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Changes in Extreme Rainfall over Mainland China Induced by Landfalling Tropical Cyclones

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Abstract

Landfalling tropical cyclones (LTCs) is one of the most serious meteorological disasters in China due to the provided severe wind and heavy rainfall. Tropical cyclone–induced rainfall in China has been proved to decrease in recent decades. However, how landfalling tropical cyclone–induced extreme rainfall (LTCER) has changed across China, as well as the relationship between LTCER and LTCs remains poorly understood. Accordingly, the spatiotemporal distribution characteristics and long-term changes of LTCER over mainland China during the past 60 years were investigated, by using an Objective Synoptic Analysis Technique to identify LTCER. Mid and high latitudes are exposed to a greater risk of extreme rainfall from northward-moving landfalling tropical cyclones (LTCs). Meanwhile, LTCER tends to increase from 1960 to 2019 across mainland China (characterized by a decrease from 1960 to 1989 and an increase from 1990 to 2019). The LTCER trend exhibits a large spatial difference, with an increase near and to the north of 30°N, but no significant change to the south of 30°N. Moreover, the central latitude of the LTCER zone to the north of 30°N has shifted significantly southwards, while that to the south of 30°N has shifted north. Further analysis revealed that the average latitude of the LTC intensity centers to the north/south of 30°N exhibits the same shift to that of LTCER, indicating that the shift of LTCER has mainly been imposed by the migration of LTCs.

Keywords: land-falling tropical cyclones, extreme precipitation, long-term change, mainland China, spatiotemporal features

1 Introduction

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Worldwide, China is one of the countries most seriously affected by tropical cyclones (TCs). TCs can result in huge economic losses, with extensive damage caused by the associated extreme rainfall [1-4]. Therefore, the distribution of, and changes in, tropical cyclone-induced rainfall (TCR) have been widely studied around the world [5-7]. In addition to the direct impact of TCs on coastal areas, some severe developing TCs can make landfall and move inland. The rainfall that such TCs deliver can change significantly after making landfall under certain conditions, in some cases greatly strengthening, such as the heavy rainfall induced by TCs Morakot (0908), Haima (0421), and Talim (0513) [3, 8, 9]. Therefore, the most significant factor for tropical cyclones-induced rainfall in China is the tracks of landfall TCs and the length of their lifetimes over the land, rather than the number of influencing TCs. The rainfall induced by landfalling tropical cyclones is as expected the key element affecting China [10-11]. Among all the LTCR, the LTCER is the most influential, disaster-causing and catastrophic event.

Regarding the complexity of landfalling tropical cyclones (LTCs), recent studies have investigated the changes in landfalling tropical cyclone rainfall (LTCR). In the prevailing seasons of TCs, the precipitation in the most affected areas is largely caused by TCs [12-14]. Although the distribution of LTCR differs quite a lot globally, it has particularly large impacts in the United States, East Asia, Mexico, Australia, and other regions, where it receives extensive attention [12, 13, 15-21]. In addition, an increasing trend of TCR has been found in the southeastern United States and South Korea [1, 13, 17], and the change in TCR can be modulated by ENSO [5, 22].

In China, TCR occurs mainly between May and November [23]. The southeastern coastal area of China suffers from the most severe damage caused by TCR, especially in the provinces of Hainan, Guangdong, Fujian, and Zhejiang [24-26]. Meanwhile, some inland areas, such as Shandong, Hunan, and Liaoning, are also affected by TCR to varying degrees [27-29]. The rainfall caused by TCs has shown a downward trend, whereas the extreme rainfall has exhibited an upward trend, which has been proven to be related to many factors including the complexity of the terrain and ENSO [10, 30, 31].

Recently, several studies have suggested that the locations of TCs have shifted and that their translation speed [32-34] and lifetime-maximum intensity have also changed worldwide [35-40]. As a direct cause of TCR change, the location and translation speed of TCs are the most important factors affecting local precipitation [41]. A slowdown in the translation speed of TCs will cause more extreme rainfall and flooding. The longer the duration and slower the speed, the stronger the TCR.

Although previous studies have disclosed several characteristics of TCR and TC-induced extreme rainfall over mainland China, including their long-term trend and spatiotemporal patterns, how landfalling tropical cyclone–induced extreme rainfall (LTCER) has changed across continental China, especially its observed climatological distribution and trend, remains poorly understood. Besides, the relationship between LTCER and LTCs is also quite unclear.

Consequently, this study analyzes the spatial and temporal variation in days, total rainfall, intensity, and location of LTCER in China. The findings are expected to be helpful in further understanding the various characteristics of LTCER over China and provide basic scientific information for studying the mechanisms of, influences on, and adaptation to, LTCER.

