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Contribution of South China Sea Tropical Cyclones to an Increase in Southern China Summer Rainfall Around 1993

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ABSTRACT

The increase in southern China summer rainfall around 1993 was accompanied by an increase in tropical cyclones that formed in the South China Sea. This study documents the connection of these two features. Our analysis shows that the contribution of tropical cyclones that formed in the South China Sea to southern China summer rainfall experienced a significant increase around 1993, in particular, along the coast and in the heavy rain category. The number of tropical cyclones that formed in the western North Pacific and entered the South China Sea decreased, and their contribution to summer rainfall was reduced in eastern part of southern China (but statistically insignificant). The increase in tropical cyclone-induced rainfall contributed up to ∼30% of the total rainfall increase along the coastal regions. The increase of tropical cyclones in the South China Sea appears to be related to an increase in local sea surface temperature.

Key words: South China Sea tropical cyclones, decadal change around 1993

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1. Introduction

Summer rainfall increased significantly in southern China around 1993 (Kwon et al., 2007; Ding et al., 2008; Qian and Qin, 2008; Qian et al., 2008; Yao et al., 2008; Ning and Qian, 2009; Wu et al., 2010). This increase was more pronounced than the summer rainfall increase in the Yangtze River region around the late 1970s. This rainfall change not only affected the water supply in southern China, but also may have induced atmospheric circulation change in the mid-latitudes of East Asia (Kwon et al., 2007). Thus, it is important to understand the factors that contributed to this rainfall increase. In this study, we focused particularly on the contribution of tropical cyclone (TC)-induced precipitation because TCs bring substantial rainfall to southern China each year (Ren et al., 2002, 2006).

The rainfall increase around 1993 has been associated with enhanced low-level convergence over southern China, which was induced by divergent flows from two anomalous anticyclones, one over North China-Mongolia and the other over the South China Sea–subtropical western North Pacific (Wu et al., 2010). The northern anticyclone has been associated with an increase in the Tibetan Plateau snow cover during the preceding winter–spring (Ding et al., 2009; Wu et al., 2010), and the southern anticyclone has been linked to an increase in the equatorial Indian Ocean SST (Wu et al., 2010). One noteworthy feature is an increase in SST in the South China Sea, which appears to be a response to anomalous descent and associated decrease in cloud amount and increase in downward shortwave radiation (Wu et al., 2010). Does SST increase have a feedback to the summer rainfall increase in south-

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*Corresponding author: WU Renguang, renguang@cuhk.edu.hk ern China? Zhou et al. (2010) indicated that winter rainfall over South China has a significant positive correlation with the South China Sea SST.

Kwon et al. (2007) indicated that the number of typhoons affecting South China increased after the early 1990s. They suggested that this increase contributed to the increase in South China summer rainfall. The purpose of this study was to quantify the contribution of TCs that formed in the South China Sea to the increase in summer rainfall in southern China. In view of the fact that TCs tend to cause more moderate to heavy rainfall, we examined the rainfall change and the TC contribution in different rain categories. The reason for the increase in the number of TCs in the South China Sea was also explored.

The organization of the text is as follows. The datasets and methods used in the present study are described in section 2. Section 3 presents summer rainfall change around 1993 in different rain categories. Section 4 addresses the changes in the number of TCs and the amount of the TC-induced rainfall; the plausible reason for the TC change is also discussed. A summary is given in section 5.

2. Datasets and methods

2.1 *Datasets*

In this study we used daily rainfall at 756 stations in China covering the period 1951–2008. This dataset was provided by the Chinese Meteorological Data Service Network. Numerous data were missing from this dataset, in particular before 1959. There were changes in the sites of some stations. Therefore, we excluded stations with missing data persisting more than 1 month in an individual year as well as stations with site changes. Thus, we used daily rainfall data from 525 stations from 1959 to 2008. We also used gridded daily rainfall ($0.5^\circ \times 0.5^\circ$ grid) over East Asia (5°–60°N, 65°–155°E; Xie et al., 2007), available from 1 January 1978 to 31 December 2006. This dataset was obtained from ftp://ftp.cpc.ncep.noaa.gov/precip/xie/EAG.

The TC track data were obtained from the Joint Typhoon Warning Center (JTWC) western North Pacific best track data for the period 1945–2010. The data of TC tracks (6-h intervals) were converted to daily mean by averaging for compatibility with daily rainfall. For verification, a parallel analysis was conducted based on the TC track data from Shanghai Typhoon Institute of China Meteorological Administration (CMA) and the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center of Japanese Meteorological Agency (JMA). In the CMA data, the positions for those TCs that affected China were previously validated (Ren et al., 2006). Most descriptions in the text refer to results based on the JTWC data; however, the use of CMA and JMA data is noted where it occurred. The atmospheric variable data were obtained from the National Center for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis 2 (Kanamitsu et al., 2002). The resolution for the reanalysis variables is $2.5^\circ \times 2.5^\circ$. We used the objectively analyzed monthly mean SST from the NOAA optimum interpolation (OI) version 2 (OISST2; Reynolds et al., 2002). The OISST2 data were available ($1^\circ \times 1^\circ$) starting from November 1981.

2.2 *Methods*

We defined three rain categories according to daily rainfall amount as follows. Light rain corresponds to daily rainfall < 25 mm d^{-1}; moderate rain corresponds to daily rainfall $\geqslant 25$ mm d^{-1} and $\leqslant 50$ mm d^{-1}; and heavy rain corresponds to daily rainfall > 50 mm d^{-1}.

We separated the TCs into the following categories: TCs that form in the South China Sea (0°–23°N, 100°–120°E) (denoted as TC_SCS_FORM), TCs that form in the western North Pacific (denoted as TC_WNP_FORM), TCs that form in the western North Pacific and enter the South China Sea (denoted as TC_SCS_ENTER), and all the TCs in the South China Sea and the western North Pacific (denoted as TC_TOTAL).

We extracted the TC-induced rainfall according to an effective radius of influence of TCs, following previous studies (Englehart and Douglas, 2001; Kubota and Wang, 2009; Chen et al., 2010; Jiang and Zipser, 2010; Lee et al., 2010). The daily station rainfall was designated as TC-induced when the station fell within the effective radius from the center of a TC. The radius of medium-sized TCs is $\sim 3^\circ$–6°, and the radius of large TCs is $\sim 6^\circ$–8° (Kubota and Wang, 2009). There is no objective way to determine the effective radius of influence of TCs. In the present study, we considered different effective radii to test the sensitivity of the results. The TC-induced rainfall was determined for the effective radii of 350 km, 450 km, 550 km, 650 km, 750 km, and 850 km in this study. Most of the figures are based on an effective radius of 550 km. Summer rainfall induced by TCs was obtained by summing the daily TC-induced rainfall. Some TCs that developed in May but continued into June were included in the number of TCs.

