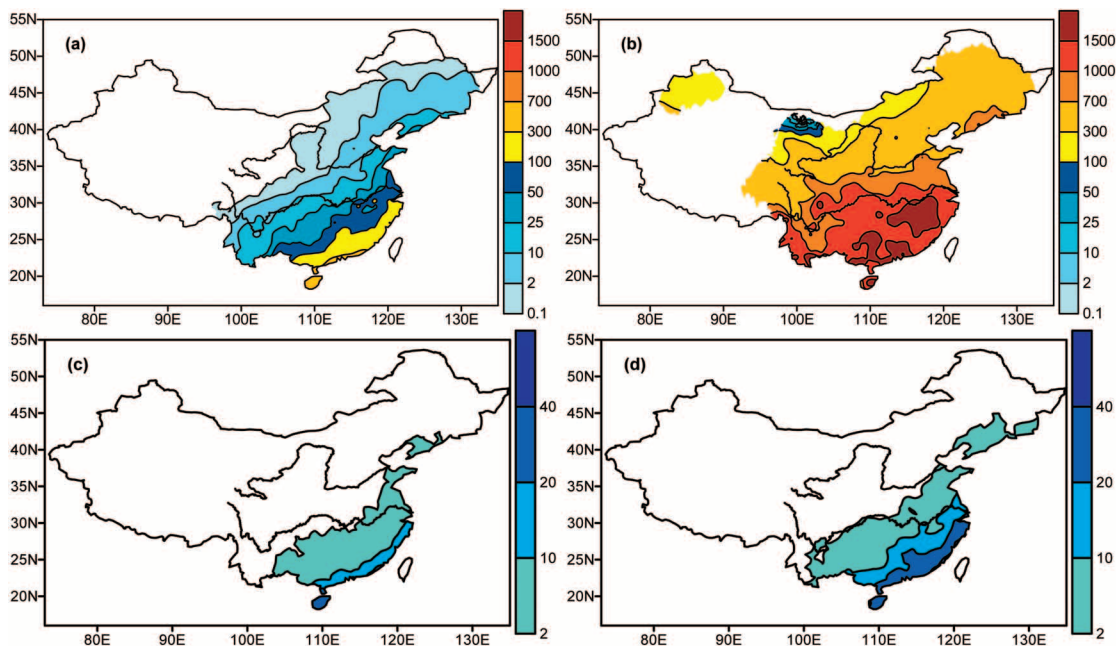


Fig. 3. (a) TC and (b) non-TC annual precipitation (mm) and the percentage of (c) annual and (d) summer (July–September) TC rainfall to the total annual and summer rainfall (%), respectively, during 1965–2009.

tracks primarily resulted from the changes in the mean translation velocity of typhoons or the large-scale steering flow, which was associated with the enhanced southwesterly steering flows over the South China Sea and the westward expansion and strengthening of the western North Pacific subtropical high. The TC rainfall changes in Fig. 4 are consistent with the prevailing track shifts reported by Wu et al. (2005). Recently, Chen et al. (2011) suggested that the increasing trends in the east coastal areas were associated with the increasing overland duration of TCs that formed over the western North Pacific. They argued that the decreasing vertical wind shear allows the landfall TCs to increase survival time over land. Since the changes in rainfall and TC tracks are derived from two independent datasets, the consistency adds our confidence levels to the derived changes in TC rainfall.

The summer precipitation variability in China is largely due to the activity of the summer monsoon (Ding 1994). The summer (June–August) trends in the total rainfall were calculated in previous studies (Gong and Ho 2002; Hu et al. 2003; Wang and Zhou 2005). Although their temporary coverages [1951–1999 in Gong and Ho (2002), 1951–2000 in Hu et al. (2003), and 1961–2001 in Wang and Zhou (2005)] were

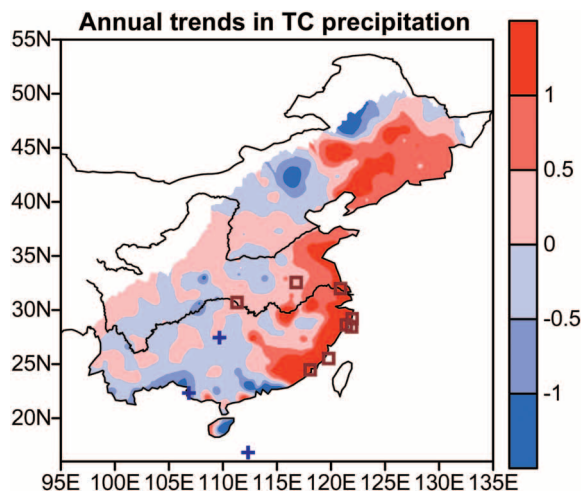


Fig. 4. Annual trends in TC precipitation (mm year^{-1}) during 1965–2009, with squares and crosses indicating significant increasing and decreasing trends.

