Observed changes in precipitation extremes and effects of tropical cyclones in South China during 1955–2013

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Daily precipitation data from 21 Chinese Surface Stations for Global Exchange in South China and historical tracks of tropical cyclones (TCs) from International Best Track Archive for Climate Stewardship (IBTrACS) during 1955–2013 are analysed to study changes in extreme precipitation and TC-related precipitation with respect to global mean temperature. On annual and seasonal bases, there have been significant enhancements in heavy precipitation and suppressions of light and moderate precipitation under global warming conditions. Except in winter, the enhancements in heavy precipitation dominate over the suppressions of light and moderate precipitation, leading to increases of seasonal total precipitation. A significant increase of consecutive dry-day episodes has been observed, especially in winter and early spring, which is detrimental to spring planting. The top 10% heavy precipitation associated with TCs has increased significantly under global warming conditions, despite a reduction in TC frequency. Finally, we find that TC-related precipitation per TC storm in South China has increased by an alarming rate of about 50% during the period of 1955–2013.

KEYWORDS
- global warming, precipitation extremes, seasonal asymmetry, South China, tropical cyclone

INTRODUCTION

As the climate warms, enhancements of heavy precipitation and suppressions of light and moderate precipitation have been observed in widespread regions in both observations (Karl and Knight, 1998; Manton et al., 2001; Fujibe et al., 2005; Liu et al., 2005; Goswami et al., 2006; Qian et al., 2007; Wang and Zhai, 2008; Liu et al., 2009; Lau and Wu, 2011; Shiu et al., 2012; Wu and Fu, 2013; Jiang et al., 2014; Liu et al., 2015; Liu et al., 2016) and climate models (Sun et al., 2007). The increase of heavy precipitation is likely to accelerate surface runoff and exacerbate the risk of floods and mudslides, while the reduction in light and moderate precipitation, which is the main source of soil moisture, may increase the risk of occurrence and severity of droughts.

Trenberth et al. (2003) hypothesized that if everything else remains the same, the precipitation of a storm would increase with temperature at the same rate as the saturation vapour pressure in a warming climate, that is, by 7% K$^{-1}$ according to the Clausius–Clapeyron equation. The precipitation intensity could even exceed the 7% K$^{-1}$ because additional latent heat released from the increased water vapour could invigorate the storm and pull in more moisture from the boundary layer, forming a positive feedback cycle and leaving less moisture available for light and moderate precipitation. In addition, a reduced lapse rate in a warmer climate (Held and Soden, 2006; Dessler and Davis, 2010) can make the atmosphere more stable and thus less likely to precipitate, especially for light and moderate precipitation that requires an unstable large-scale environment (Dai et al., 2002; O’Gorman and Schneider, 2009; Shiu et al., 2012).
For changes of seasonal precipitation, a tendency for wet (dry) seasons to get wetter (drier) over climatologically rainy (dry) regions has been seen in both model (Chou and Lan, 2012) and observations (Chou et al., 2013). This enhancement of precipitation asymmetry between wet and dry seasons has been observed over most areas of the world, especially for the regions with distinct wet and dry seasons (Chou and Lan, 2012). On the other hand, Liu et al. (2016) suggested that changes of regional precipitation are primarily driven by the changes in the top 30% heavy precipitation events in the context of global warming, which also implies an enhancement of precipitation asymmetry because the top 30% heavy precipitation mostly occurs in the wet seasons.

South China, one of the regions with abundant precipitation in China (Zhai et al., 2005; Chen et al., 2009; Ren et al., 2015), has a bimodal distribution of precipitation, with peaks in April, May, June and in July, August, September, respectively. This precipitation distribution forms a distinct asymmetry seasonal cycle of precipitation with the ratio of precipitation between wet (April–September) and dry (December–March) seasons at 5.47 (Table 1). This large asymmetry contributes significantly to the frequent floods and droughts in south China (Liu et al., 2005; Xu and Li, 2011; Li et al., 2012).