We counted the number of TCs that bring rainfall to southern China based on the following criterion. For a specific effective radius, if one or more stations in the region of 22.5°–27.5°N, 105°–120°E fell within the effective radius of a TC, this TC was considered to bring rainfall to southern China. This method was applied to TCs in all categories and to different effective radii of influence. Herein, we only show results based on an effective radius of 550 km, but we note that the change in the number of TCs from 1983–1992 to 1993–2002 is qualitatively consistent among different radii of influence.

The year of the summer rainfall increase is somewhat different according to Wu et al. (2010) and Kwon et al. (2007). The rainfall change in coastal regions was more obvious in 1994 (Kwon et al., 2007), but the difference was more significant for southern China in 1993 (Wu et al., 2010). In this study, we used 1993 as the changing point, following Wu et al. (2010). We focused on a contrast between the 1983–1992 mean and the 1993–2002 mean. A Student's *t*-test was used to examine the significance of the differences between the two periods.

3. Rainfall change in different categories

Figure 1 shows the area-mean summer (June–July–August or JJA) rainfall anomalies in light, moderate, and heavy rain categories and the total anomalies in southern China based on station data during the period 1978–2008 and from gridded data during the period 1978–2006. The area mean was obtained based on the average over the region of 22.5°–27.5°N, 105°–120°E, following Wu et al. (2010). As shown in the figure, the relative contribution of different rain categories varied from year to year. A consistent switch from negative to positive anomalies can be seen around 1993 for all the rain categories. This is true for both station rainfall data and the gridded rainfall data. This result indicates that the summer rainfall increase in southern China occurred in all three rain categories.

Table 1 presents the differences of 10-year mean rainfall amount between 1983–1992 and 1993–2002 in different categories. All of these differences are significant at the 95% confidence level according to the Student's *t*-test. According to the station rainfall data, heavy rain contributes to the increase the most (∼ 40%), and light rain contributes only ∼ 23%. Comparing the station and gridded rainfall data, the heavy rain contribution is smaller and the light rain contribution is much larger in the gridded data than in the station data. This discrepancy indicates that the spatial interpolation performed to obtain gridded rainfall overestimates the light rain amount and underestimates the heavy rain amount. This inconsistency appears to be larger when there is more heavy rain (Fig. 1). These results indicate a redistribution of the contribution from different rain categories in the gridded data compared to that in the station data. Thus, caution is recommended when using the gridded data to estimate light and heavy rain changes. On the other

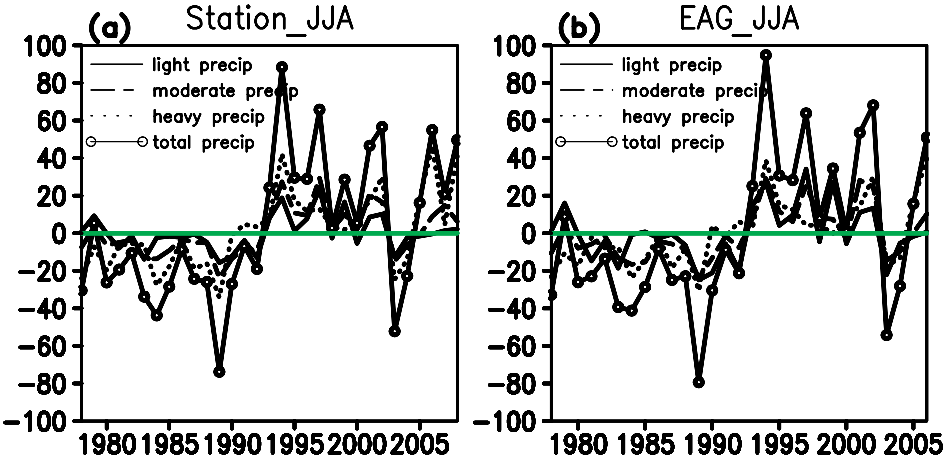

Fig. 1. Summer rainfall anomalies (mm month^{-1}) averaged over southern China (22.5°–27.5°N, 105°–120°E) for light rain (solid lines), moderate rain (dashed lines), heavy rain (dotted lines), and total rain (circle lines) based on station data (a) and gridded data (b). The reference period for anomalies is climatology over 1978–2006.

Table 1. Differences in the 1993–2002 mean and the 1983–1992 mean of summer rainfall averaged over southern China (22.5°–27.5°N, 105°–120°E) for light, moderate, heavy, and total rain. Units: mm month^{-1}.

Category	Light rain	Moderate rain	Heavy rain	Total
Station data	15.1	24.5	26.3	65.9
Gridded data	23.0	25.6	22.7	71.3

hand, area-averaging based on station data cannot account for the uneven distribution of stations in space. In the next section, we only consider the estimation of TC-induced rainfall contribution based on station rainfall data.

Figures 2 and 3 show changes of summer rainfall from 1983–1992 to 1993–2002 for light, moderate, heavy, and total rain. Apparently, an increase in rainfall is seen in southern China in all categories. In comparison, the increase in the heavy rain category is larger than that in the light rain category, based on station rainfall data (Fig. 2). In some local regions, the increase in the heavy rain category reached 60 mm month^{-1}. The increase in the light rain category was < 40 mm month^{-1}. The gridded data show an increase in all categories as well (Fig. 3). Compared to station rainfall, the gridded rainfall shows a larger increase in the light rain category and a smaller increase in the heavy rain category. The gridded data also show accompanying changes in several other places, such as southeast coast of Indo-China Peninsula and northern Vietnam. A significant increase can also be seen in Myanmar.

