



Changes in tropical cyclone precipitation over China

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[1] The Tropical Cyclone (TC) Precipitation (TCP) is partitioned from the station observations in China using the Objective Synoptic Analysis Technique (OSAT). The TCP spatial distribution, its ratio to total annual rainfall, the changes in the TCP volume, and the annual frequency of the torrential TCP events during the period 1957–2004 are examined with a focus on their long-term trends in this study. Tropical cyclones significantly contribute to the annual rainfall in southern, southeastern, and eastern China, including Taiwan and Hainan islands. The TCP in most of the southeastern coastal regions can be more than 500 mm a year, accounting for 20–40% of the total annual precipitation. Together with interdecadal and interannual variations, significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years. The downward trends were accompanied with the decreases in the numbers of TCs and typhoons that affected China during the period 1957–2004. These changes strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP. **Citation:** Ren, F., G. Wu, W. Dong, X. Wang, Y. Wang, W. Ai, and W. Li (2006), Changes in tropical cyclone precipitation over China, *Geophys. Res. Lett.*, *33*, L20702, doi:10.1029/2006GL027951.

1. Introduction

[2] For more than a decade, the importance of analyzing changes in temperature and precipitation extremes has been realized and extensive analyses were carried out [*Intergovernmental Panel on Climate Change (IPCC)*, 2001]. Recently, an effort was made to design a realistic global distribution of extreme indices [*Alexander et al.*, 2006]. While changes in tropical cyclone (TC) activity have drawn more and more attention, a few studies have addressed the precipitation associated with TCs [*IPCC*, 2002] either in climate models or in observations. *Harr and Elsberry* [2001] analyzed TC structural characteristics during extratropical transition as they related to expansion of torrential precipitation regions. *Shuman et al.* [2001] studied torrential precipitation events from TC remnants in the eastern United States. A. G. Laing (Satellite estimates of tropical cyclone precipitation using TRMM, GOES, and

SSM/I, unpublished manuscript, 2001) carried out satellite estimates of TC precipitation (TCP) using Tropical Rainfall Measuring Mission (TRMM), Geostationary Operational Environmental Satellites (GOES), and Special Sensor Microwave Imager (SSM/I) data sets. Meanwhile, by simply defining TCP as that within a radius of 1000 km from the center of a TC, *Hasegawa* [2005] studied TC and TC torrential precipitation over the western North Pacific (WNP) in present and doubled CO₂ climates simulated by climate models. *Englehart and Douglas* [2001] explored the role of tropical storms over the eastern North Pacific in the rainfall climatology of western Mexico by defining TCP as that within a radius of 550 km from the center of a TC. Using an objective analysis technique, *Ren et al.* [2002] and *Gleason et al.* [2000] analyzed the climate characteristics of TCP in China and the United States, respectively.

[3] Some studies indicate that there was no statistically significant long-term trend in both the number and the intensity of TCs in WNP over the past 4–5 decades [*IPCC*, 2001; *Yeung et al.*, 2005; *Chan and Shi*, 1996]. However, two recent studies argued that TC intensity has increased markedly in recent decades [*Emanuel*, 2005; *Webster et al.*, 2005]. In addition, *Wu et al.* [2005] found that the TC influence on the South China Sea has considerably decreased and the two prevailing typhoon tracks in the WNP have shifted westward over the past four decades, leading to increasing typhoon influence over the subtropical East Asia. However, little is known about the influence of the documented intensity and track changes on TCP.

[4] Several discontinuous spiral rain belts often occur in a TC, which are generally asymmetric around the TC center [*Elsberry et al.*, 1987]. Therefore, simply using the distance between station location and TC center location, namely a circle around the TC center, cannot accurately catch TCP. Recently, an advanced technique named the Objective Synoptic Analysis Technique (OSAT), which is capable of partitioning TCP in China, has been proposed [*Ren et al.*, 2006].

[5] In the present study, we use the TC track data set and a station precipitation data set to examine the climatological characteristics of TCP, with special focus on its long-term changes and TC-induced torrential precipitation events in China.