The precipitation in April–June in South China is mainly composed of frontal rainfall, impacted by North Pacific Subtropical High and East Asian monsoon (Gao et al., 2013; Zhang et al., 2017), contributing about 40.8% of annual precipitation, while the precipitation over the period of July–September, the most active period of summer monsoon and TCs (Chang et al., 2012), accounts for 36.4% to annual total precipitation (Supporting Information Figure S1) (Wu et al., 2007; Gao et al., 2013; Wang et al., 2015b). Furthermore, Wang et al., 2015b have indicated that the decadal variations of summer precipitation in south China are closely correlated with the South Asian summer monsoon, the West Pacific Subtropical High and the indirect impacts of the Pacific SST and snow cover on the Tibetan Plateau. An abrupt eastward (westward) shift in the western North Pacific subtropical high is associated with extreme dry (wet) episodes, generally leading the extreme negative (positive) precipitation anomaly in south China (Mao et al., 2010; Gao et al., 2013). The West Siberia Low is also important to heavy precipitation (Fang et al., 2012).

Precipitation of tropical cyclones (TCs) accounts for 20–40% of total precipitation, but about 60% of heavy precipitation (Ren et al., 2006; Wu et al., 2007; Chang et al., 2012; Zhang et al., 2013). However, various studies both from observational perspectives and models, indicate that the frequency of TCs has significantly decreased with global warming in South China (Ren et al., 2002; Wu et al., 2005; Wu et al., 2007; Ying et al., 2011; Chang et al., 2012), and in western North Pacific (WNP) (Bengtsson et al., 2007; Gualdi et al., 2007; Lau and Zhou, 2012; Walsh et al., 2016). In WNP, a tendency of decreased but more intense TCs has been observed due to the rise of the static stability, the reduction of vertical circulation and the more energy as temperature and water vapour increase (Bengtsson et al., 2007; Gualdi et al., 2007).

Considering the importance of seasonal precipitation asymmetry in South China, it is of interest to see how this asymmetry changes with global temperature. Here, we examine how the seasonal precipitation asymmetry changes during 1955–2013, what mechanism is the primary driver and its impact on local hydrologic risks. Section 2 describes the data and methods used. Section 3 presents the seasonal changes of total precipitation and their influence on south China as global temperature has risen, and the quantitative contribution of TC-related precipitation to total precipitation has also been discussed. Summaries are given in Section 4.

### TABLE 1 Changes of precipitation intensity for total and TC-related precipitation

| Period | Types | Long-term average [mm] | Changes of precipitation [mm/K] |
|--------|-------|------------------------|---------------------------------|
|        |       |                        | Total                           |
|        |       |                        | Bottom 80%                      |
|        |       |                        | Top 20%                         |
| Annual | TP    | 1,616.0                | +62.4 ± 28.4**                  |
|        | TCP   | 280.7                  | −38.8 ± 21.9                     |
|        |       |                        | +101.2 ± 11.6***                 |
|        |       |                        | −67.6 ± 15.6***                  |
|        |       |                        | −89.9 ± 9.3***                   |
|        |       |                        | +22.3 ± 7.7***                   |
| AMJ    | TP    | 660.9                  | +28.3 ± 18.0                    |
|        | TCP   | 35.4                   | −0.7 ± 13.4                     |
|        |       |                        | +29.0 ± 6.9***                   |
|        |       |                        | −21.1 ± 6.5***                   |
|        |       |                        | −17.5 ± 4.2**                    |
|        |       |                        | +3.6 ± 3                         |
| JAS    | TP    | 587.6                  | +23.9 ± 18.2                    |
|        | TCP   | 208.8                  | −5.7 ± 13.6                     |
|        |       |                        | +29.6 ± 7.0***                   |
|        |       |                        | −59.0 ± 13.1***                  |
|        |       |                        | −66.2 ± 8.8***                   |
|        |       |                        | +7.2 ± 5.7                       |
| ON     | TP    | 139.0                  | +18.3 ± 10.3                    |
|        | TCP   | 35.6                   | −15.6 ± 7.8                     |
|        |       |                        | +33.9 ± 4.1***                   |
|        |       |                        | +21.3 ± 3.2**                    |
|        |       |                        | +4.5 ± 3.6                      |
|        |       |                        | +25.8 ± 3.3***                   |
| DJFM   | TP    | 228.4                  | −8.0 ± 12.9                     |
|        | TCP   | 0.9                    | −26.8 ± 7.9***                   |
|        |       |                        | +18.7 ± 5.9***                   |
|        |       |                        | −1.4 ± 3.4                       |
|        |       |                        | +0.5 ± 1.7                       |
|        |       |                        | −1.8 ± 1.0*                     |

