Atmospheric moisture shapes increasing tropical cyclone precipitation in southern China over the past four decades

Si Gao\textsuperscript{1,2}, Jiali Mao\textsuperscript{3}, Wei Zhang\textsuperscript{1,6}, Feng Zhang\textsuperscript{1,6} and Xinyong Shen\textsuperscript{1,5}

\textsuperscript{1} School of Atmospheric Sciences, and Key Laboratory of Tropical Atmosphere-Ocean System, Ministry of Education, Sun Yat-sen University, Zhuhai, People's Republic of China
\textsuperscript{2} Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, People's Republic of China
\textsuperscript{3} Key Laboratory of Meteorological Disaster, Ministry of Education, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disaster, Nanjing University of Information Science and Technology, Nanjing, People's Republic of China
\textsuperscript{4} IIHR-Hydroscience and Engineering, The University of Iowa, Iowa City, IA, United States of America
\textsuperscript{5} Department of Atmospheric and Oceanic Sciences, and Institute of Atmospheric Sciences, Fudan University, Shanghai, People's Republic of China
\textsuperscript{6} Shanghai Qi Zhi Institute, Shanghai, People's Republic of China

E-mail: gaosi5@mail.sysu.edu.cn and wei-zhang-3@uiowa.edu

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Abstract

Although slower translation speed can induce a larger amount of local rainfall for an individual tropical cyclone (TC), whether change in total TC precipitation (TCP) affecting China is related to TC translation speed in the satellite era remains unclear. Based on multiple TC best-track datasets and a reanalysis dataset, we find a significant increasing trend in total TCP over two regions of southern China during 1980–2018. This upward trend can be attributed to the enhancing atmospheric water vapor content and moisture transport over southern China, however, TC intensity, frequency, and translation speed have no contributions. Given the potential linkage between the increasing atmospheric water vapor content over southern China and the western Pacific warming under global warming, our results suggest a likely role of anthropogenic global warming in the increasing TCP over southern China during the past 4 decades.

1. Introduction

Torrential rain induced by tropical cyclones (TCs) poses a huge threat to people's life and property in developed and highly populated coastal regions of China (Zhang et al 2009), change in TC precipitation (TCP) over China is therefore of great concern to the public. Recently Kossin (2018) found a global slowdown of TC translation speed over the past 7 decades, with the maximum slowdown for the western North Pacific TCs, and suggested that this may lead to an increase in local TCP under global warming. Later, several studies (Chan 2019, Lanzante 2019, Moon et al 2019) argued that the TC slowdown may be attributed to data inhomogeneity in the pre-satellite era. Thus, it remains an open question regarding whether the observed change in TCP over China is related to TC translation speed over the past few decades.

Changes in TCP over China have been examined by a number of studies. Ren et al (2006) reported a significant decreasing trend in the TCP volume over China during 1957–2004, while Ying et al (2011) showed significant increasing trends in precipitation per TC and maximum hourly TCP over Southeast China during a similar period 1955–2007. Wu et al (2007) found a slight decrease in TCP over Hainan Island during 1962–2005, while Zhang et al (2013) identified a significant increasing trend in precipitation per TC over Southeast China during a similar period 1965–2009 and suggested that the trend was not related to TC intensity or translation speed. Most recently, Liu and Wang (2020) found that landfalling TCP in total or per storm had a significant increasing trend in East China and a decreasing trend in South China but TCP induced by landfalling strong (weak) TCs showed a significant increasing trend in South (Southeast) China during 1980–2017. Lai et al (2020) showed a significant slowdown of TCs affecting the coast of China during 1961–2017 and more frequent occurrence of TCs with slower translation speed and heavier precipitation after 1990 in the Pearl River Delta in southern China.
Table 1. Summary of the dataset information.

| Dataset                      | Production agency | Temporal resolution | Spatial resolution |
|------------------------------|-------------------|---------------------|--------------------|
| Tropical cyclone best track  | CMA, JMA, and JTWC| 6 hourly            | 0.1°               |
| Precipitation                | CMA               | Daily               | 0.5° × 0.5°        |
| MERRA-2 reanalysis           | NASA              | Monthly             | 0.5° × 0.625°      |

Note. CMA = China Meteorological Administration; JMA = Japan Meteorological Agency; JTWC = Joint Typhoon Warning Center; MERRA-2 = version 2 of the Modern-Era Retrospective Analysis for Research and Applications; NASA = National Aeronautics and Space Administration.

