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THE EFFECTS OF STATION NETWORK DENSITY ON STATISTICAL ANALYSES OF TROPICAL CYCLONE PRECIPITATION

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Abstract: In this paper, 1416 conventional ground-based meteorological observation stations on the mainland of China were subdivided into groups of differing spatial density. Data from each subgroup were then used to analyze variations in the tropical cyclone (TC) precipitation statistics derived from each subgroup across the mainland of China (excluding Taiwan, Hong Kong, and Macao), as well as in two regions (east China and south China) and three provinces (Guangdong, Hainan, and Jiangxi) between 1981 and 2010. The results showed that for the mainland of China, total precipitation, mean annual precipitation, mean daily precipitation, and its spatial distribution were the same regardless of the spatial density of the stations. However, some minor differences were evident with respect to precipitation extremes and their spatial distribution. Overall, there were no significant variations in the TC precipitation statistics calculated from different station density schemes for the mainland of China. The regional and provincial results showed no significant differences in mean daily precipitation, but this was not the case for the maximum daily precipitation and torrential rain frequency. The maximum daily precipitation calculated from the lower-density station data was slightly less than that based on the higher-density station schemes, and this effect should be taken into consideration when interpreting regional climate statistics. The impact of station density on TC precipitation characteristics was more obvious for Hainan than for Guangdong or Jiangxi provinces. In addition, the effects were greater for south China (including Guangxi Zhuang Autonomous region, Guangdong, and Hainan provinces) than east China (including Shandong, Jiangsu, Zhejiang, Shanghai, Fujian, Anhui, and Jiangxi provinces). Furthermore, the analysis proved that the statistical climatic characteristics began to change significantly when the station spacing was between 40 and 50 km, which are close to the mean spacing for all stations across the mainland of China. Moreover, TC areal precipitation parameters, including mean total areal precipitation and mean daily areal precipitation, also began to change significantly when the spacing was between 40 and 50 km, and were completely different when it was between 100 and 200 km.

Key words: station density; tropical cyclone precipitation; climatic characteristic
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1 INTRODUCTION

China is one of the countries that is most heavily affected by tropical cyclones (TCs) (Chen and Ding[1]). The winds and torrential rain generated by TCs often cause significant loss of life and property. Consequently, TC precipitation and associated disasters have a particularly serious impact on China. Therefore, the number of researches into the climatic characteristics of TC precipitation has been gradually increasing in recent years (Cheng et al.[2]; Wang et al.[3]; Ding and Li[4]; Ying et al. [5]; Lin et al. [6]; Liu et al. [7]). However, most of the research into the climatic characteristics of TC precipitation has focused on such factors as whether the length of the station datasets covers the research target period, the station grade, and historical changes (Easterling et al.[8]; Pan and Zhai[9]; Wu et al.[10]; Ying and Wan[11]), but the density of stations and their spatial distribution are seldom considered. In fact, the spatial distribution and density of stations may also influence the results of climatic analysis of TCs.

In terms of the development of station network, which is gradually becoming denser, how to best use the observational data scientifically and effectively is a prime concern. Domestic and foreign scholars have carried out a great deal of research into quality control, homogeneity verification, and extreme value verification of the observational data. By comparing two methods for the correction of data homogeneity, Easterling et al. found that the use of a homogeneity correction and of different

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homogeneity correction methods for the observational data directly affects the results of climatic analysis[8]. When researching extreme temperature values, Pan and Zhai used adjacent stations as reference stations to avoid the influence of abnormal or erroneous values and removed any outliers[9]. Wu et al. proposed that station relocation is the main reason for the heterogeneity of data; therefore, special attention should be paid to the selection of stations used in climate research[10].