2. Data

[6] The information about the WNP TC positions used in this study is from Shanghai Typhoon Institute of China Meteorological Administration (CMA). The data set ranges from 1949 to 2004 and is believed to be more accurate for those TCs that affected China because the positions have been carefully validated. The daily precipitation data set used in this study includes 677 stations in China that

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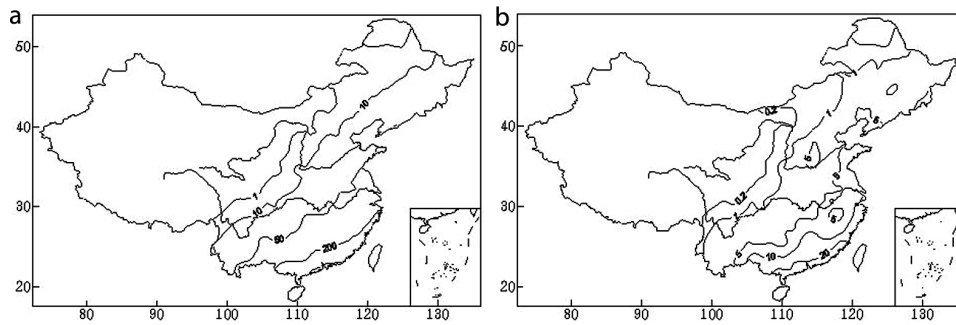


Figure 1. Climatology station observations of TC precipitation during 1971–2000: (a) spatial distribution of the average annual TC precipitation (mm) and (b) spatial distribution of the ratio of average annual TC precipitation to average total rainfall.

represented the spatial distribution of precipitation in China, in which 659 stations are over the mainland of China and the Hainan Island from National Meteorological Information Center/CMA and the other 18 stations are in the Taiwan Island. A close inspection of the data set reveals that time coverage of the daily precipitation for the 659 stations ranged from 0UTC to 24UTC, and the number of stations increased sharply from about 170 in 1951 to about 570 in 1957. Since the number of stations can affect the results of the estimated TCP, the period 1957~2004 is selected as the period for analyzing long-term trend in TCP.

3. Analysis Method

[7] The TCP can result from the TC eye wall and spiral rainbands, and from the interactions between the TC circulation and other weather systems. The spiral rainbands are generally asymmetric with respect to the TC center. The OSAT imitates the analysis procedure taken by an operational weather forecaster. There are two steps: First, based on the spatial structure of the observed station precipitation, all of the precipitation observations can be grouped into different rain belts. Then, given the distances between a station and the TC center, between the precipitation center of the rain belt which includes the station and the TC center, and the distance function between the TC center and the distribution of the rain belt, one can identify whether the station precipitation is TCP by comparing these distances with the specified TC maximum size (D_1) and minimum size (D_0) [Ren et al., 2006]. In this study, D_0 and D_1 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 given as the maximum radius for a TC outlet [Brand, 1972; Elsberry et al., 1987], respectively.

[8] In this study, a TC is defined as an influencing TC when its rain belt is over the mainland of China or any of the two biggest islands of China, Taiwan, and Hainan. The influencing TCs include landfall TCs and those passing offshore around China.

[9] The rainfall data are interpolated on $0.5^\circ \times 0.5^\circ$ latitude-longitude grids to calculate the rainfall volume for a TC. Inverse-distance interpolation was applied to transform the TC rainfall data. To limit the possible expansion of the TC rain belt, the gridding procedure is limited to the rain

belt region. The area represented by a given grid can be calculated as,

$$A_{\text{grid}} = (\pi r / 360)^2 \times \cos(\varphi), \quad (1)$$

where r is the radius of the Earth, φ is the latitude of the grid, and A_{grid} is in km^2 .

[10] The rainfall volume for a given grid can be

$$V_{\text{grid}} = A_{\text{grid}} \times P_{\text{grid}} \times 10^{-6} \quad (2)$$

where P_{grid} is the grid precipitation in mm, V_{grid} is in km^3 . The TCP volume is the total of the grid rainfall volume (V_{grid}) in the TC rain belt.