4. Tropical cyclone-induced rainfall change

4.1 *Tropical cyclone number change*

Figure 4a shows the number of TCs in summer in different categories for the period 1978–2008. Apparently, more TCs formed in the South China Sea during 1993–2002 than during 1983–1992. Only one or no TC formed in the South China Sea during individual years of 1983–1992, except for 1984 (two TCs). In contrast, two or more TCs formed in the South China Sea each year during 1993–2002, except for 1993 (no TCs) and 1998 (one TC). This change in the number of TCs that formed in the South China Sea is consistent with the increase in summer rainfall in southern China. However, the inconsistency between year-to-year variations of the TC number and southern China summer rainfall is noteworthy. For example, during 2005–2008, there are positive rainfall anomalies in southern China (Fig. 1), while fewer TCs formed in the South China Sea (Fig. 4). This inconsistency suggests an important contribution of other factors to summer rainfall in southern China.

The number of TCs that formed in the western North Pacific and entered the South China Sea, however, decreased after 1995. An out-of-phase variation can be seen between TCs that formed in and that entered the South China Sea both according to the decadal mean and on an interannual time scale. The number of TCs that formed in the western North Pacific was low in 1995, 1998, 2003, and 2007. All of these are El Niño decaying years, indicating the influence of El Niño-Southern Oscillation (ENSO) on the western North Pacific TCs (e.g., Chan, 2000; Chu, 2004; Kim et al., 2010). Recent studies have suggested the influence of the tropical Indian Ocean SST on the western North Pacific TC activity (Du et al., 2011; Zhan et al., 2011a, b).

Before 1993, the two curves for the total number of TCs and the number of TCs that formed in the western North Pacific are quite close because few TCs formed in the South China Sea. After 1994, the two curves split because of the increase in the number of TCs that formed in the South China Sea.

Table 2a shows the average number of different categories of TCs in summer during 1983–1992 and 1993–2002 and the differences between the two periods. The number of TCs that formed in the South China Sea increased by ~ 2 per year on average, which is significant at the 99% confidence level. The number of TCs entering the South China Sea decreased by ~ 1 each year on average, but the change is not significant. The total number of TCs that formed in the western North Pacific remained nearly the same. This suggests that there is a change in the track of those TCs that formed in the western North Pacific. These results are consistent with previous studies. Goh and Chan (2010) showed an increase of South China Sea TCs for the season of May–August. Lee et al. (2006) indicated an increase of South China Sea TCs for May–June. Kim et al. (2010) showed an increase in northern South China Sea TCs for July–September.

Analysis based on CMA and JMA TC data verifies the change in the number of TCs that formed in the South China Sea. On average, there are more TCs during 1993–2002 than during 1983–1992 in this category (Tables 3a, 4a), although the number of increases is smaller and the significance of the difference is lower compared to JTWC. Following the increase of TCs forming in the South China Sea, more TCs brought rainfall to southern China during 1993–2002 than during 1983–1992 in JTWC (Fig. 4b and Table 2b) and CMA and JMA (Table 3b and 4b). The number of TCs that entered the South China Sea decreased based on both CMA and JMA, which is quite consistent with the decrease based on JTWC. Correspondingly, fewer TCs brought rainfall to southern China in all the three datasets (Tables 2b, 3b, 4b). The number of TCs that formed in the western North Pacific decreased in CMA and JMA, which differed from JTWC. In this category, the number of TCs that brought rainfall to southern China decreased in CMA and JMA, which was consistent with JTWC. The total number of TCs in the South China Sea and western North Pacific decreased in CMA and JMA, which was opposite to JTWC. This

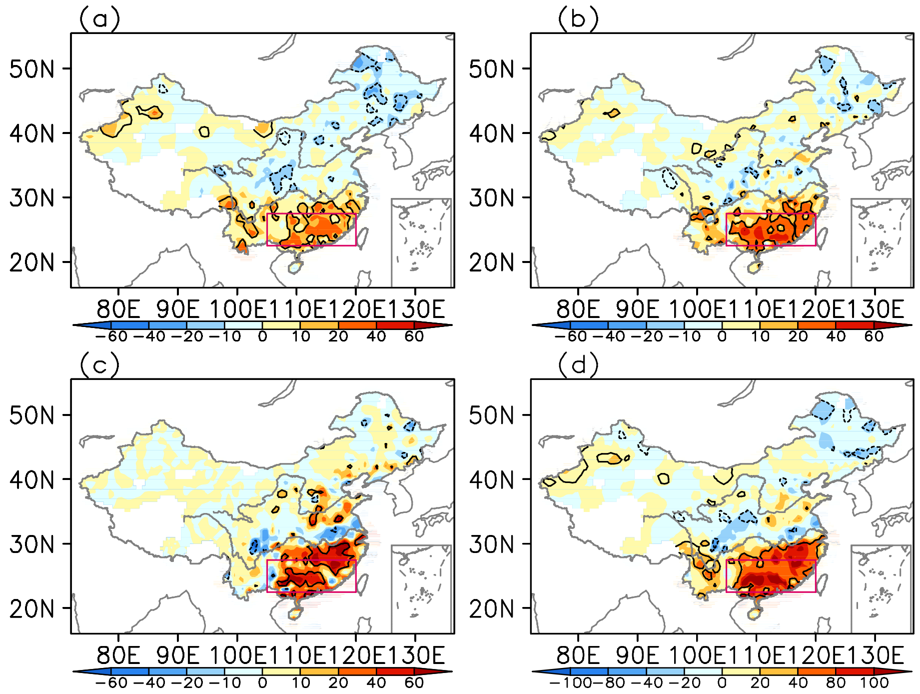

Fig. 2. Difference as 1993–2002 mean minus 1983–1992 mean of summer rainfall (mm month^{-1}) for light rain (a), moderate rain (b), heavy rain (c), and total rain (d) based on station data. The difference in regions enclosed by black lines is statistically significant at the 90% confidence level according to the Student's t test.