Note. Thresholds of the bottom 80% and top 20% of total precipitation (TP) and TC-related precipitation (TCP) are shown in Table S1. Changes followed by *, **, *** are significant at 90, 95, 99% confidence level, respectively.
(available at http://data.cma.cn/en/?r=data/detail&dataCode= SURF_CLI_CHN_MUL_DAY_CES_V3.0). The dataset has been quality controlled, and the quality and integrity of the various elements in version 3.0 has been improved and the availability of various weather elements is generally above 99%. There are 21 stations in South China (including Guangxi Province, Guangdong Province, Fujian Province and Hainan Province) shown in Figure S2. The annual average of global temperature anomaly is from National Climatic Data Center (NCDC) (available at https://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytld/12/1955-2014). The TCs historical tracks are taken from International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010).

Ten categories of precipitation with increasing intensities are calculated by dividing the 59 years (1955–2013) average spectrum of precipitation into 10 categories with equal precipitation amount. Thresholds for the 10 intensity categories of each season and annual precipitation are listed in Table S1. An interannual difference method (IDM) which has been used successfully before (Liu et al., 2009; Shiu et al., 2012; Liu et al., 2016) is adopted here to evaluate the correlation between the precipitation and global temperature. A key approach of IDM is that differences of precipitation amount (dP) and annual global temperature (dT) between any 2 years (not just adjacent years) in 1955–2013 are included to obtain better statistical results for the correlation (Liu et al., 2016). The slope of the linear regression (dP/dT) is interpreted as the change of precipitation intensity as a function of global temperature. Due to the subtropical seasonal distribution of precipitation in south China (Chen et al., 2009; Gao et al., 2013; Wang et al., 2015b Wu et al., 2007), the seasons in this study are defined as April–June, July–September, October–November, and December–March.

The Objective Synoptic Analysis Technique (OSAT) developed by Ren et al. (2007) is adopted to estimate the historical track of TCs and partition the TC-related precipitation from total precipitation. Based on the structure of the daily precipitation distribution, South China is separated into several independent rain belts and then the TC rain belt is singled out according to the intensity and position of a given TC and the distance between the TC centre and the rain belt (Ren et al., 2007).

3 | RESULTS AND DISCUSSION

3.1 | Changes of precipitation intensity

Changes of annual and seasonal precipitation intensity in 10 categories as a function of annual global temperature (i.e., dP/dT) calculated by IDM and the linear time series method (LTSM) are shown in Figure 1a and b, respectively. There is an obvious consistency between Figures 1a and b. Since the LTSM filters out nonlinear temporal variations in both the precipitation and the global temperature, the consistency between Figure 1a and b implies that the changes in precipitation in South China with respect to global temperature are dominated by the long-term trends. The difference between Figure 1b and c suggests that global temperature oscillations induced by internal variabilities and dynamic conditions affect the precipitation intensity in a significant different way from the global warming, although retain some of the general characteristics of increase in heavy precipitation and reduction in light precipitation. Figure 1a and b depicts a general feature of relatively large enhancements of top two categories of heavy precipitation, and moderate reductions in light precipitation of the bottom three categories. This feature is consistent with the theory summarized by Trenberth et al. (2003). In addition, it agrees well with observations analysed in a number of previous studies in China (Liu et al., 2005; Qian et al., 2007; Wang and Zhai, 2008; Liu et al., 2009; Wu and Fu, 2013; Jiang et al., 2014; Liu et al., 2015). Specifically, increase in the top 10% heavy precipitation in annual total, April–June, July–September, October–November and December–March are 75.7 mm/K (46.9% K⁻¹), 23.3 mm/K (35.2% K⁻¹), 14.5 mm/K (24.7% K⁻¹), 25.2 mm/K (181.6% K⁻¹) and 14.4 mm/K (63.1% K⁻¹), respectively. While decreases in the bottom 30% light precipitation in annual total, April–June, July–September, October–November and December–March are 69.0 mm/K (14.2% K⁻¹), 20.2 mm/K (10.2% K⁻¹), 16.6 mm/K (9.4% K⁻¹), 13.1 mm/K (31.5% K⁻¹) and 17.5 mm/K (25.6% K⁻¹), respectively. Considering the fact that annual global temperature has increased by about 0.8 K since 1955 (Figure S3), these changes in the top 10% heavy precipitation and bottom 30% light precipitation which have practically already occurred are alarmingly large, especially in terms of percentage changes. A comprehensive assessment of their impacts on the environment, particularly on possible increased risk of floods and droughts, is imperative.