4. Results and Discussion

[11] Figure 1a presents the distribution of the annual mean TCP averaged over 1971–2000. TCs mainly influenced central and eastern China, roughly east of 98°E . Generally, annual TCP above 200 mm is observed in the southeastern coastal regions including the Taiwan, and Hainan Islands. Significant TCP usually occurred in the mountainous regions, which is not shown in Figure 1a. The annual TCP exceeds 500 mm in central-eastern Taiwan, central-eastern Hainan and along the eastern coastline in South China. Some Taiwan stations received 1000~1350 mm annual TCP. The TCP decreased northwestward quickly, with values less than 10 mm in northern and western parts of the TC influenced region, while the annual TCP was 50~200 mm in the lower valley of the Yangtze River, most regions south of the middle and lower valleys of the Yangtze River.

[12] Figure 1b shows the distribution of the ratio of annual TCP to total annual rainfall averaged over the period 1971–2000. In Taiwan, Hainan, the southeastern coastal regions, and the easternmost Shandong Peninsula, TCP contributes more than 10% precipitation, with 20~30% in most of Taiwan, the coastline south of 25°N , and 30~40% in most of Hainan and locations of Taiwan and the coastline. In southernmost Taiwan and westernmost Hainan, TCP accounts for 40–45% of the total precipitation. Meanwhile, the ratios decrease northwestward quickly, with values less than 1% in northern and western parts of the TC influenced region.

[13] Figure 2a displays time series of the total annual TCP volume for China. First, a downward linear trend can

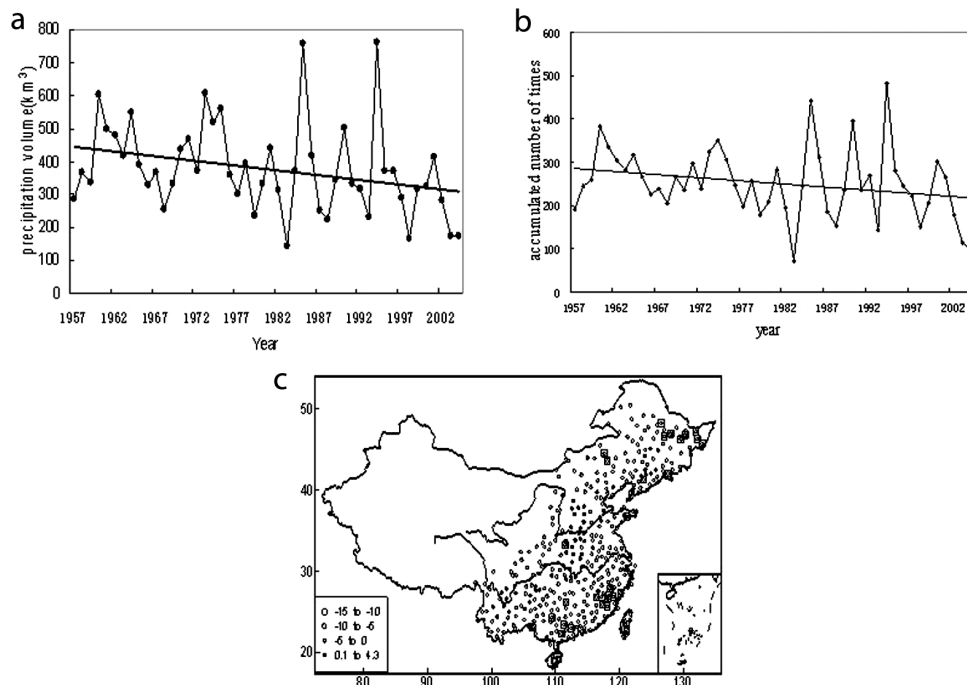


Figure 2. Variations of TC precipitation: (a) total annual volume of TC precipitation for China (km^3) and (b) accumulated number of times with torrential TCP events (≥ 50 mm/day) for individual stations. (c) Spatial distribution of trends in annual typhoon precipitation (mm/yr). Square boxes indicate decreasing trends are statistically significant at 0.05 level by the Kendall test.

be found during 1957~2004, with a rate of $-3.0 \text{ km}^3/\text{yr}$. A Kendall test indicates that the trend is statistically significant (0.01 significance level). Second, the TCP includes interdecadal variation and prominent year-to-year fluctuations. In the early 1960s, early 1970s, 1985, and 1994, China received much above-normal TCP, with maximums of 761.3 km^3 and 759.2 km^3 in 1994 and 1985, respectively. Meanwhile, in the late 1960s, 1983, and 1998, much below-normal TCPs were observed in China, with minimum of 141.8 km^3 in 1983.