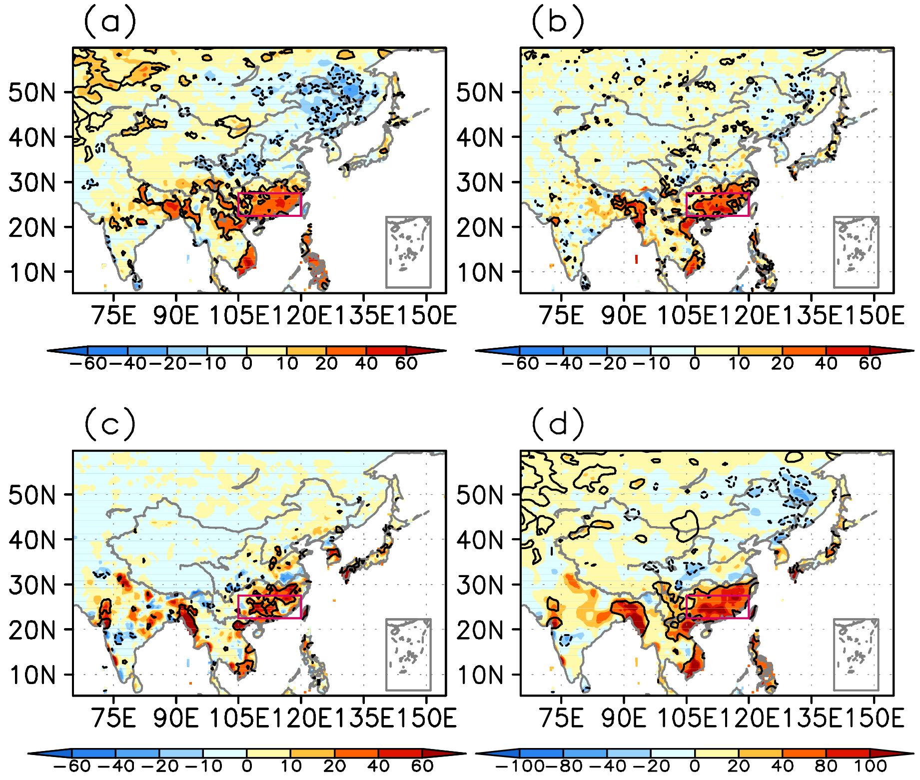

Fig. 3. The same as Fig. 2 except based on gridded data.

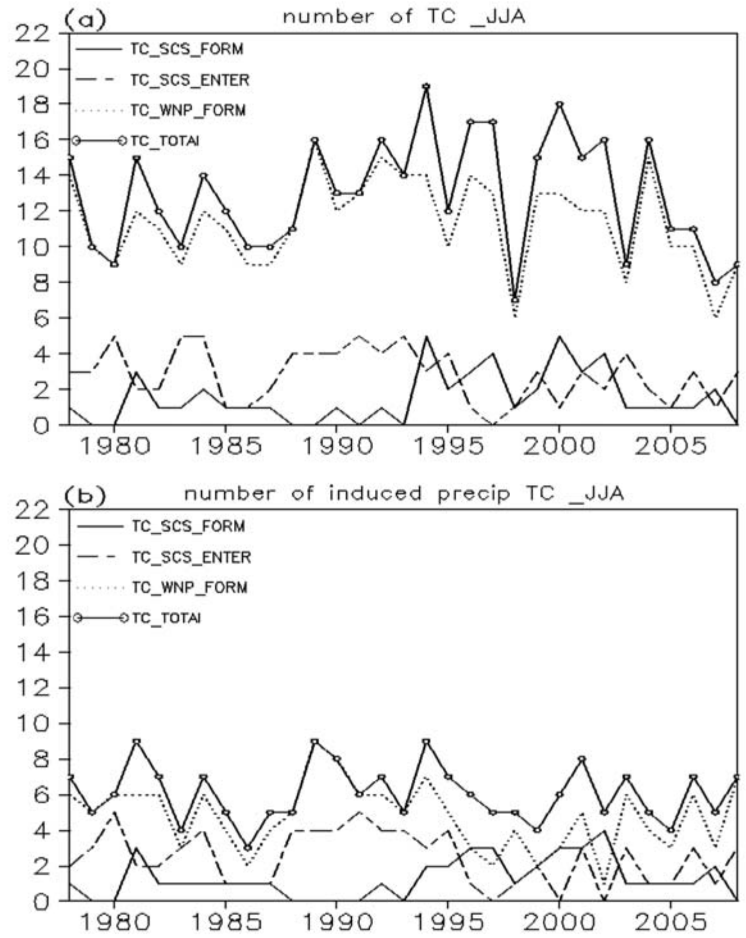

Fig. 4. (a) The number of summer tropical cyclones. (b) The number of summer tropical cyclones that bring rainfall to southern China.

inconsistency is mainly due to the difference during 1993–2002 during which the number of TCs in CMA and JMA was smaller than that in JTWC.

4.2 *Tropical cyclone-induced rainfall change*

Figure 5 shows the summer rainfall change induced by TCs that formed in the South China Sea for differ-

Table 2. (a) Average number of TCs in summer during 1983–1992 and 1993–2002 and their difference. TC_SCS_FORM, TC_SCS_ENTER, TC_WNP_FORM, and TC_TOTAL refer to TCs that form in the South China Sea, that form in the western North Pacific and enter the South China Sea, that form in the western North Pacific, and that form in both the South China Sea and the western North Pacific, respectively. The percentage in brackets denotes the level of confidence of the change. (b) The same as (a) except for those TCs that bring rainfall to southern China for an effective radius of influence at 550 km.

		TC_SCS_FORM	TC_SCS_ENTER	TC_WNP_FORM	TC_TOTAL
(a)					
	1983–1992	0.8	3.5	11.7	12.5
	1993–2002	2.9	2.3	12.1	15.0
	Difference	2.1 (99%)	−1.2	0.4	2.5 (90%)
(b)					
	1983–1992	0.5	3.0	5.0	5.5
	1993–2002	2.3	1.7	3.5	4.7
	Difference	1.8 (99%)	−1.3(90%)	−1.5	−0.8

Table 3. The same as Table 2 except based on CMA data.

		TC_SCS_FORM	TC_SCS_ENTER	TC_WNP_FORM	TC_TOTAL
(a)					
	1983–1992	2.1	3.6	12.7	14.8
	1993–2002	3.2	2.2	10.2	13.4
	Difference	1.1 (90%)	−1.4 (95%)	−2.5 (90%)	−1.4
(b)					
	1983–1992	1.7	3.0	5.5	7.2
	1993–2002	2.7	1.9	3.6	6.3
	Difference	1.0 (90%)	−1.1(90%)	−1.9 (95%)	−0.9

Table 4. The same as Table 2 except based on JMA data.