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2 Data and Methods

2.1 Data

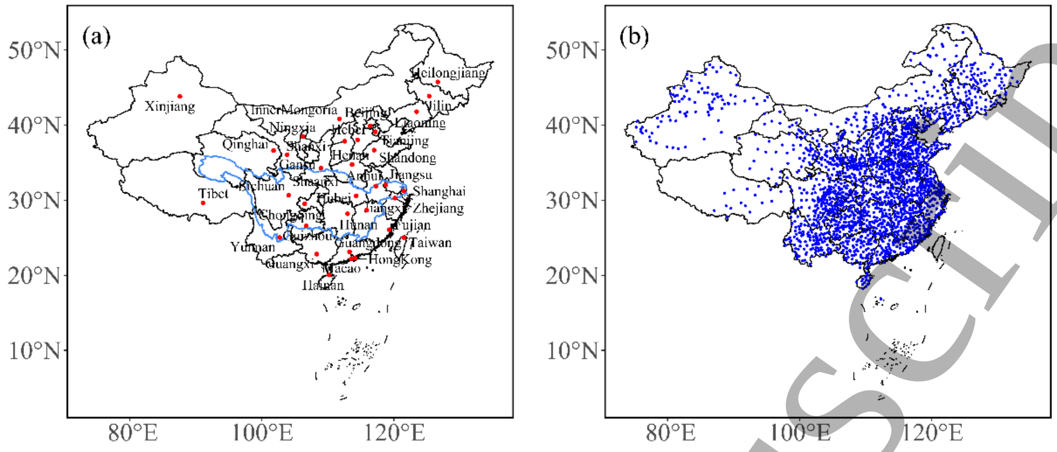

Figure 1. Distribution of (a) Chinese provinces and (b) the 1981 China Meteorological Administration national stations used in this study. The blue border in (a) is the Yangtze River Basin, and the red dots are the capital cities of each province.

The best-track TC dataset used in this study is from the Shanghai Typhoon Institute of the China Meteorological Administration [42, 43], and includes the latitude and longitude of the TC center, center minimum pressure, satellite-derived current intensity, and landfalling TC identification, during the period 1960–2019. The gauge-based observational precipitation dataset is from version 3.0 of the basic historical meteorological dataset of a dense national network released by the National Meteorological Information Center of the China Meteorological Administration. The total number of national stations is 2479, and all the daily data used here have been subjected to quality control procedures by the National Meteorological Information Center. Considering China's meteorological station network is confined to the large number of construction stages before 1960, a final 1981 stations with missing data of less than 50 months during 1960–2019 are selected (Figure 1b). Figure 1a shows the administrative divisions of China and the location of the Yangtze River Basin.

2.2 Methods

Recent studies have simply defined TCR as all the rainfall within 550 km or 5° from the TC center [14, 44]. In this study, we choose the Objective Synoptic Analysis Technique (OSAT) [10] to identify TCR. This method is mainly divided into two steps. Firstly, all stations with rainfall are selected and clustered into different rainfall bands. Then, TCR is selected as the closest weighted center of the rainfall band to the TC center.

Considering the ability to withstand extreme rainfall varies between different regions, a set threshold is not rational. Thus, we define LTCER by using the relative threshold method. For one station, all of the daily precipitation from 1961 to 1990 is sorted in ascending order, and the 95th percentile value is defined as the extreme threshold. LTCER needs to meet two conditions simultaneously: firstly, the station's precipitation needs to be identified as TCR; and secondly, the station's precipitation needs to reach the extreme threshold. That is, when the rainfall at a certain station is identified as both extreme precipitation and TCR, it is ultimately defined as LTCER.

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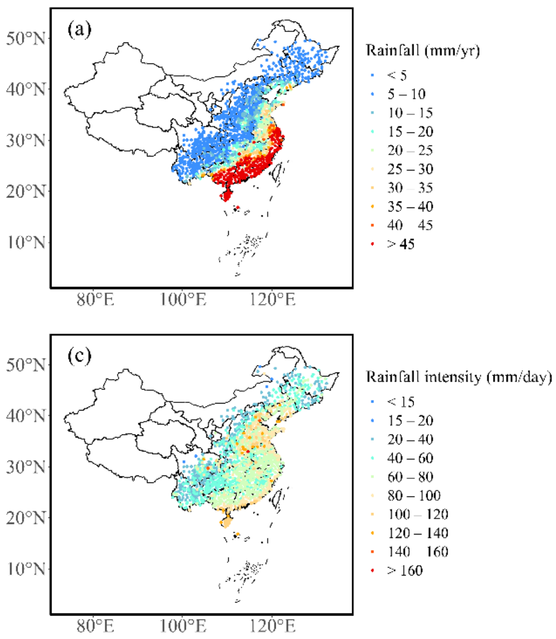

Figure 2. Annual mean of the (a) accumulated LTCER amount, (b) LTCER days, and (c) LTCER intensity defined as LTCER amount divided by LTCER days, from 1960 to 2019.