different, these studies indicated increasing trends in the summer rainfall in southeastern China (south of 35°N, east of 105°E) with the most significant ones in the mid-lower reaches of the Yangtze River, while

pronounced drying occurred in parts of North and Northeast China. Figure 4 suggests that TC rainfall may contribute to the “wetting in the south and drying in the north” pattern by enhancing the rainfall in the south.

Figure 5 further shows the spatial distribution of the linear trends in the summer (June, July, and August) rainfall and the components for TC and non-TC rainfall, respectively. Our calculation of the observations over 1965–2009 generally agrees with those in previous studies (Fig. 5a). The wetting trends occurred mainly south of 35°N and east of 110°E, while drying trends were dominated in central and northern China. Our calculation confirms that the “wetting in the south and drying in the north” pattern is a robust feature in the climate change in rainfall in China.

Figure 5a also shows the stations with increasing trends above the 95% confidence level. In the areas with all rainfall, the significant stations appeared mainly along the southeastern coast of China and the region between the Yangtze River and the Yellow River. When the TC contribution is removed (Fig. 5b), the significant stations along the southeastern coast of China disappeared although little change occurs to the general trend pattern. Figure 5c further displays the trends in the summer (June–August) TC rainfall. Significant trends occurred in the lower reach of the Yangtze River and southeastern China. It is suggested that the summer TC rainfall contributes to the “wetting in the south and drying in the north” pattern by enhancing the rainfall in Southeast China. Since TC precipitation trend is weaker than the total precipitation trend, other factors should also contribute to the precipitation trend.

4. Changes in the average rainfall per TC

Since the peak TC activity season is July–September, we focus on the peak season in this section. Figure 6 shows the spatial distribution of the linear trends in the average rainfall for a single TC during 1965–2009. The annual rainfall at a specific station is normalized with the annual number of TCs affecting the station. Squares and crosses indicate stations with increasing and decreasing trends at the 95% confidence level, respectively. The significant changes in the annual TC rainfall are dominated by the upward trends, with the decreasing trend at a few stations in southwestern China (west of 110°E). The significant rainfall trends per TC mostly occurred in the coastal areas of Southeast China (Fig. 6a), where TC activity contributes more than 10% rainfall to the annual total rainfall (Fig. 3c). In the peak TC season, all significant changes