[14] Figure 2b presents variations of the total annual frequency of the torrential TCP events (≥ 50 mm/day) for individual stations. A significant (0.05 level) decreasing trend can be clearly seen with similar interdecadal variations and year-to-year fluctuations as shown in Figure 2a for the annual TCP volume. The greatest variation in frequency of the torrential TCP events occurred in 1994 and 1985, with least variation in frequency occurring in 1983. Further examination shows that the total annual frequency of the torrential TCP events is well correlated with the annual TCP, with a correlation coefficient being 0.94.

[15] The time series of annual TCP at each station were also examined for the long-term trends. Results displayed in Figure 2c show that decreasing trends exist in most of the stations, with less than -5 mm/yr in southern Taiwan, central-eastern Hainan. The decreasing trends reached $-10 \sim -15$ mm/yr in southeastern Taiwan. The increasing trends primarily occurred along two belts extending from southwest to northeast. One is from the middle valleys of the Yangtze and Yellow Rivers to northeastern China. Further inspection reveals that, while decreasing trends are statistically significant at the 0.05 level by a Kendall test, the increasing trends are very small (between $0.05 \sim 0.5$ mm/yr)

and no increasing trend is statistically significant during the period 1957–2004.

[16] Figure 3 shows time series of the frequency of TCs and typhoons that affected China from 1957 to 2004. The frequencies of the influencing TCs and typhoons also display significant decreasing trends during the period, with 0.05 and 0.01 significant levels, respectively. Both of them also show obvious year-to-year fluctuations, with maximums of 27 and 17 both in 1971. The variations in frequency of influencing TCs and TCP imply that, during the past 48 years, China experienced decreasing typhoon influence.

[17] In order to explain the variations in TCP, the relationships between the TCP and the influencing TCs and typhoons were calculated. The two correlation coefficients are 0.62 and 0.47, which are both statistically significant. Therefore, the

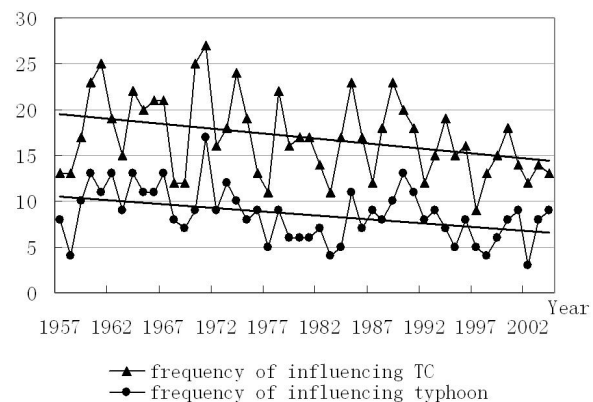


Figure 3. Variations of the frequency of influencing TCs and typhoons ($\text{MSWS} \geq 32.7$ m/s) in China.

decrease in influencing TCs may be the main reason for the decrease in TCP. For year-to-year fluctuation, TC tracks were inspected for three years in 1971, 1985, and 1994, which showed the most significant year-to-year fluctuations. It suggests that the most important factor for annual variation in TCP in China is the tracks of landfall TCs and the length of their lifetimes over the land, rather than the number of influencing TCs.

5. Summary

[18] In this study, the TCP of the 677 weather stations in China from 1957 to 2004 was analyzed with a special focus on its long-term changes because some recent studies have argued that tropical cyclone activity over the WNP has been changed in response to the ongoing global warming. We examined the TCP spatial distribution, its ratio to total annual rainfall, and the changes in the TCP volume and the total annual frequency of the torrential TCP events.

[19] As expected, tropical cyclones significantly contribute to the annual rainfall in southern, southeastern, and eastern China. Primarily Taiwan, Hainan, and most of the southeastern coastal regions received more than 500 mm annual TCP, contributing about 20~40% of the total annual precipitation. The TCP and its contribution to annual precipitation generally decrease with the increase of latitude.