Due to the skewness of rainfall distribution, in assessing the long-term trend of the LTCER series, the non-parameter Theil–Sen trend estimator [46] and Mann–Kendall test [47, 48] are thus adopted, which are less dependent on the distribution of the data. The outliers and possibly autocorrelated data of extreme weather data may easily cause incorrect results. Therefore, a pre-whitening procedure described in Wang et al. [49] is imposed to reduce the lag-1 series effect.

Given the different locations of stations in the grid and the different densities of stations in the various regions, employing the simple arithmetic average will produce time series inaccuracies. Therefore, we first grid the station's LTCER series on a regular latitude–longitude grid (0.5° × 0.5°), and then use the grid area–weighted averaging method [45] to obtain the regional average time series.

We use the latitudinal variation of the weighted center of LTCER to examine the location of LTCER, and the weight of its rainfall. All station LTCER on a certain day is added to obtain P_{all}, and the position proportion of a given station is determined according to the proportion of its rainfall in the total rainfall. The weighted center of LTCER is obtained by addition, as follows:

$$L_{\mathrm{center}} = \sum_{k=1}^{l} \frac{P_k}{P_{\mathrm{all}}} \cdot L_k,$$

where L_{center} is the latitudinal center of LTCER, P_k is the LTCER for station k, l is the number of stations, and L_k is the location of station k.

3 Results

3.1 Spatial Distribution of LTCER

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Figure 2a shows the annual mean LTCER amount over mainland China from 1960 to 2019. As can be seen, LTCER affects more than half of China's mainland area, and shows spatial heterogeneity. The LTCER amount decreases from south to north and from coastal to inland areas. The maximum annual mean LTCER is more than 45 mm/yr, and mainly located in southeastern China.