Major progress has been made in understanding TCP over China over the past 2 decades. However, there are notable discrepancies among the reported trends in TCP over China, potentially due to different study periods or the use of different definitions of TCP. In addition, the previous studies only used individual TC best-track dataset to examine the trends in TCP. This may limit the robustness of their findings, given the discrepancies among best-track datasets from different agencies and sources. Here we reexamine the long-term changes in TCP over China and possible causes in the satellite era (1980–2018) based on three TC best-track datasets and a state-of-the-art reanalysis dataset.

2. Data and methods

Table 1 summarizes the information of TC best-track data, precipitation data, and atmospheric reanalysis data used in this study. TC best-track data produced
Figure 2. Time series of JJASO mean translation speed (first row, km h\(^{-1}\)), intensity (second row, knot), and frequency (third row) of TCs affecting Region B (left column) and Region A (right column) during 1980–2018 derived from CMA (purple lines), JMA (blue lines), and JTWC (orange lines) best-track datasets. Their trends (unit decade\(^{-1}\)) and respective p values based on Student’s t test are indicated in each panel.

by three agencies (CMA, JMA, and JTWC, see their full names in Table 1) are obtained from version 4 of the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010). Gridded precipitation dataset in mainland China and Hainan Island are acquired from the CMA/China Meteorological Data Service Center. Based on high-quality precipitation observations from over 2400 national stations in China, the dataset is constructed using the thin plate spline interpolation method (Zhao et al. 2014). Specific humidity and wind data are obtained from version 2 of the Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) reanalysis (Gelaro et al. 2017).

Given different definitions of TC maximum sustained winds used in the three agencies, we convert JMA’s 10 min winds to 1 min winds using the relationships between Current Intensity (CI) numbers and winds in the Koba et al. (1991) table and in the Dvorak (1975) table (Knapp and Kruk 2010, Bai et al. 2019), and convert CMA’s 2 min winds to 1 min winds using an adjustment factor of 1.01 (Li et al. 2017). TCP in this study is defined as land precipitation within 500 km from the center of each TC with intensity \(\geq 17.2\) m s\(^{-1}\). The use of 500 km radius is consistent with some previous studies (e.g. Dare et al. 2012, Gao et al. 2017b, Rios Gaona et al. 2018, Zhang et al. 2019a). We consider the peak-season (June–October, JJASO) TCs affecting China, including those making landfall in China and passing offshore China. In line with Zhang et al. (2013), tropical depressions are not included in this study, as best-track data for tropical depressions among the three agencies may differ markedly (Liu and Chan 2008, Gao et al. 2018).

3. Results

Figure 1 shows the spatial distributions of total JJASO TCP averaged during 1980–2018 and its trend. Results based on three best-track datasets are fairly consistent. Large TCP occurs in the coastal areas of southern China, including Guangdong, Guangxi, Fujian, and Zhejiang Provinces, and Hainan Island, with the maximum exceeding 300 mm in Hainan Island (figures 1(a), (c), and (e)). This is in line with Ren et al.
Figure 3. Trends in JJASO mean (a) TPW (mm decade$^{-1}$) and (b) column-integrated HMFC (g m$^{-2}$ s$^{-1}$ decade$^{-1}$) during 1980–2018. Stippled regions represent trends significant above the 90% confidence level determined by the GFDL-CM3 model control run variability.

(2006) and Zhang et al (2013). Significant increasing trends in TCP can be consistently found in Guangxi, western Guangdong, northern Fujian, and southern Zhejiang Provinces (figures 1(b), (d), and (f)). Different from our result, Zhang et al (2013) and Liu and Wang (2020) showed no significant trend in TCP in Guangxi and western Guangdong Provinces, and Liu and Wang (2020) showed significant decreasing trend in TCP in Hainan Island using CMA best-track data. The differences are possibly due to different study period in Zhang et al (2013) or different definition of TCP in Liu and Wang (2020). Liu and Wang (2020) only considered the precipitation induced by TCs (including tropical depressions) landfalling in China and thus may neglect the precipitation induced by TCs passing offshore China, which is an important component of TCP (Feng et al 2020).