		TC_SCS_FORM	TC_SCS_ENTER	TC_WNP_FORM	TC_TOTAL
(a)					
	1983–1992	1.2	2.9	11.6	12.8
	1993–2002	2.3	1.9	9.0	11.3
	Difference	1.1 (95%)	−1.0	−2.6 (95%)	−1.5
(b)					
	1983–1992	1.0	2.6	4.4	5.4
	1993–2002	2.0	1.7	3.3	5.3
	Difference	1.0 (95%)	−0.9	−1.1	−0.1

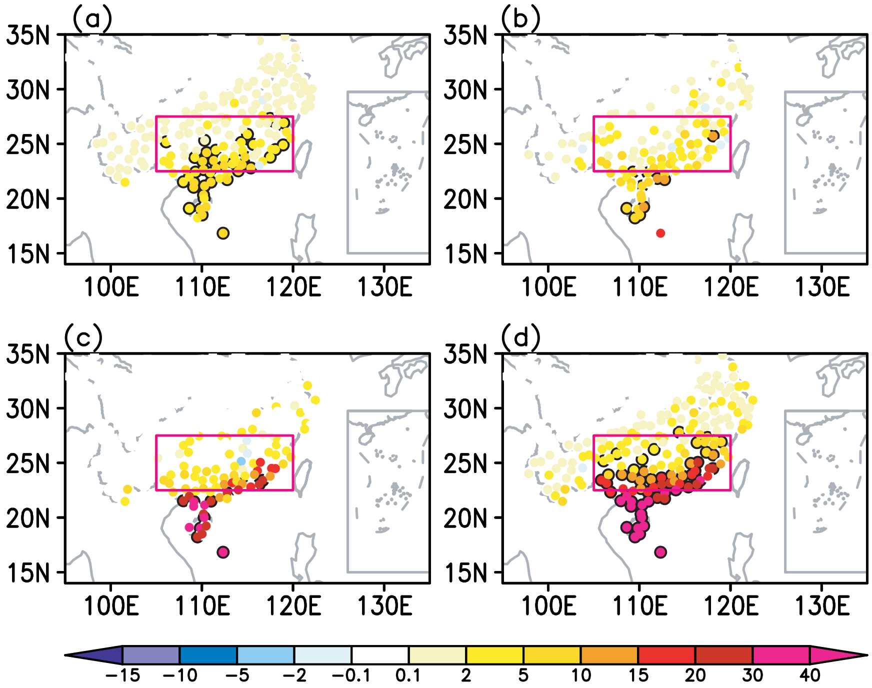

Fig. 5. Difference as 1993–2002 mean minus 1983–1992 mean of summer rainfall (mm month^{-1}) induced by tropical cyclones forming in the South China Sea with an effective radius of influence at 550 km for light rain (a), moderate rain (b), heavy rain (c), and total rain (d) based on station data. The circled dots denote differences significant at the 90% confidence level according to the Student's *t*-test.

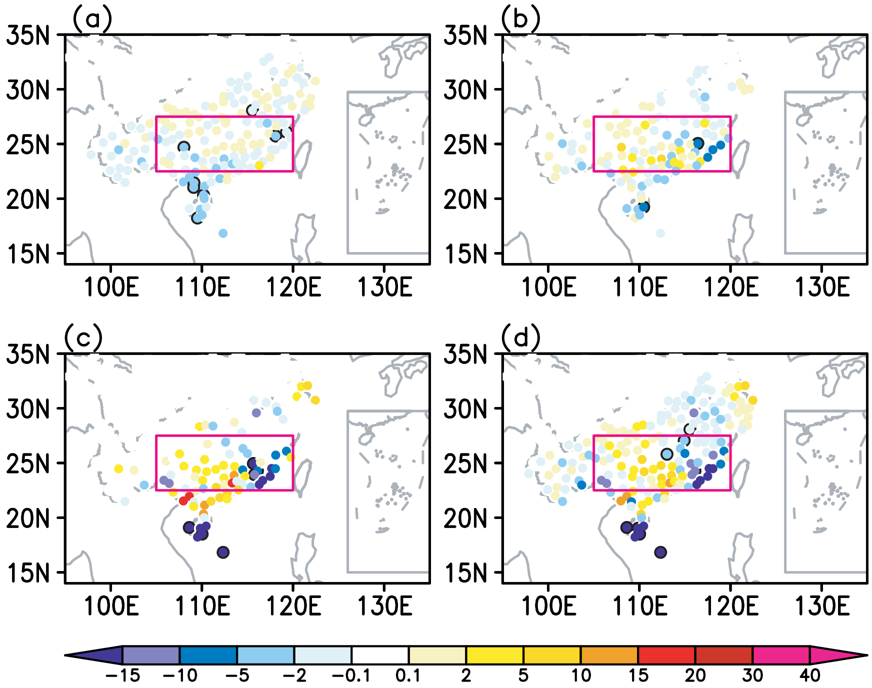

Fig. 6. The same as Fig. 5 except for rainfall induced by tropical cyclones entering the South China Sea.

ent rain categories when the effective radius of influence of TCs was set at 550 km. The rainfall increase was seen at most stations for light, moderate, and heavy rain categories. The light rain category contains more stations that showed significant change. The heavy rain change was larger at coastal stations and on Hainan Island, where the increase reached as much as 15–20 mm month^{-1}. The total rainfall increase was larger near the coast and decreased inland.

Figure 6 is similar to Fig. 5 but shows TCs entering the South China Sea. The light and moderate rain changes were small except for a few stations that showed a decrease. The heavy rain change decreased in the eastern part and increased in the western part of southern China. The decrease can also be seen at Hainan Island. The change, however, was insignificant at most stations. The total rainfall change bears a pattern similar to that of heavy rain change.

The estimated TC-induced summer rainfall change based on CMA and JMA data shows both consistency and difference from that based on JTWC data. The total rainfall change induced by TCs that formed in the South China Sea based on CMA and JMA data (Figs. 7a, b) is consistent with that based on JTWC data (Fig. 5d) over most of southern China, except for a few stations. In comparison, the magnitude of the increase is smaller and the significance of the change is lower in CMA and JMA data than in JTWC data. Large discrepancies can be seen for the total rainfall change induced by TCs entering the South China Sea. In southwestern part of the southern China box, negative difference dominates in CMA data (Fig. 7c), where positive and negative differences are seen in JTWC data (Fig. 6d) and JMA data (Fig. 7d). The rainfall change in eastern part of the box tends to be consistent in CMA data (Fig. 7c) and JTWC data (Fig. 6d), and, to a lesser degree, in JMA data (Fig. 7d).