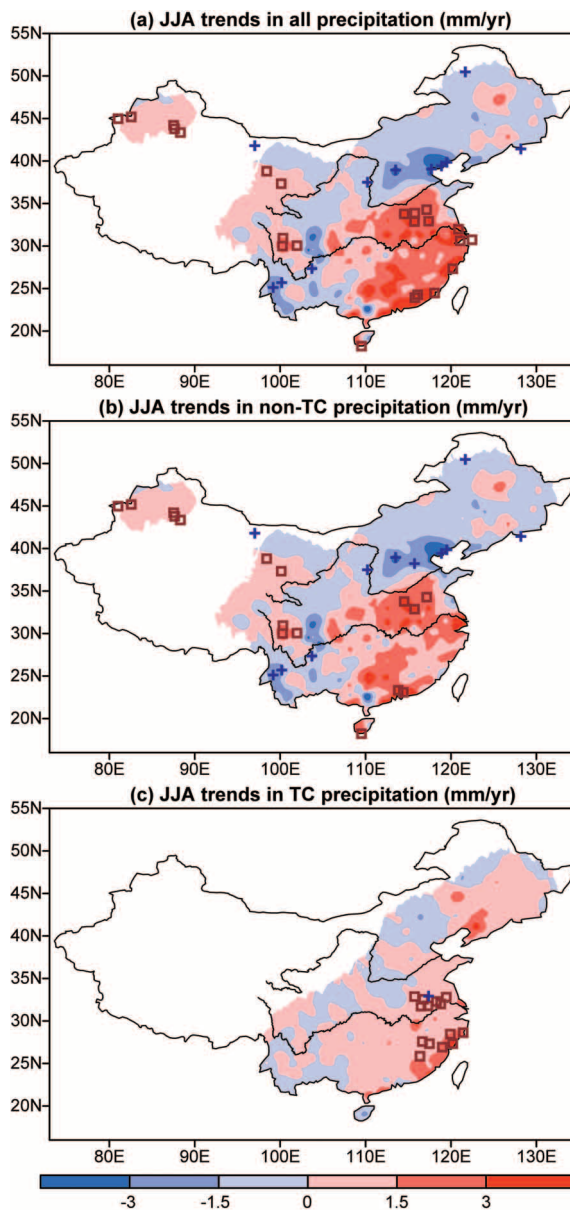


Fig. 5. June–August trends in (a) total, (b) non-TC, and (c) TC precipitation (mm year^{-1}) during 1965–2009, with squares and crosses indicating significant increasing and decreasing trends.

are upward trends that occur south of the Yangtze River east of 110°E (Fig. 6b). Figures 6a and 6b suggest that the average rainfall per TC has significantly increased in Southeast China during 1965–2009. Chen et al. (2011) found that the average duration of landfall TCs in Southeast China trended upward, which may contribute to the upward trends in the rainfall per TC.