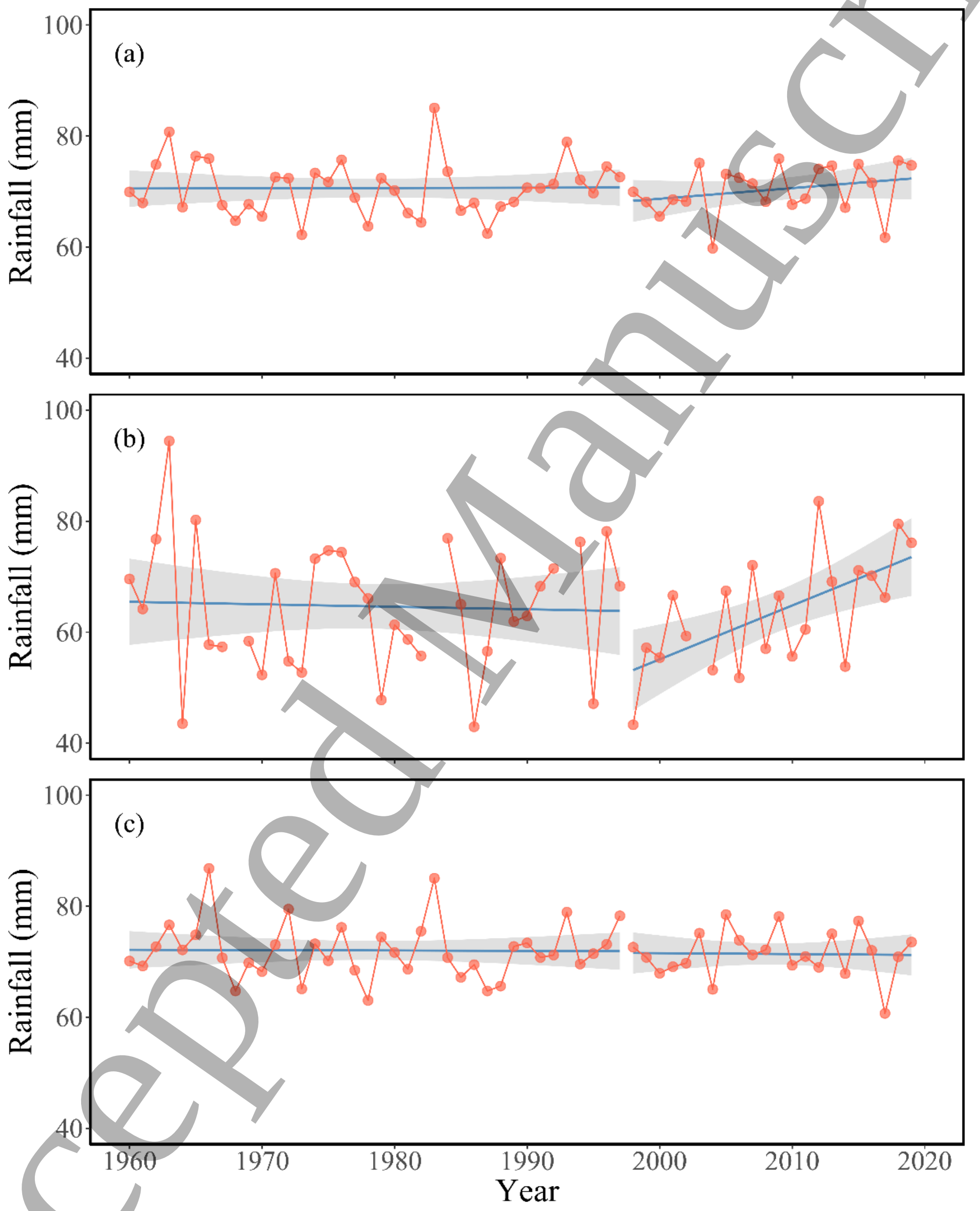

Figure 3. Variation in the annual LTCER amount over (a) the whole of mainland China, (b) northern, and (c) southern China, from 1960 to 2019. The orange line represents the LTCER amount, the blue line is the trend line fitted by the least-squares method, and the gray area indicates the 95% confidence interval. There is no LTCER over the region north of 30°N in 1968, 1983, 1993, and 2003.

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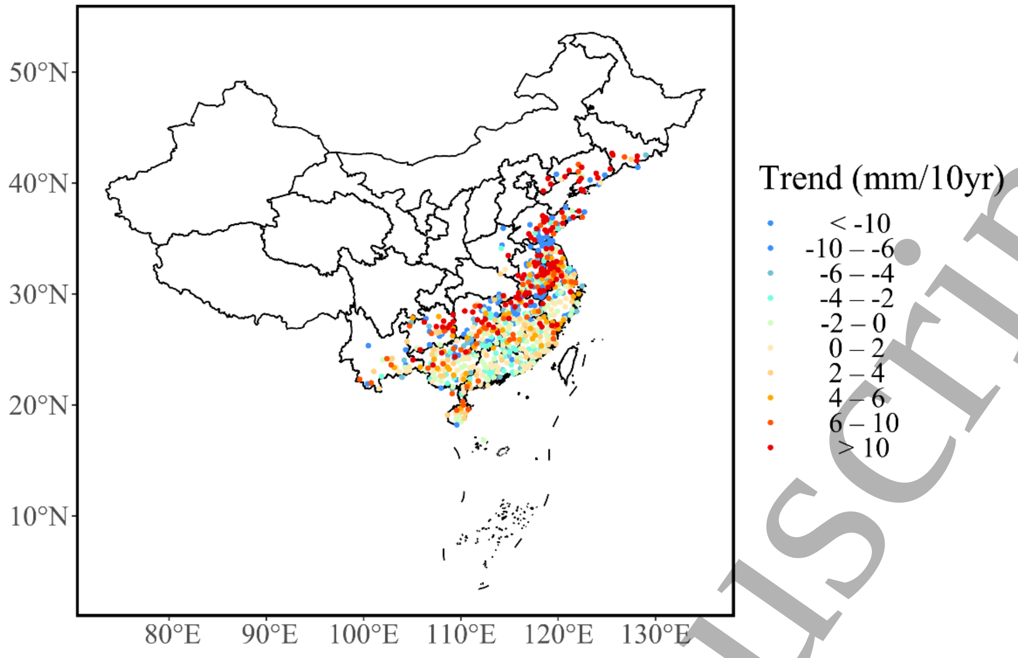

Figure 4. Spatial distribution of the trend in the LTCER amount from 1960 to 2019.

The spatial distribution of the average annual number of LTCER days from 1960 to 2019 is similar to that of the annual mean LTCER amount, exhibiting a gradual decrease from the southeastern coast to the northwestern inland area (Figure 2b). The maximum number of LTCER days is found in the southeastern coastal areas, especially in the provinces of Hainan, Guangxi, Guangdong, Fujian, and Zhejiang, where it is more than 2.5 days. The number of LTCER days in the region stretching from central Guangxi to central Jiangsu ranges between 0.3 and 0.8, while it is 0.1–0.3 days in the region from central Yunnan to the Shandong Peninsula, and less than 0.1 days in most inland areas.