Figure 8 shows the percentage of rainfall change due to TCs that formed in the South China Sea compared to the total rainfall change for different rain categories. The percentage was large near the coast and decreases inland. The percentage near the coast reached 30%–40% at some stations for heavy and light rain categories. The contribution of the South China Sea TCs to the total rainfall reached 30% near the coast. A negative percentage was seen at some stations in the heavy rain category (Fig. 8c) because the total and the TC-induced rainfall changes were opposite (Figs. 2c, 5c).

As noted previously, there is no consensus about the selection of the effective radius of influence of TCs. To test the sensitivity of the results, we used various effective radii to estimate the TC-induced rainfall. Figure 9 shows area-mean southern China summer rainfall estimates based on different radii. It can be seen that the estimation is very sensitive to the radius in some years. In comparison, the sensitivity is larger for light rain than for heavy rain. This is expected because heavy rain mostly fell within a few degrees of the ra-

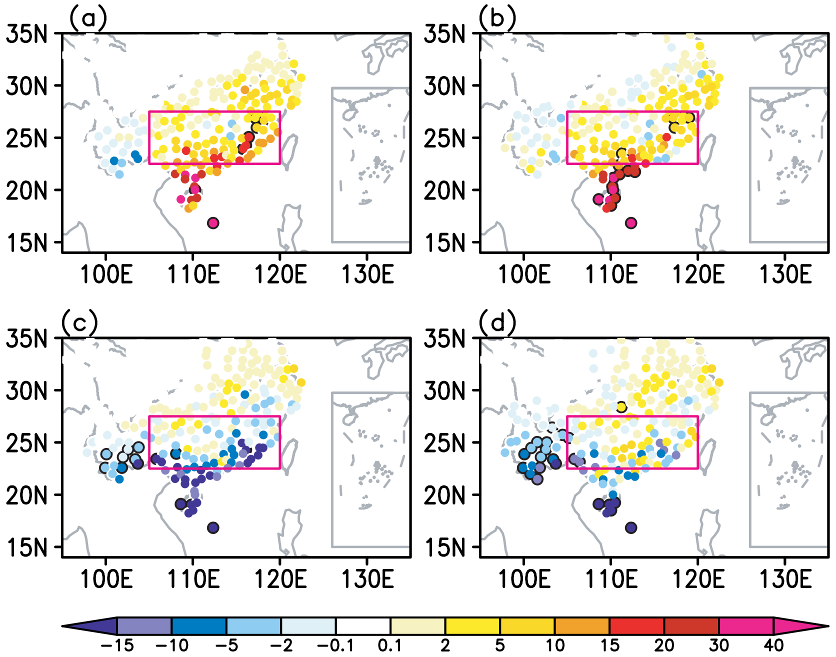

Fig. 7. Difference as 1993–2002 mean minus 1983–1992 mean of summer rainfall (mm month^{-1}) induced by (a, b) tropical cyclones forming in the South China Sea and (c, d) tropical cyclones entering the South China Sea with an effective radius of influence at 550 km for total rain based on station data. The circled dots denote differences significant at the 90% confidence level according to the Student's *t*-test. (a, c) are based on CMA data and (b, d) are based on JMA data.

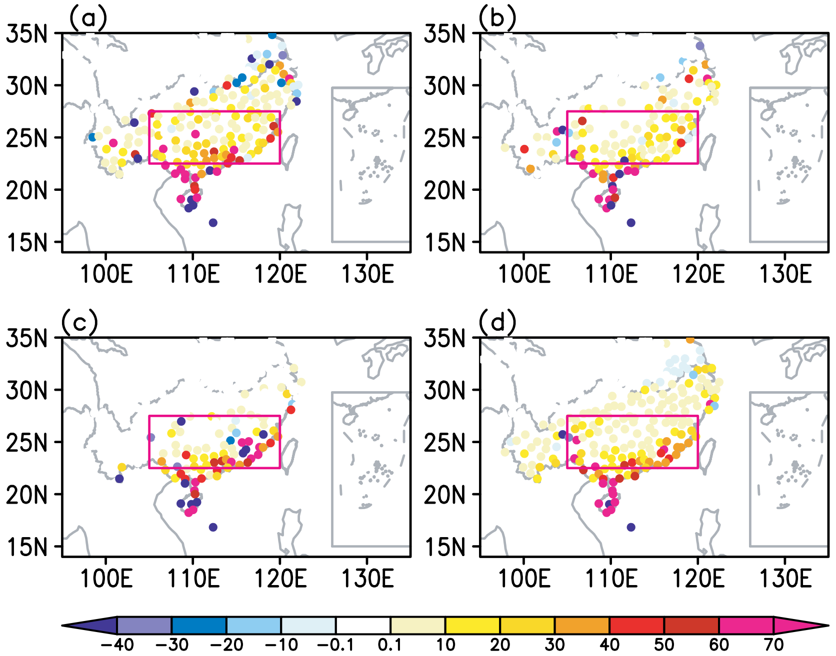

Fig. 8. Percent (%) of rainfall change due to tropical cyclones forming in the South China Sea with an effective radius of influence at 550 km for light rain (a), moderate rain (b), heavy rain (c), and total rain (d).