Results shown in Figure 1a are derived from correlation analysis of observations (hereafter denoted as raw data) of precipitation and global temperature during the period of 1955–2013, which include the effects of both long-term linear trends for the entire period of 1955–2013 (Figure S3) and short-term interannual variabilities. A critical test of the robustness of the results of Figure 1a is to use detrended data (Figure S3) from which all linear trends of raw data are removed. Figure 1c shows the interannual response of precipitation intensity in South China with respect to short-term interannual variation of global temperature anomaly. The general feature of a relatively large enhancement of top 10% category of heavy precipitation and moderate reductions in light precipitation of the bottom three categories in Figure 1a remains visible in Figure 1c. Increases in the top 10% heavy precipitation based on detrended data are consistent with those based on raw data except for October–November.
Suppressions of the bottom 30% precipitation are also consistent with those of raw data except for July–September. Nevertheless, there are significant differences between Figure 1c and a. The major differences are:

1. All 10 precipitation intensity categories of October–November become negative for detrended data.
2. All 10 categories of July–September become positive.
3. The ninth category of precipitation intensity turns from all positive to mostly negative.

All three differences are likely due to removal of long-term trends of precipitation affected by tropical cyclones which will be addressed in Section 3.3.

The change of seasonal precipitation asymmetry can be seen in Table 1. The total precipitation increases by 52.2 mm/K (4.2% K\(^{-1}\)) in wet seasons (April–June and July–September), and decreases by 8.0 mm/K (3.5% K\(^{-1}\)) in dry season (December–March), respectively. The ratio of total precipitation between wet and dry seasons enhances marginally from 5.47 to 5.90. This enhancement is consistent with the tendency for wet seasons to get wetter suggested by Chou et al. (2013). However, the increase in total precipitation of wet seasons is not significant at 90% confidence level, nor is the decrease in dry season.

Table 1 shows that the increases in top 20% heavy precipitation are significant at 99% confidence level on both annual and seasonal bases. On the annual basis, the increase in heavy precipitation is more than twice of the reduction in light and moderate precipitation, resulting in a significant increase in the annual total precipitation of about 62.4 mm/K. In other words, the change of annual total precipitation is mainly driven by the considerable increase of heavy precipitation. This is consistent with the finding of
Liu et al. (2016) in which they argued that under global warming condition the trend of regional annual precipitation is primarily driven by the change of top 30% heavy precipitation. In wet seasons, there is a large increasing trend in the heavy precipitation (top 20%), and a small decreasing trend in the light and moderate precipitation (bottom 80%), resulting in an increase in the total precipitation at a rate of 28.3 mm/K in April–June and 23.9 mm/K in July–September (Table 1). Thus, the changes in total precipitation in wet seasons are also dominated by substantial enhancements of heavy precipitation in a warmer climate. In dry seasons, increases in heavy precipitation and decreases in light and moderate precipitation can also be seen in Table 1. However, the dominance of heavy precipitation over light and moderate precipitation is absent in December–March, apparently because the top 20% heavy precipitation of December–March is only moderate as measured by the threshold of annual precipitation (Table S1).