Based on the above results, we define two regions with significant upward trends in TCP to perform further analyses. Guangxi and western Guangdong Provinces are defined as Region A (106$^\circ$–113$^\circ$ E, 22$^\circ$–25.5$^\circ$ N; red box in figure 1(b)), and northern Fujian and southern Zhejiang Provinces as Region B (116.5$^\circ$–120.5$^\circ$ E, 25.5$^\circ$–29$^\circ$ N; blue box in figure 1(b)). Given TCP is potentially related to TC frequency (e.g. Liu and Wang 2020), intensity (e.g. Lonfat et al 2004), and translation speed (e.g. Chien and Kuo 2011), we calculate trends in JJASO mean frequency, intensity, and translation speed of TCs affecting the two regions of southern China.
during 1980–2018. Note that these TC variables are calculated only when TCs affect each region (i.e. TC centers are within 500 km from any grid box in the region). Translation speed is calculated following Kossin (2018), who divided the distance between every two adjoining locations along each TC track by the 6 hourly interval. There are no significant trends in frequency, intensity, or translation speed of TCs affecting Regions A and B (figure 2), suggesting that none of them contributes to the increasing TCP in the two regions of southern China over the past 4 decades, which is generally consistent with Zhang et al (2013). No significant trend in translation speed of TCs affecting southern China shown here is consistent with Zhang et al (2020) and does not contradict the work by Lai et al (2020), in which the slowdown of TCs affecting the coast of China during 1961–2017 is mostly attributed to high translation speed in 1960s and 1970s, and there is hardly any meaningful trend in translation speed during 1980–2017 (see their figure 1(a)).

Environmental moisture supply including total precipitable water (TPW, i.e. column-integrated specific humidity) and horizontal moisture flux convergence (HMFC) is another possible factor regulating TCP (e.g. Jiang et al 2008, Gao et al 2017a, 2017b). Figure 3 indicates the spatial distribution of trends in JJASO mean TPW and column-integrated HMFC during 1980–2018 derived from MERRA-2. Following Barkhordarian et al (2013), trends in twelve 39 year segments of 500 year GFDL-CM3 model control run (its spatial resolution is 2.5° × 2°) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al 2012) are used as the null hypothesis to test the observed trends in TPW and HMFC. Both TPW and HMFC show significant upward trends in Regions A and B at the 90% confidence level, indicating their crucial roles in the increasing TCP over the two regions in southern China over the past 4 decades.

4. Summary

Based on TC best-track datasets (i.e. CMA, JMA, and JTWC) and MERRA-2 reanalysis data, we have investigated the trend in TCP over China during the satellite era (1980–2018) and its possible causes. Results from the three best-track datasets consistently exhibit a robust increasing trend in TCP over southern China, including Guangxi, western Guangdong, northern Fujian, and southern Zhejiang Provinces. The increasing TCP over southern China is not related to TC frequency, intensity, or translation speed. Rather, this trend in TCP is mainly contributed by the increasing TPW and HMFC. The increasing TPW over southern China is consistent with previous studies related to the Clausius–Clapeyron scaling (e.g. Trenberth et al 2005, Byrne and O’Gorman 2018, Zhang et al 2019b). It is also potentially linked to the western Pacific warming (e.g. Cravatte et al 2009, Zhang et al 2011) over recent decades, according to an analytical theory proposed by Byrne and O’Gorman (2018). In addition, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) detection/attribute finding (Bindoff et al 2013) suggested that ‘an anthropogenic contribution to increases in specific humidity at and near the Earth’s surface is found with medium confidence’. Therefore, the increasing TCP over southern China could be indirectly attributed to anthropogenically forced global warming. Given there is still great uncertainty about anthropogenic influence on total TCP on a regional scale (Knutson et al 2019), attribution of the increasing trend in total TCP over southern China using climate models is needed in future studies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.ncdc.noaa.gov/ibtracs, http://data.cma.cn/data/cdc detail/dataCode/SURF_CLI_CHN_PRE_DAY_GRID_0.5.html, and https://disc.sci.gsfc.nasa.gov/datasets?page=1&keywords=MERRA-2.

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ORCID iDs

Si Gao https://orcid.org/0000-0003-3036-6508
Wei Zhang https://orcid.org/0000-0001-8134-6908

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