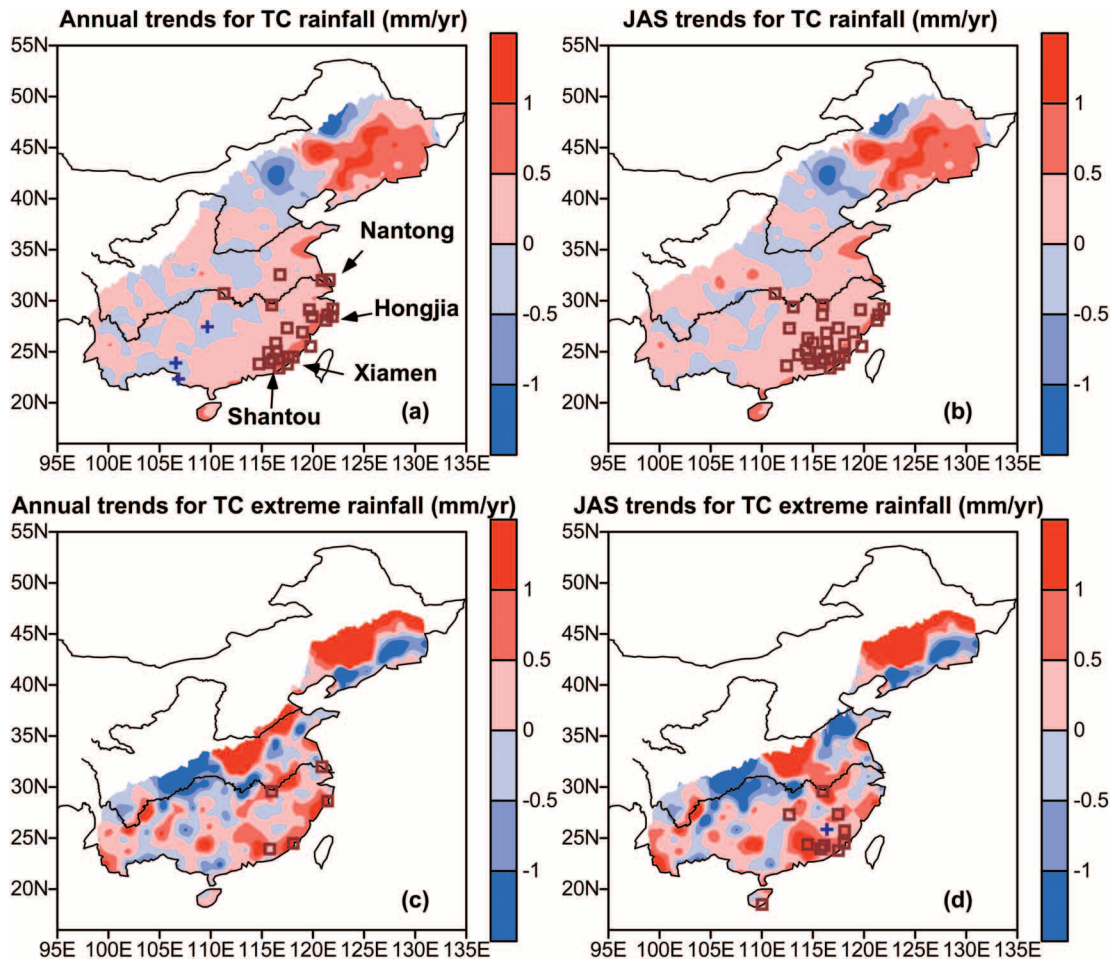


Fig. 6. Linear trends in annual (a) and summer (b) mean TC precipitation (mm year^{-1}) and in annual (c) and summer (d) extreme precipitation (mm year^{-1}) for each TC during 1965–2009 with crosses and squares indicating stations that are statistically significant at the 95% level.

To closely examine the changes in the average rainfall per TC, we select four stations in the coastal areas of East and Southeast China (Fig. 7). Nantong, which is located in the delta of the Yangtze River, was rarely affected by TCs prior to the mid-1980s, but since then it experienced increasing TC influence (Fig. 7a). Hongjia, Xiamen, and Shantou stations are located in Zhejiang, Fujian, and Guangdong, respectively, which are the provinces that experience the most TC influence in China. Despite the obvious interannual and decadal variations in the annual TC rainfall, the upward trends can be clearly seen at these stations since the 1980s.

Wu et al. (2007) studied the impact of TC rainfall on Hainan Island during 1962–2005 and showed that the

rainfall amount and the number of days of extreme events related to each TC have been significantly increased, although the number of TCs that affected Hainan Island has significantly decreased over the past four decades due to the prevailing track shifts reported by Wu et al. (2005). In this study, the extreme rainfall for each TC at a specific station is obtained by normalizing the annual extreme rainfall with the number of TCs affecting the station (Figs. 6c and 6d). The count of the stations with a significant increasing trend in the extreme rainfall per TC decreases considerably, compared to the annual average rainfall per TC, although the linear trends in Figs. 6c and 6d are stronger than those in Figs. 6a and 6b. In the peak season (July–September), the significant trends are

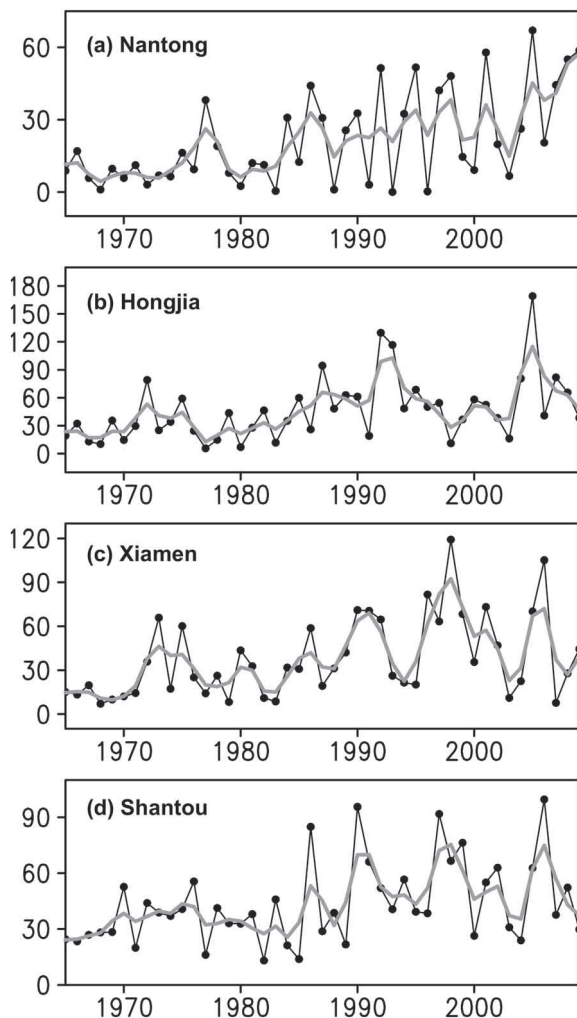


Fig. 7. Time series of annual average precipitation (mm) for each TC at a) Nantong, b) Hongjia, c) Xiamen, and d) Shantou during 1965–2009. Their locations are shown with the four arrows from north to south in Fig. 6a and thick lines are the 9-year running average.

mainly in the areas near Xiamen, Fujian Province (Fig. 6d). In agreement with Wu et al. (2007), the increasing trend in the extreme rainfall per TC is statistically significant in southern Hainan Island. Note that the significant trends were calculated with a sample size of more than 30 TCs. We also examined the contributions of individual categories to the TC extreme rainfall and found that the extreme rainfall does not increase with TC intensity.