Remarkably, the increase in top 20% heavy precipitation in October–November (33.9 mm/K) is even higher than that in wet seasons (Table 1). The difference is particularly drastic in terms of percentage changes (121.9% K$^{-1}$) because the precipitation in this season is substantially smaller. The larger increase of heavy precipitation is caused by an increase in precipitation of TCs in October–November (Table 1). The impact of TCs on precipitation intensity will be elaborated further in Section 3.3.

### 3.2 Impacts of changes in precipitation intensity

Figure 2a shows the variation in days of annual bottom 10% precipitation, days of annual top 10% precipitation and annual non-precipitation days (< 0.1 mm/day) as a function of annual global temperature. All linear regressions in Figure 2a are significant at 95% confident level. Specifically, the annual days of top 10% precipitation have an increasing trend of 0.38 day/K (37.2% K$^{-1}$, relative to the multiyear mean); the annual days of the bottom 10% precipitation have a decreasing trend of 17.5 day/K (19.3% K$^{-1}$); while the annual non-precipitation days have an increasing trend of 18.8 day/K (8.6% K$^{-1}$). The changes of days of bottom 10% precipitation (17.5 day/K) is about one order of magnitude higher than the variations in days of other precipitation intensity categories (−1.65~0.27 day/K), contributing about 93.1% of the decrease of precipitation days (increase of non-precipitation days). In particular, there is a remarkably high anti-correlation coefficient of −0.92 between the days of bottom 10% precipitation and the number of non-precipitation (Figure S4). It indicates that the increase of annual non-precipitation days, to a large extent (over 90%), are resulted from the reduction in annual days of bottom 10% precipitation. This is in excellent agreement with the finding of Liu et al. (2015) for eastern China. In fact, it can be logically understood as the category of non-precipitation day is theoretically the lightest category in the precipitation intensity spectrum, a shift in light precipitation toward heavy precipitation leave more non-precipitation days (Liu et al., 2015).

Changes in the number of dry episodes with consecutive non-precipitation days equal or greater than 5, 10, 15, 20 and 25 days (denoted as ND5, ND10, ND15, ND20, ND25, respectively) as a function of annual global temperature are shown in Figure 2b. Remarkably, in a warmer climate, there are significant increases of dry episodes, especially for dry episodes more than 15 days in October–November and December–March. In addition, there is a strong anti-correlation between the number of dry episodes more than 15 days and days of bottom 10% precipitation in October–November and December–March (R$\sim$0.67−0.73, significant at 99.9% confident level) (Table S2). Days of bottom 10% precipitation in October–November and December–March have decreasing trends of 3.9 day/K (40.2% K$^{-1}$) and 4.6 day/K (18.3% K$^{-1}$), respectively, both at 95% confidence level. The higher occurrence of dry episodes in October–November and December–March may have a serious detrimental impact on agriculture and even the entire ecosystem as the dry episodes occur in the early growing season (Wang et al., 2015a).

### 3.3 Changes in TC-related precipitation

We have calculated TC-related precipitation by applying OSAT on the historical tracks based on IBTrACS-ALL data.
The annual average number of TCs affecting precipitation in South China is about 15.7, and the majority of them (82.2%) occur in July–November. These values are in good agreement with findings of Ren et al. (2006). A significant decreasing trend (−7.4 K−1) in yearly TC frequency as a function of global temperature can be seen in Figure 3, also consistent with results of previous studies (Ren et al., 2006; Ying et al., 2011; Lau and Zhou, 2012). In comparison, the number of TCs in July–September decreases at a rate of about −6.1 K−1, while no significant change of TC frequency can be observed in October–November. However, the mechanism of the seasonal variation in TCs frequency between July–September and October–November is still not clear. Long-term average of the annual TC-related precipitation is 280.7 mm (17.4% of the annual total precipitation) which is slightly less than the ratio of 20–40% reported by Ren et al. (2006). The difference is probably due to different locations and time periods. There is a substantial reduction of annual TC-related precipitation (−67.6 mm/K or −24% K−1) under global warming conditions, especially in July–September (−59 mm/K or −28% K−1), which can be attributed to the decrease in the TC frequency (Figure 3). The contribution of the TC-related precipitation to total precipitation decreases by 5.5% K−1 on the annual basis; and it decreases as much as 12.7% K−1 in July–September (Table 1). But in October–November, because of an increase in precipitation per TC (Figure 4b) and no change in TC frequency, the amount of TC-related precipitation and its contribution to total precipitation increase by 21.3 mm/K (83% K−1) and 15% K−1, respectively. The reductions in TC-related precipitation and TC frequency on annual basis and in July–September are consistent with reductions found previously in Hainan province (Wu et al., 2007), South China Sea (Wu et al., 2005; Ren et al., 2006) and Northwestern Pacific (Lau and Zhou, 2012).