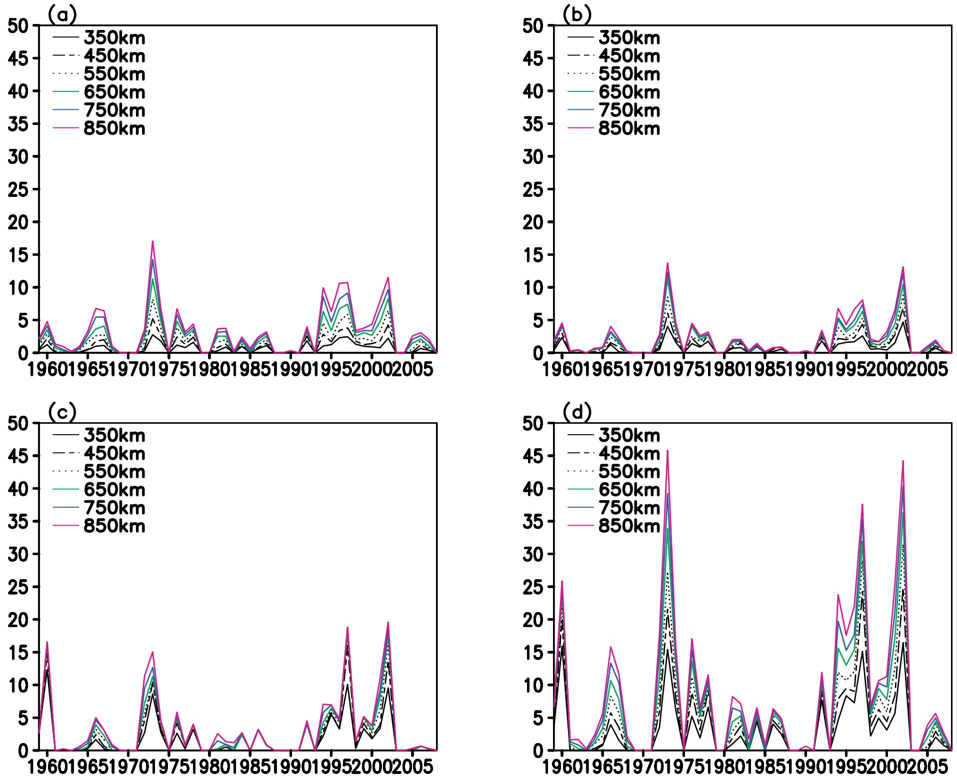

Fig. 9. Area-mean southern China summer rainfall (mm month^{-1}) induced by South China Sea formed tropical cyclones at different radii of influence for light rain (a), moderate rain (b), heavy rain (c), and total rain (d).

dius from the center of the TCs. In some years, the estimated TC-induced total rainfall tripled when the radius is 850 km compared to 350 km.

The increase in the number of TCs that formed in the South China Sea was expected to lead to an increase in local rainfall. The total rainfall, however, decreased in the northern South China Sea (Wu et al., 2010). Thus, the non-TC rainfall likely accounts for a larger part of total rainfall and its change in the northern South China Sea region. The non-TC and TC-induced rainfall change was opposite in the northern South China Sea, which was different from southern China where the non-TC and TC-induced rainfall contributed to the rainfall increase in concert.

For comparison, in Fig. 10 we show non-TC induced rainfall changes for different categories. These changes were obtained by subtracting the total TC-induced rainfall changes from the total rainfall changes. As shown in Fig. 10, a significant increase in non-TC-induced rainfall can be seen to be more widespread, whereas significant increases in the South China Sea TC-induced rainfall were mostly confined to the coastal regions. Near the coast, the change of the South China Sea TC-induced rainfall was ~ 30%–40% of that of non-TC rainfall.

4.3 *Reasons for the increase in South China Sea tropical cyclones*

Previous studies have suggested the role of the Pacific decadal oscillation (Goh and Chan, 2010), the zonal gradient of SST in the tropical Pacific (Kim et al., 2010), and tropical North Pacific SST (Lee et al., 2006) in the increase of the TC formation in the South China Sea region. Matsuura et al. (2003) suggested the role of the decadal ENSO-like ocean–atmosphere coupling in modulating the western North Pacific TC activity. Yumoto and Matsuura (2001) suggested that the main causes for the interdecadal variability of the western North Pacific TC activity are Pacific SST and large-scale circulation changes.

Here, we contrast the changes in mean vertical wind shear between 850 hPa and 200 hPa, 850-hPa vorticity, and 600-hPa relative humidity between 1983–1992 and 1993–2002 (Fig. 11). All of these factors are considered important in TC activity (Gray, 1979; Camargo et al., 2007). In Fig. 11, we can see an increase in vertical wind shear, an increase in anticyclonic vorticity at 850 hPa, and a decrease in relative humidity at 600 hPa over the northern South China Sea where most of the TC activity in summer was observed (Wang et al., 2007). Thus, the increase in South

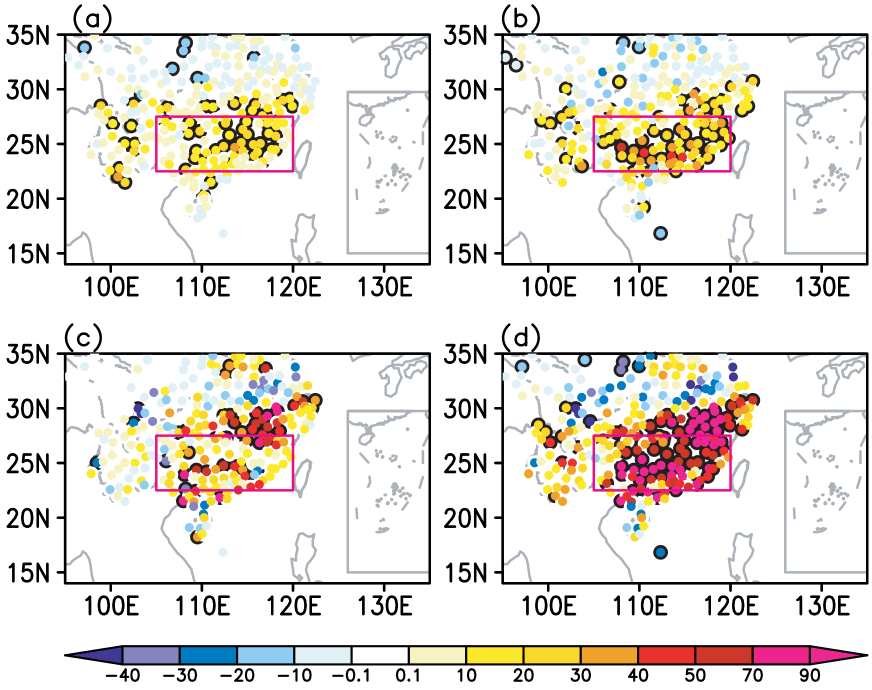

Fig. 10. The same as Fig. 5 except for non-TC induced rainfall.

China Sea TCs around 1993 cannot be explained by these changes. Notably, the increase in 850-hPa anticyclonic vorticity is consistent with low-level anticyclonic wind change, and the decrease in 600 hPa relative humidity is consistent with the weakening of ascent motion after 1993, as documented by Wu et al. (2010).