The LTCER intensity is generally high along the southeastern coast and low over northern inland areas (Figure 2c). The LTCER intensity along the southeastern coast is generally more than 100 mm/day. However, notably, the LTCER intensity in the south of north China and Liaoning Peninsula can also reach 100 mm/day, and some areas even exceed 160 mm/day. This indicates that a northward-moving TC can cause extreme rainfall in the north, resulting in high rainfall intensity. The LTCER intensity over the middle and lower reaches of the Yangtze River, especially the northern part of the Yangtze River, is between 60 to 80 mm/day, while it is less than 40 mm/day in other areas further inland. Therefore, the LTCER intensity in north and northeast China can even be compared with that in the southeastern coastal areas, demonstrating that TCs can cause extreme rainfall not only in the tropical and subtropical regions of China, but also in northern China and even inland when TCs interact with mid–high-latitude systems.

3.2 Characteristics of LTCER amount's Variation

Previous studies have suggested that the maximum intensity of TCs has migrated polewards [32-40]. However, it is not clear whether LTCER has undergone similar changes.

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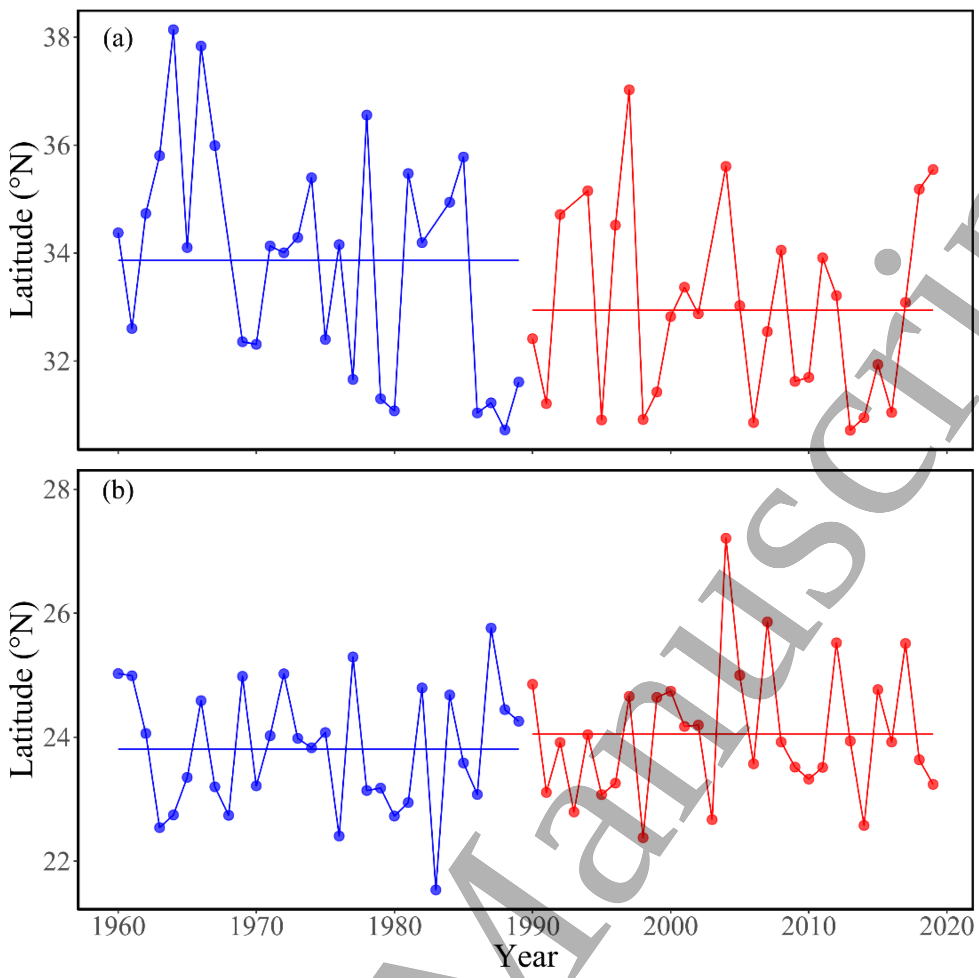

Figure 5. Variations in the central latitude of LTCER over (a) northern and (b) southern China from 1960 to 2019. The blue and red graphs represent the latitudes from 1960 to 1989 and from 1990 to 2019, respectively, with the straight lines through them representing their averages.