However, there has been little research into how changes in station density affect the resolution and accuracy of the data sampled and hence the resultant climate statistics. In fact, scientists will screen stations for climate research. To monitor global climate change, Peterson et al. selected the "best" global real-time exchange climate observation station net through analysis of station observation length (continuous duration), homogeneity, whether the stations were reference climatological stations, station real-time performance, the environment around the station, whether the stations were part of a specific observation network, as well as a range of other relevant factors[12]. As the correlation between surface temperature and latitude decreases from low to high latitudes, Peterson et al. followed the principle that the selected station density should increase from the equator to the poles[12]. Madden and Meehl considered that a higher station density should be used whenever possible in areas of maximum temperature variability or potential climate change[13]. With the aim of creating the most efficient global daily climatological dataset, Wang et al. removed stations within 150 km of each other, as they had determined that this was the critical distance in ensuring that the data collected were representative of the actual climatic conditions in the region[14]. Most of this previous research has focused on temperature that generally has strong spatial continuity, and there has been no research into precipitation that has relatively poor spatial continuity.

As pointed out by Peterson et al., the spatial distribution of stations should be chosen and optimized according to different research objectives[12]. TC precipitation is characterized mainly by its high intensity and poor spatial continuity. The development of the observation station network over the past 60 years has greatly enhanced the accuracy of the available TC precipitation data. However, for the study of climate over regional and larger scales, variations in the spatial sampling density are significant. Therefore, it is necessary to determine to what extent the density of the observation stations affects the statistical characteristics of the climatic analysis to provide an estimate of the uncertainty associated with the forecasts derived from these data. Meanwhile, at a time when the China Meteorological Administration is planning to compile the *Climatological Atlas of Tropical Cyclones over the Western North Pacific* (*1981–2010*) (Lei and Ying[15]), it is particularly important to explore the influence of the selection of meteorological observation stations on the statistical analysis of climatic characteristics. In this paper, we analyze the climatic precipitation characteristics associated with TCs over the mainland of China to determine the influence of the spatial density of different schemes of observation stations on the statistical characteristics of TC precipitation (such as the frequency, extreme values, and spatial distribution). The rest of the paper is organized as follows. Section 2 introduces the dataset used, section 3 describes the station selection process based on their spatial distribution, section 4 compares the influence of the different spatial densities of the station schemes on TC precipitation statistics, section 5 considers the differences in the statistical characteristics of areal rainfall generated by TCs, and the last section presents a discussion and our conclusions.

2 DATA AND METHODS

The data used to generate station density schemes were obtained from the *Climatological Atlas of Tropical Cyclones over the Western North Pacific* (*1981–2010*)[15]; therefore, the period analyzed was 1981-2010. Based on the distance that stations have been moved during the analysis period, only stations that have moved less than 7.8 km (i.e., the first 95% of the samples in ascending order of maximum station migration distance) were selected, which ensured the selection of some typical reference climate stations and that the changes in the station positions do not affect the presentation of the meteorological elements representing the grid points. This left 1,416 conventional ground-based meteorological observation stations in the mainland of China (excluding Taiwan, Hong Kong, and Macao), including the national basic weather station, the national reference climatological station, and the national general weather station. The station metadata information was obtained from the meteorological station metadata dataset (V1.0, 2013) compiled by the National Meteorological Information Center. The center also provided the station number, the start and end time of observations, the station level, the province where the station is located, the station location (central latitude and longitude), the station height above sea level (m), the station migration time, the station migration distance (m), and details of the surrounding environment.

The TC precipitation dataset for the mainland of China was obtained from Shanghai Typhoon Institute and covered the period 1981–2010. It contains TC number, station number, date, and daily precipitation (mm).

To analyze the influence of the differing spatial density of various subgroups of observation stations on the climate statistics, we performed sparsing of the current station network based on the Distance Analysis Method (DAM)[12]. This research focuses mainly on those regions most often affected by TCs, including east China, south China, and coastal areas, and so covers the middle and low latitudes and is a relatively small area. Thus, the DAM was carried out by removing stations within a critical distance of each other to make the station spacing wider and following the principle that the reference climatological station is preferred.