As we know, the water holding capacity of air is a function of temperature. Trenberth et al. (2005) found that atmospheric moisture content increased in many

regions due to global warming. As the water vapor content of the tropical atmosphere increases, the moisture convergence for a given amount of mass convergence is enhanced, increasing rainfall rates in systems including TCs. Using satellite data, Lau and Wu (2007) reported an increase in the occurrence of heavy rain events in the tropics during 1979–2003. Several studies of land-based precipitation data have identified increasing trends in the frequency of very heavy precipitation events (IPCC 2007). Since TCs derive their primary energy from the condensation of water vapor, the enhanced moisture convergence should increase TC intensity. To examine this, we calculate the maximum intensity for each TC that caused rainfall in China. The time series derived from the STI and JTWC datasets show no significant trends in the maximum intensity for each TC (Figs. 8a and 8b). Further examination of the TC intensity of the selected four stations indicates that there was no increasing trend in TC intensity during the period 1965–2009 based on the STI dataset (Fig. 9), although the average rainfall per TC increased significantly. It is clearly suggested that the increasing TC rainfall per TC in China did not result from the enhanced TC intensity.

Unlike the projected TC-related rainfall rates in climate models, which are calculated within a certain radius from the TC center, the average TC rainfall per TC is also a function of TC translation in this study. The increasing (decreasing) translation speed tends to reduce (enhance) the average TC rainfall per TC at a station. For this reason, we also examine the average translation speed of TCs that caused rainfall in China (Fig. 8c). No significant trend can be found in the translation speed during 1965–2009. It is suggested that the increasing TC rainfall per TC in China was not due to the change in TC translation.

5. Summary

The torrential rainfall associated TC activity often causes disasters in China. Numerical simulations of TCs in a warmer climate suggest that TC-related rainfall rates are likely to increase (Knutson and Tuleya 1999; Knutson et al. 2010). Although studies show widespread increases in heavy precipitation events, the TC rainfall rate change has not been well understood in extant observational studies (Knutson et al. 2010). Using daily precipitation observations at 514 meteorological stations during 1965–2009, this study investigates the primary features of TC rainfall in China, with a special focus on the contribution of TC rainfall to the so-called “wetting in the south and

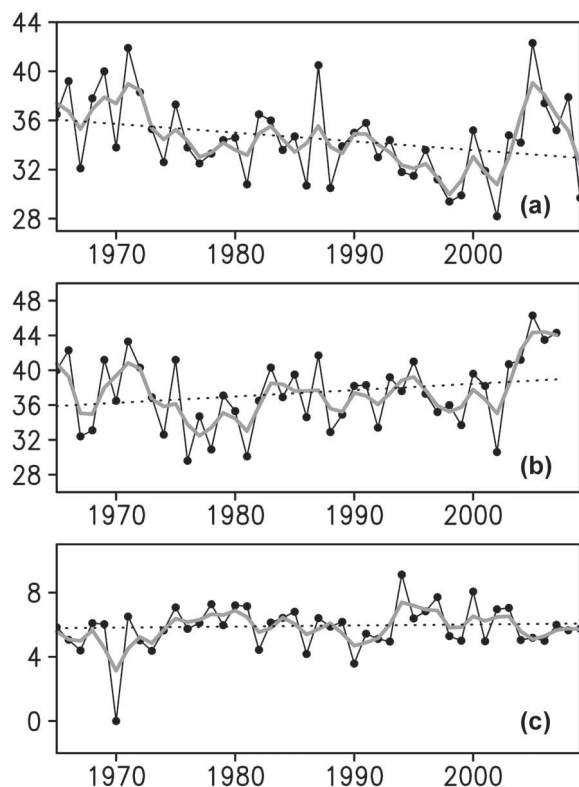


Fig. 8. Time series of annual mean TC maximum intensity (m s^{-1}) from (a) the CMA-STI dataset and (b) the JTWC dataset, and (c) TC translation speed (m s^{-1}) for JAS (July–September) TCs that affected mainland China and Hainan Island based on the STI dataset during 1965–2009. Thick and dashed lines indicate the 9-year running average and linear trends, respectively.

drying in the north” pattern in China and the changes in the average rainfall per TC.