Considering the different characteristics of LTCER in the northern and southern regions of mainland China, we distinguish the north (northern China) and south (southern China) with 30°N as the dividing line, which is near the geographical dividing line: the Qinling Mountains section and the Huaihe section [50].

Figure 3a displays the time series of the LTCER amount for the whole of mainland China. As can be seen, the LTCER amount has a weak increasing trend at a rate of 0.22 mm/10 yr. During the first 30 years (1960–1989), the LTCER amount shows a downward trend (-1.81 mm/10 yr), while during the last 30 years (1990–2019) there is an increasing trend (0.23 mm/10 yr). In addition, the time series possesses obvious interannual and interdecadal changes. There is an abundance of above-normal LTCER amounts in the mid-1960s, mid-1980s, mid-1990s, and post-2010s, with maxima in 1963, 1983, and 1993, respectively. However, in the 1970s, the late 1980s, and 2000s, below-normal LTCER amounts are apparent over mainland China.

As shown in Figure 3b, the LTCER amount exhibits a non-significant increasing trend at a rate of 0.31 mm/10 yr in northern China. However, the LTCER amount shows no obvious trend over southern China (Figure 3c). The interannual and interdecadal variations in northern China are significantly greater than

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those in the southern region. In addition, since 1998, the LTCER has shown a significant increasing trend in northern China at a rate of 8.51 mm/10 yr (0.1 significance level), while weakly decreasing in southern China. In the overall context, the LTCER amount throughout China does have an increasing trend at a rate of 2.03 mm/10 yr.

regions of southern China. Consequently, the increase in LTCER occurs mainly in the inland and northern regions of China. The magnitude of increasing trends in the inland areas is relatively larger than that in the coastal areas (Figure 4). Recent studies showed that TCs had a poleward and inland migration, meanwhile TCs exhibited a westward shift to land in China [34, 40], which likely result in the increase of LTCER in the northern and inland regions, as shown in Figure 4. Although LTCER in most inland places increased obviously, LTCER in a few inland areas decreased instead. This inconsistent change in LTCER may be related to different