3 STATION SELECTION BASED ON SPATIAL DENSITY

The construction of the meteorological observation station network was carried out across the mainland of China between 1949 and 2011. In 1949, there were only 108 ground-based meteorological observation stations in the mainland of China, but this had increased to 925 by 1956, and 2,048 by 1959. Over the past decade, the number of meteorological observation stations in China has increased by a factor of 19, and the station network now covers most parts of the country reasonably well, except for the sparsely populated areas. Since then, a few stations have been closed due to changes in the observation environment such as urban construction. By 2011, the number of conventional ground-based stations in real-time operation had reached 2,405. The stations are relatively sparsely distributed in the west and north, and more densely concentrated in the middle, east, and south of the country, providing increased observation elements and greatly enhanced observation quality.

First, we calculated the spatial density of 1,416 stations across the mainland of China in different provinces and municipalities (Table 1). The mean distance between stations is 47.0 km, with the maximum mean separation being in Qinghai (107.1 km) and the minimum in Shanghai (28.0 km). The maximum distance between two stations is in Inner Mongolia (370.1 km), and the minimum in Qinghai (2.7 km). These stations are unevenly distributed across the provinces and municipalities. There are more stations in the southern and eastern coastal areas which are affected more frequently by TCs, such as Guangxi Region, Guangdong, Fujian, Hainan, Zhejiang, and Jiangsu, whereas the stations are more widely spaced in the western and northern inland areas, such as Qinghai, Inner Mongolia, and Heilongjiang.

We set the value of R to 0, 20, 30, 40, 50, 100, and 200 km. The DAM was then carried out for the 1,416 selected stations to obtain seven station network schemes of different spatial densities (Table 2).

Table 1. Station densities in various provinces and municipalities (in ascending order according to the mean spacing).

Provinces/municipalities	Number of selected stations	Mean spacing between stations/km	Maximum spacing between stations/km	Minimum spacing between stations/km
Shanghai	5	28.0	37.3	22.7
Jiangsu	57	31.5	57.2	12.3
Guangdong	78	33.1	66.1	11.4
Hunan	87	33.3	65.2	10.2
Fujian	59	33.7	53.4	16.8
Guangxi Region	84	33.8	68.9	9.8
Shandong	69	34.3	50.6	10.0
Shanxi	63	34.4	71.3	18.8
Zhejiang	50	35.3	84.8	17.4
Jiangxi	62	36.0	57.9	16.8
Anhui	56	37.0	97.9	16.9
Chongqing	29	39.2	88.8	23.2
Hubei	47	40.9	86.9	16.3
Ningxia	17	42.1	72.2	10.6
Guizhou	48	42.2	91.2	19.8
Hainan	19	42.6	82.7	23.2
Henan	52	42.7	68.9	15.4
Hebei	54	43.9	106.9	23.1
Liaoning	37	45.7	68.3	21.9
Sichuan	96	46.0	121.8	16.5
Shaanxi	53	48.4	98.9	26.1
Yunnan	80	50.1	149.9	9.4
Jilin	41	51.6	113.0	22.3
Beijing	4	55.1	79.3	32.2
Heilongjiang	60	61.6	158.3	25.9
Gansu	24	75.0	125.7	31.5
Tianjin	3	78.9	111.1	62.8
Inner Mongolia	70	79.4	370.1	27.6
Qinghai	12	107.1	173.5	2.7

Table 2. Criteria used to define the different spatial density station schemes.

Scheme	R/km	Number of selected stations	Comments
A	0	1,416	Station density unaltered in Scheme A
B	20	1,380	
C	30	1,227	
D	40	983	
E	50	821	R is the approximate average distance between all stations across the mainland of China
F	100	645	
G	200	614	

4 EFFECTS OF DIFFERENT STATION DENSITIES ON CLIMATE STATISTICS

Our aim was to investigate the effect of station density on the statistical climatic characteristics derived from the data provided by each scheme. Therefore, having defined seven station networks in which the distance between stations increased from 0 km in Scheme A, to 200 km in Scheme G (Table 2), we then calculated the daily TC precipitation statistics (i.e., total, maximum, and mean values, as well as spatial characteristics of torrential rain frequency) using data from each scheme as applied to the study areas of the mainland of China, the regions (east China and south China), and provinces (Hainan, Guangdong, and Jiangxi).