Another factor for the enhanced TC activity in the South China Sea is the SST change. As shown in Wu et al. (2010), the SST increased in the South China Sea around 1993. This increase is attributed to anomalous descent over the South China Sea, which is induced by anomalous heating over the tropical Indian Ocean associated with *in situ* oceanic warming (Zhan et al., 2011a, b). While the interdecadal SST increase in the South China Sea was observed through the year, the TC increase was obvious only in summer. The anomalous descent over the South China Sea formed a north–south contrast with anomalous ascent over southern China (Wu et al., 2010). Thus, the anomalous circulation change accompanying the summer rainfall increase in southern China may make an additional contribution to the South China Sea SST increase, especially in late summer. The SST increase, in turn, provides a favorable condition for more TC formation in the South China Sea. These TCs bring more rainfall to southern China and contribute to the increase in southern China rainfall. Thus, there appears to be a positive feedback of TCs to the interdecadal rainfall increase in southern China. Notably, a regional climate model simulation obtained a pronounced increase in the South China Sea TC occurrence when the atmospheric CO_2 concentration was set at 6 times the present-day value (Stowasser et al., 2007).

To assess the synthesized importance of various factors in TC genesis, Emanuel and Nolan (2004) developed a genesis potential index (GPI). We have estimated the GPI difference between 1983–1992 and 1993–2002 and the contributions of different parameters: potential intensity (PI), vertical wind shear, absolute vorticity, and relative humidity. The contribution of different factors was estimated by considering the change only in one parameter with the other parameters set at the climatological mean values, following previous studies (e.g., Camargo et al., 2007). The results indicate an increase of PI over the South China Sea. However, the GPI increase was only found north of 18°N. This may suggest that either the GPI cannot properly represent the TC change over the South China Sea or that some unknown factors were involved.

5. Discussion and summary

Our analysis shows that the summer rainfall increase in southern China around 1993 included rain in all rain categories. In comparison, the contribution from the heavy rain category was large, accounting for ∼ 40%, and that from the light rain category was relatively small.

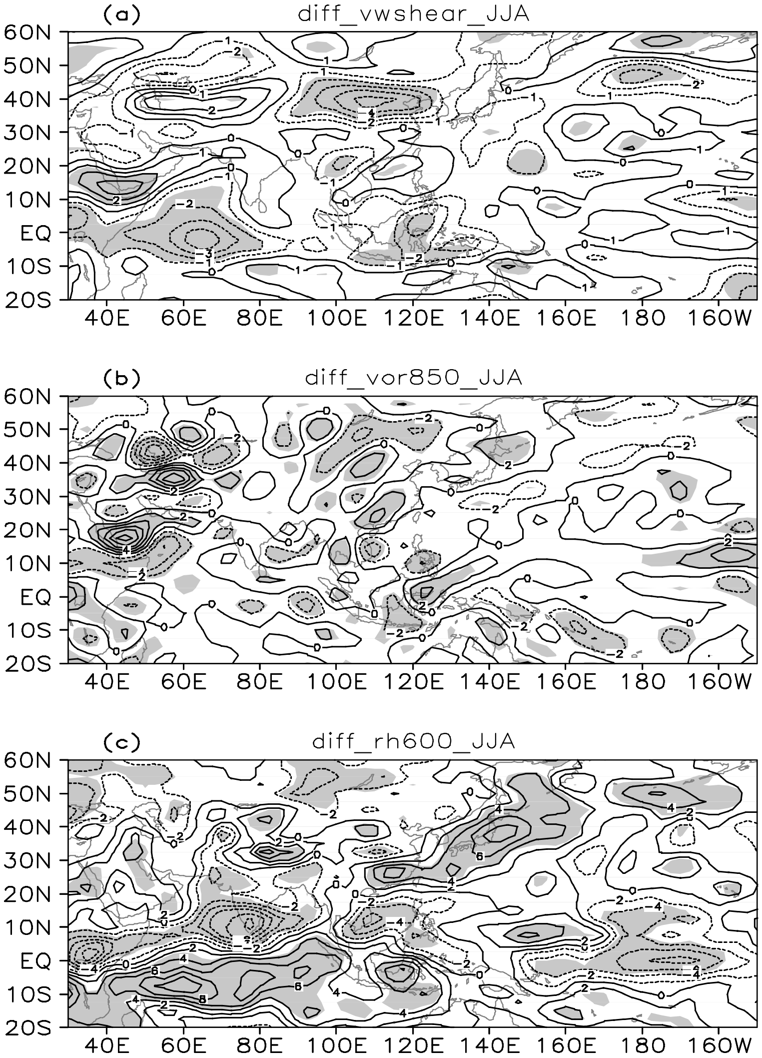

Fig. 11. Difference as 1993–2002 mean minus 1983–1992 mean of summer vertical wind shear (m s^{-1}) between 200 hPa and 850 hPa (a), relative vorticity (10^{-6} s^{-1}) at 850 hPa (b), and relative humidity (%) at 600 hPa (c). The contour interval is 1 m s^{-1} in (a), 2×10^{-6} s^{-1} in (b), and 2% in (c). The shadings denote differences significant at the 90% confidence level according to the Student's *t*-test.

The increase in the number of TCs in the South China Sea in summer led to an increase in the TC-induced southern China summer rainfall. This TC-induced rainfall contribution was seen in all the rain categories, but with larger contribution from heavy rain. The TC-induced rainfall increase in the South China Sea contributed ~ 30% to the total increase in the coastal regions.

The increase in the number of South China Sea TCs may be attributable to an increase in local SST induced by anomalous descent accompanying the warming of the tropical Indian Ocean. Other factors may have also contributed to the South China Sea TC increase. The couplet of anomalous vertical motion between northern South China Sea and southern China suggests an interaction between the interdecadal rain and circulation changes and the South China Sea TC changes. Anomalous ascent over southern China was accompanied by anomalous descent over the South China Sea, which reduced cloud amount and enhanced downward shortwave radiation, thus leading to an increase in SST in the South China Sea. The warmer SST favors formation of more TCs that subsequently bring more rain to southern China, enhancing the rainfall increase. This positive feedback might be disrupted when other factors come into play for the TCs in relation to large interannual variations.

The overall contribution of TC-induced rainfall was largest near the coast and decreased towards inland. Thus, non-TC rainfall in relation to low-frequency circulation change was the major reason for increase in summer rainfall in southern China around 1993 away from the coast. While the TC-induced rainfall increase only accounts for a limited percent of the total rainfall increase, its impact may have been amplified through circulation–rainfall interaction. For example, the enhanced southern China rainfall increase due to TCs may have intensified anomalous descent and low-level divergent winds, which in turn may have enhanced low-level wind convergence over southern China, further increasing rainfall amounts.

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