[20] Despite interdecadal and interannual variations, a significant downward trend is found in both the TCP volume and the total annual frequency of the torrential TCP events over the past 48 years. Both influencing TCs and typhoons also show significant decreasing trends during the period 1957–2004. These changes strongly suggest that the TC influence has decreased over the past 48 years. We also examined the time series of the TCP ratio to the annual precipitation averaged over the southern and southeastern China, where TCP contributes significantly to the annual precipitation. A decreasing trend is also found in the ratio, further indicating that China has experienced decreasing TCP over the past 48 years.

[21] Although further study is needed for the exact cause of the decreasing trends found in this study, correlation analysis indicates that the decrease in number of the influencing TCs may be the main reason for the decreasing trend in the annual TCP. Recently, *Wu et al.* [2005] examined the changes in the prevailing tropical cyclone tracks in the WNP basin and found that more and more tropical cyclones took the two recurving prevailing tracks over the WNP while decreasing tropical cyclones moved westward and northwestward. As a result, the influence of tropical cyclones on the South China Sea and southern China decreased over the past 40 years. Their results are consistent with decreasing TCP in China. Note that the decreasing TCP trend is dominated by the TCP changes in southern China.

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References

- Alexander, L. V., et al. (2006), Global observed changes in daily climate extremes of temperature and precipitation, *J. Geophys. Res.*, *111*, D05109, doi:10.1029/2005JD006290.
- Brand, S. (1972), Very large and very small typhoons of the western North Pacific Ocean, *J. Meteorol. Soc. Jpn.*, *50*, 332–341.
- Chan, J. C. L., and J. Shi (1996), Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific, *Geophys. Res. Lett.*, *23*, 2765–2767.
- Elsberry, R. L., W. M. Frank, G. J. Holland, J. D. Jarrell, and R. L. Southern (1987), *A Global View of Tropical Cyclones*, 185 pp., Univ. of Chicago Press, Chicago, Ill.
- Emanuel, K. A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688.
- Englehart, P. J., and A. V. Douglas (2001), The role of eastern North Pacific tropical storms in the rainfall climatology of western Mexico, *Int. J. Clim.*, *21*(11), 1357–1370.
- Gleason, B. E., D. R. Easterling, and F. Ren (2000), Trends in tropical cyclone precipitation over the eastern United States, paper presented at 12th Conference on Applied Climatology, Am. Meteorol. Soc., Asheville, N. C.
- Harr, P. A., and R. L. Elsberry (2001), An overview of the development of heavy precipitation associated with the extratropical transition of tropical cyclones, paper presented at 81st Annual Meeting, Am. Meteorol. Soc., Albuquerque, N. M.
- Hasegawa, A. (2005), Tropical cyclone and heavy precipitation over the western North Pacific in present and doubled CO₂ climates simulated by the CCSR/NIES/FRCGC T106 AGCM, paper presented at 2nd International Workshop on the Kyosei Project, Cent. for Clim. Syst. Res., Kona, Hawaii, 24–26 Feb.
- Intergovernmental Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis: Contribution of the Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.
- Intergovernmental Panel on Climate Change (IPCC) (2002), IPCC workshop report on changes in extreme weather and climate events, Beijing, China, 11–13 June, 2002, report, Geneva, Switzerland.
- Ren, F., B. Gleason, and D. Easterling (2002), Typhoon impacts on China's precipitation during 1957–1996, *Adv. Atmos. Sci.*, *19*(5), 943–952.
- Ren, F., Y. Wang, X. Wang, and W. Li (2006), Estimating tropical cyclone precipitation from station observations, *Adv. Atmos. Sci.*, in press.
- Shuman, M. P., J. P. Koerner, and S. D. Reynolds (2001), Heavy precipitation events from tropical cyclone remnants in the eastern United States, paper presented at 81st Annual Meeting, Am. Meteorol. Soc., Albuquerque, N. M.
- Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*(5742), 1844–1846.
- Wu, L., B. Wang, and S. Geng (2005), Growing typhoon influence on east Asia, *Geophys. Res. Lett.*, *32*, L18703, doi:10.1029/2005GL022937.
- Yeung, K. H., M. C. Wu, W. L. Chang, and Y. K. Leung (2005), Long-term change in tropical cyclone activity in the western North Pacific, paper presented at Scientific Assembly of International Association of Meteorology and Atmospheric Science, Beijing, China, 2–11 Aug.
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