4.1 *Statistical results for the mainland of China*

4.1.1 STATISTICAL CHARACTERISTICS OF TOTAL PRECIPITATION GENERATED BY TCS OVER MAINLAND OF CHINA

The total, mean, and spatial distributions of precipitation generated by TCs over the mainland of China are shown in Table 3 and Figs. 1 and 2. Table 3 shows that over the decrease in station density (Schemes A-G), the maximum total precipitation over China is 1,323 mm, the mean range is 55.5-56.5 mm, and the standard deviation is 63.9-64.9 mm. The statistical characteristics of total precipitation are essentially the same for different spatial densities of the station schemes.

Table 3. Statistical characteristics of total precipitation generated by TCs over the mainland of China.

Station schemes (number of selected stations)	Maximum/mm	Mean value/mm	Standard deviation
A (1,416)	1,323	56.5	64.9
B (1,380)	1,323	56.4	64.9
C (1,227)	1,323	55.7	64.1
D (983)	1,323	55.5	64.5
E (821)	1,323	55.5	63.9
F (645)	1,323	55.9	64.3
G (614)	1,323	56.0	64.3

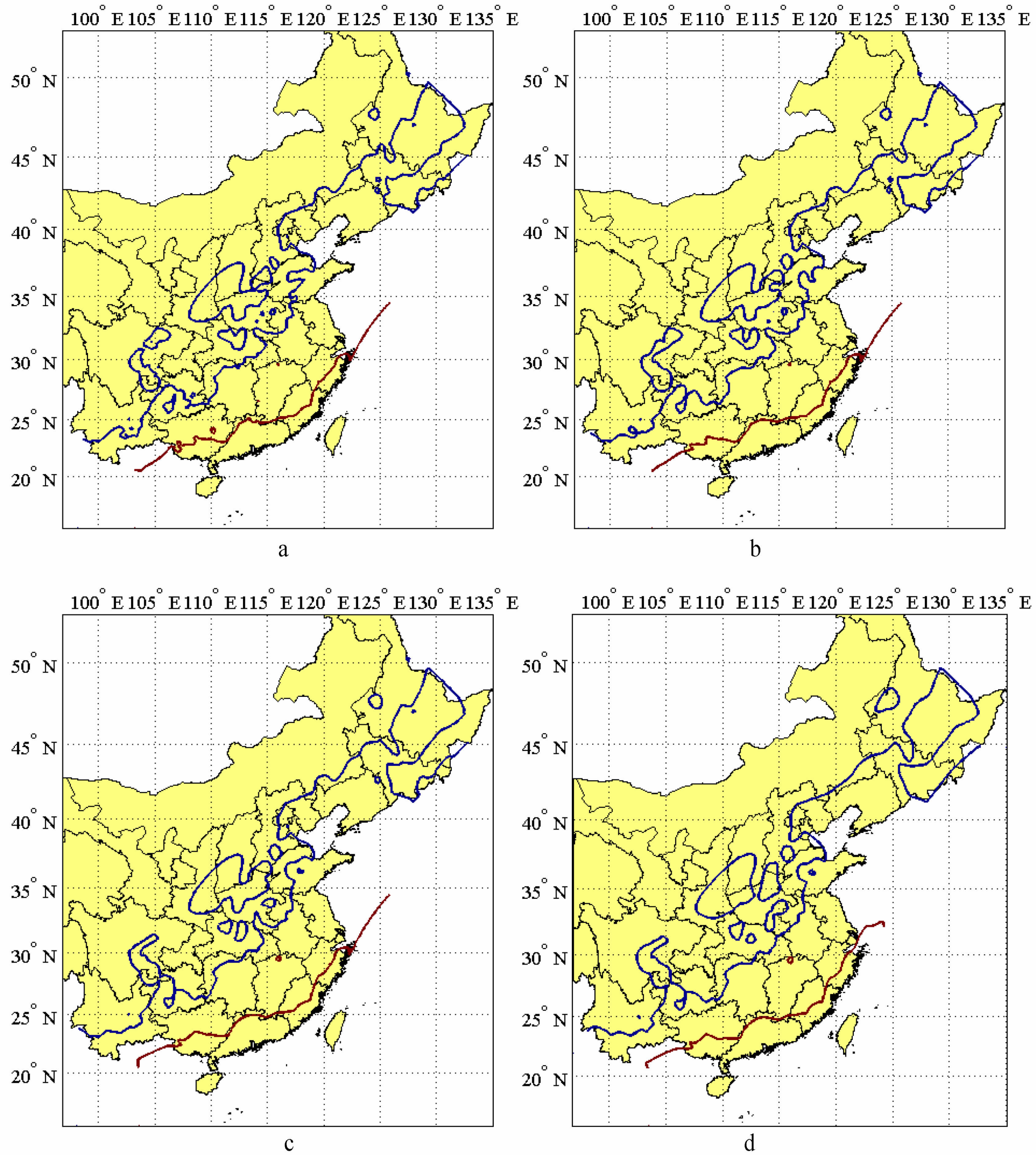
As the spatial distribution of stations changes from dense to sparse, the number of stations in each scheme declines from Scheme A to G, and so the statistical results also differ. However, for simplicity, we just focus on the results from schemes A (no reduction in station density, statistical results similar to those of schemes B and C), D (reduction in station density carried out with R = 40 km), E (reduction in station density carried out with R = 50 km), and F (reduction in station density carried out with R = 100 km, statistical results similar to those of scheme G). The annual mean precipitation and the spatial distribution of the maximum total precipitation are shown in Figs.1 and 2 for these four schemes.