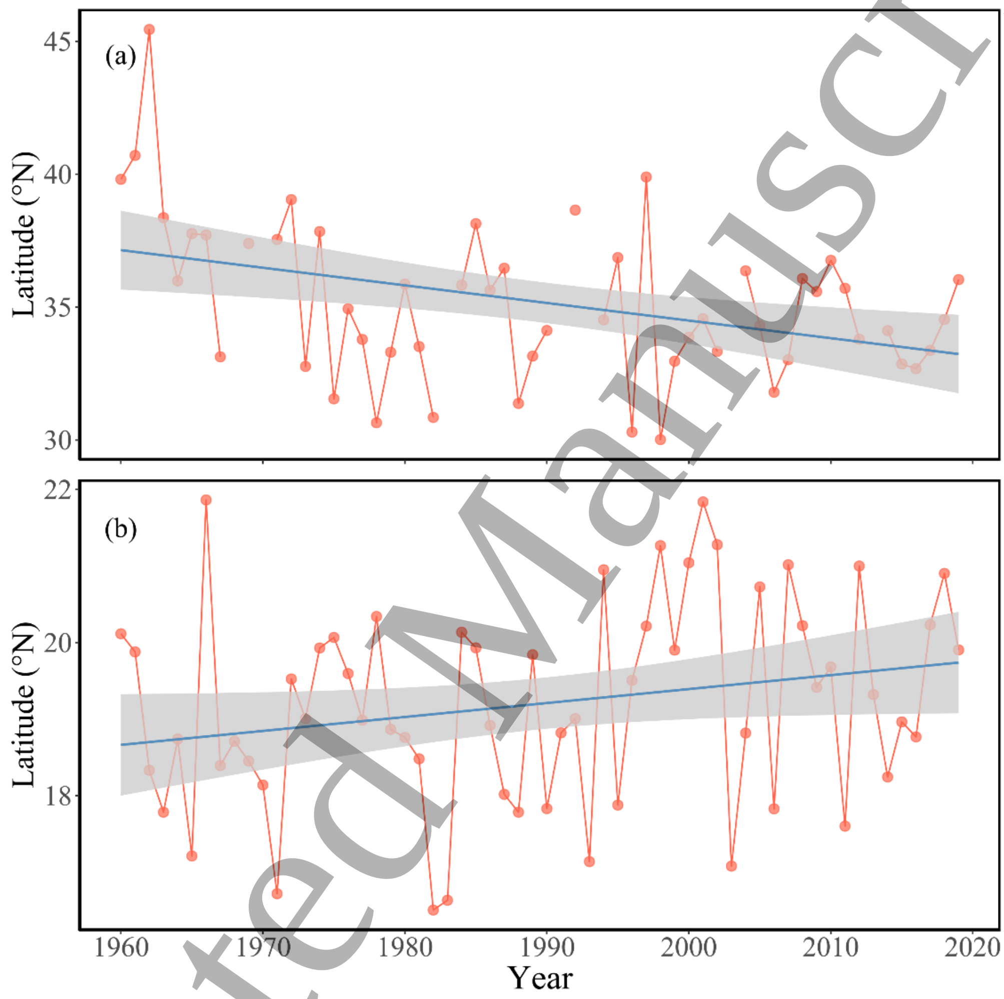

Figure 6. Variations in the central latitude of LTCs over (a) northern and (b) southern China. There are no LTCs in the region north of 30°N in 1968, 1970, 1983, 1991, 1993, 2003, and 2013.

Figure 4 shows the spatial distribution of the trend in the LTCER amount at those stations where the influence of LTCER exceeds 20 years. An upward trend in the area north of 30°N and inland areas can be seen, especially in Shandong, Jiangsu, Anhui, and some regions of Liaoning. Meanwhile, downward trends dominate most

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typhoon tracks and different terrains of observation stations

3.3 Variation of LTCER location

Figure 5a shows the variations in the central latitude of LTCER over northern China. In terms of yearly fluctuation, the northernmost/southernmost locations of LTCER occur in 1964 and 1988, with values of 38.14°N and 30.72°N. The average location from 1960 to 1989 is 33.87°N, while from 1990 to 2019 it is 32.94°N. The difference in location between these two periods is almost 1°. Besides the large interdecadal and interannual variations, a significant southward shifting trend is apparent from 1960 to 2019, at a rate of 0.36°N/10 yr (0.05 significance level). In addition, the southward shifting trend of LTCER from 1960 to 1989 is very large and significant (0.1 significance level), at 1.24°N/10 yr, while there is no obvious meridional shift after 1990.

In southern China (Figure 5b), the LTCER location has its northernmost latitude in 2004 (27.21°N) and southernmost latitude in 1983 (21.54°N). The average central latitude from 1960 to 1989 is 23.81°N, while from 1990 to 2019 it is 24.05°N. A northward shifting trend of 0.05°N/10 yr during 1960 to 2019 is apparent. The central latitude of LTCER does not change significantly during 1960 to 1989; whereas, a significant northward shifting trend at rate of 0.10°N/10 yr can be observed during 1990 to 2019.

According to Lai et al. [41], one of the direct causes of TC precipitation is the TC's translation speed. Thus, the influence of a change in location of LTC intensity on extreme precipitation is analyzed next. The intensity-weighted central latitude of LTC in northern China shows clear interannual fluctuation, with the northernmost location seen in 1962 (45.45°N) (Figure 6a). In addition, from 1960 to 2019, the central latitude of LTC intensity shows a relatively obvious southward shifting trend, at a rate of 0.51°N/10 yr, with a statistical significance of greater than 90%. In southern China (Figure 6b), a significant northward trend of 0.23°N/10 yr (0.05 significance level) is observed.

Previous studies have shown that the maximum intensity center of TCs has gradually migrated polewards; however, this study suggests that the impact of this poleward migration on LTCER is not simply linear. This is because the location of LTCER in southern China has mainly shifted northwards, while that in northern China has migrated southwards.

4 Discussion

This study found that the spatial distribution of the LTCER amount gradually decreases from the coast to inland areas, and from south to north, and that the LTCER amount for the whole of mainland China exhibits an increasing trend, which is consistent with the results of Qiu et al. [31]. Several studies have also shown a decreasing trend in LTCR but an increasing trend in LTCER in Asian countries [7, 17, 31]. Previous studies have shown that annual TC precipitation over mainland China as a whole presents a slightly decreasing linear trend primarily due to the decreasing trend in the frequency of landfalling TCs [10, 51]. However, LTCER is found to increase in this study. This may be related to the observed enhanced landfalling intensity of strong TCs and extended duration after landfall in recent decades [51]. On the other hand, global temperature has been increasing since 1960 [52]. A warmer climate behaves to increase temperature and evaporation which contribute to raise the atmosphere moisture content, which means more energy is

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required to condense water vapor. Before precipitation, clouds take longer time to accumulate energy. Increased heavy rainfall to the detriment of decreased moderate rainfall are the feedback of warmer climate [53, 54]. Thus, the increase of LTCER can be regarded as a part of the increase of heavy rainfall. In addition, we also found that LTCER exhibited opposite trends characterized by a decrease in former thirty years and an increase in latter thirty years. The landfalling intensity of strong TCs in China decreased first and then increased during the past several decades, and the turning point was in late 1980s (figure omitted). This trend change of the landfalling intensity of strong TCs is suggested to result in the similar change of LTCER, because strong TCs tend to induce high rainfall rates [51]. Besides, the observed warming in China showed flat trend before mid-late 1980 but a rapidly upward trend after mid-late 1980 [52, 55]. The accelerated warming since mid-late 1980 may provide a favorable background for increased LTCER with more atmosphere moisture content.