Figure 4a shows changes in the intensity of TC-related precipitation in South China as a function of global temperature calculated by IDM. The thresholds of TC-related precipitation intensity categories are shown in Table S1. Remarkably, despite the reduction in TCs frequency, the top 10% heavy precipitation associated with TCs increases significantly. This lends a strong support for the positive feedback cycle of temperature-water vapour-latent heat under the global warming conditions (Trenberth et al., 2003; Liu et al., 2016). The bottom 90% precipitation decreases with global temperature, primarily because of a reduction of TCs frequency at a rate of 47.1% K−1 annually and 48.8% in July–September (Figure 3). This is evident in Figure 4b in which the TC-related precipitation is normalized by the TC number. In this figure, the general feature of relatively large enhancements in heavy precipitation categories and small reductions in light precipitation categories (similar to Figure 1a) emerges. In addition, Figure 4b indicates that TC-related precipitation would increase considerably if TC frequency stays the same in South China under global warming conditions in 1955–2013. This also implies that TC-related precipitation of each TC has increased considerably (about 50%) in South China during the period of 1955–2013.

Contributions of TC-related precipitation to total precipitation occur mainly at the top 10% precipitation, about 63.0% and 59.4% in July–September and October–November, respectively. This is in good agreement with the value of 60% in Hainan province reported in Wu et al. (2007). Comparing the changes of top 10% precipitation in Figures 1a and 4a, over half of the increases of top 10% heavy precipitation during July–September and October–November can be attributed to the TC-related precipitation. In fact, TC-related precipitation in October–November contributes an astonishing 95.2% to the increase of top 10% precipitation.

4 | SUMMARY

The daily station observations of precipitation from CMDC and historical tracks of tropical cyclones from IBTrACS in
South China during 1955–2013 have been analysed to explore the annual and seasonal changes of precipitation extremes and TC-related precipitation in the context of global warming. It indicates that the changes of precipitation with respect to global temperature is controlled by the long-term trend and large enhancements of heavy precipitation and moderate reductions of light precipitation have been observed. Furthermore, the greater increases in heavy precipitation, at 99% confidence level in both wet and dry seasons, lead to the enhancements of total precipitation.

Changes in the days of annual top 10% precipitation, bottom 10% precipitation and the non-precipitation days are 0.38 day/K (37.2% K$^{-1}$), $-17.5$ day/K ($-19.3$ K$^{-1}$) and 18.8 day/K (8.6% K$^{-1}$), respectively. There is an obvious cause–effect relationship between changes in the number of days of bottom 10% precipitation and non-precipitation days. There are significant increases of dry episodes with consecutive non-precipitation days in a warmer climate, especially for episodes of more than 15 days in dry seasons.

A significant decrease of the annual TC-related precipitation under global warming has been observed, which is mainly associated with a reduction of TC frequency. The contribution of TC-related precipitation is mainly concentrated on the top 10% precipitation, about 63.0 and 59.4% in July–September and October–November, respectively. Furthermore, over half of the increase in the top 10% total precipitation can be attributed to the precipitation associated with TCs, the proportion can be even 95.2% in October–November. Finally, we find that TC-related precipitation would increase considerably if TC frequency stays the same in South China under global warming conditions in 1955–2013. This also implies that TC-related precipitation of each TC has increased considerably (about 50%) in South China during the period of 1955–2013.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

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