TC rainfall mainly affected eastern and northeastern China, accounting for more than 10% of the summer rainfall in South and Southeast China. In agreement with the reported shifts in prevailing TC tracks and elongated survival time of landfall TCs (Wu et al. 2005; Chen et al. 2011), TC rainfall trended upward in the lower reach of the Yangtze River and Southeast China. It is suggested that the summer TC rainfall contributes to the “wetting in the south and drying in the north” pattern by enhancing the rainfall in Southeast China.

This study suggests that the average rainfall per TC has significantly increased in Southeast China during 1965–2009. The changes in the average rainfall per TC are mostly dominated by the upward trends. In the

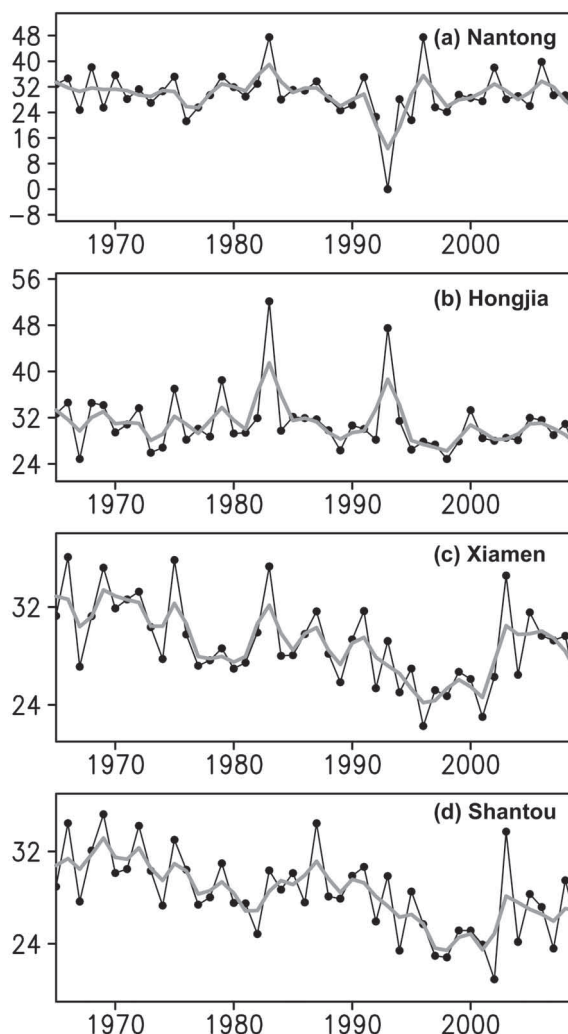


Fig. 9. Same as Fig. 7, but for the average intensity (m s^{-1}) of TCs that affected the selected four stations during 1965–2009 based on the STI dataset.

peak season (July–September), all significant changes are upward trends that occur south of the Yangtze River east of 110°E . Although TCs derive their primary energy from the condensation of water vapor, this study finds that the increasing rainfall per TC was not accompanied with the enhanced TC intensity, which was suggested over oceans in previous studies (Knutson and Tuleya 1999; Knutson et al. 2010). In addition, no significant trend can be found in the translation speed of TCs that affected China during 1965–2009, suggesting that the increasing TC rainfall per TC in China was not due to the slowdown of the TC movement.

TC activity in the western North Pacific basin is closely associated with the monsoon activity in the South China Sea and western North Pacific, including prominent atmospheric variability ranging from the synoptic-scale tropical disturbance (Liebmann and Hendon 1990; Lau and Lau 1990; Chang et al. 1996) to the quasi-biweekly oscillation (Murakami and Frydrych 1974; Murakami 1975; Kikuchi and Wang 2009) to the Madden-Julian oscillation (MJO) (Madden and Julian 1971, 1972; Wang and Rui 1990). The interaction between Asian monsoon systems and TCs can affect temporary changes and spatial distributions of TC rainfall (Chien et al. 2008; Wu et al. 2009). TCs may tend to be associated with more precipitation without the intensification of their surface circulation. Here we argue that the changes in the average rainfall per TC in China may be associated with changes in the summer monsoon activity. It is also possible that the increasing rainfall per TC results from the bias in the dataset due to the limited sample size. For example, increasing TCs that closely examine a station can lead to an increasing rainfall trend at the station.

Acknowledgments

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