Besides, this study also found that LTCER changes inconsistently in different regions of mainland China, i.e., a significant increasing trend in northern China but no obvious trend in southern China (with 30°N as the dividing line). Kossin et al. [33] found that TCs have migrated polewards; however, we found a nonlinear correlation between the location of LTCER and its migration, and a spatial difference in the change. This is because TC precipitation is also affected by topography, water vapor transport, wind shear, and other factors [56-58]. The LTCER in southern China has generally shifted northwards, whereas the LTCER in the north has migrated in the opposite direction. This change is understandable, because the intensity-weighted center of LTC in northern/southern China changes consistently with the position of LTCER. Thus, the positional change of TCs themselves is the main reason for the migration of LTCER. In the past 60 years, the changes in location of LTCER in China have concentrated to 30°N from the south and north, respectively. This indicates that LTCER has increased over the middle and lower reaches of the Yangtze River Basin, which is located at around 30°N and east of 110°E. We found the growth rate of the LTCER amount in this region to have been 2.75 mm/10 yr in the past 20 years, which has greatly increased the risk of flooding there caused by LTCER.

The study of LTCER in this paper is limited to mainland China. Whether LTCER has similar or different characteristics in other parts of the world remains unclear and needs to be further studied. Furthermore, changes in LTCER are affected by many other factors besides TCs themselves. For example, one of the most import factors is the western Pacific subtropical high (WPSH), which can directly or indirectly affect TCR. The WPSH are highly associated with TC activity, while this relationship between WPSH and TC tracks is interactive. The position of the WPSH can guide the direction of TC movement, while its intensity can affect a TC’s moving speed [59-61]. The westward and northward moving WNP contributes to the northward of TC tracks, therefore, causing the high LTCEP over the inland China [62-65]. Moreover, the WPSH is associated with ocean signals such as ENSO and the Pacific Decadal Oscillation [66-68], which, depending on their phase, can affect the formation pattern of TCs. In addition, large-scale circulation can transport moisture from TCs and interact with high-latitude weather systems, resulting in remote rainfall from TCs and extreme rainfall locally, such as the extreme

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rainfall events in July 2021 in Henan—one of the most populated provinces in China [69, 70].

Also, other factors such as ENSO, weather systems, water vapor transport, and urbanization, all have effects (to varying degrees) on LTCER [17, 71-74]. Moreover, some recent studies have extended the time series of TCs to the late 19th century in East Asia [75, 76], and these new findings can be combined with historical precipitation data to further study the changes in LTCER at the centennial scale. In addition, past observations show that the LTCER over the middle and lower reaches of the Yangtze River Basin has increased; plus, the future change in the flood risk caused by LTCER in this region is also worthy of further discussion.

5 Conclusions

Applying OSAT to identify LTCER, this study explored the spatiotemporal distribution characteristics and long-term changes of LTCER over mainland China during the past 60 years. The main conclusions can be summarized as follows:

(1) LTCER affects more than half of mainland China. The LTCER amount and number of LTCER days exhibit their maxima in the southeastern coastal areas, and decrease from south to north and from west to east over mainland China. However, the LTCER intensity in southern parts of north and northeast China reaches the same level as that in the southeastern coastal areas, indicating that the influence of LTCER in some northern inland areas of China is significantly large, albeit with the frequency being relatively low.

(2) From 1960 to 2019, LTCER shows an overall increasing trend, especially in the latter 30 years. The increasing trend of LTCER has mainly occurred in northern China, while such a trend in southern China is inapparent. Although overall the TC maximum intensity has migrated polewards, the average LTC center locations in north and south China exhibit opposite shifts. The northern LTC center has moved southwards, while southern LTCs have migrated northwards. This has led to an average southward/northward shift of 0.93°/0.24° for northern/southern LTCER between the early 30 years and latter 30 years. The position of LTCER in northern and southern China offsets to 30°N, which has increased the flood disaster risk caused by LTCER in the middle and lower reaches of the Yangtze River Basin.

Acknowledgments

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