Figure 1 compares the distribution of annual mean precipitation from the four schemes under consideration. The 200 mm isolines (in dark red) of the four schemes shown are identical, whereas the 50 mm isolines (in blue) are slightly different in eastern Sichuan, northern Hubei, and eastern Henan. Fig.2 shows the distribution of the maximum total precipitation. The overall tendencies of the 100 (in blue) and 300 mm isolines (in dark red) are similar moving from southwest to northeast, although the difference between the four schemes is obvious at the junction of Jilin and Heilongjiang. In addition, there are a few differences at the junction of the three provinces of northern Anhui, southwestern Shandong, and eastern Henan, as well as at the junction of southern Sichuan, northern Yunnan, and western Guizhou. Considering that these differences may be related to contour analysis and smoothing method, the spatial distributions of climate characteristics obtained by different schemes are basically the same.

4.1.2 STATISTICAL CHARACTERISTICS OF DAILY PRECIPITATION GENERATED BY TCS OVER MAINLAND OF CHINA

Table 4 demonstrates that, for the daily TC precipitation statistics, as station density decreases

(Schemes A-G) the mean daily precipitation remains relatively unchanged between 22.5 and 22.8 mm. However, there is a change in the maximum daily precipitation at Scheme E, with a value of 645 mm for Schemes A-D to 634 mm for Schemes E-G. The mean frequency of torrential rain is between 12 and 14. The standard deviation of daily precipitation is between 31.5 and 31.9 mm. It appears that there are only small differences in mean value and frequency across all schemes, but a clear difference in the maximum daily precipitation. The daily precipitation extreme values are shown in Fig.3. In the four schemes, the spatial characteristics of the 40 (in blue) and 100 mm isolines (in dark red) of the daily precipitation are basically the same. However, there is a difference in the 100 mm line between Hebei and northwestern Shandong, and there are also some differences at the junction of the three provinces of northern Anhui, southwestern Shandong, and eastern Henan, and at the junction of southern Sichuan, northern Yunnan, and western Guizhou.



a b

c d

Figure 1. Annual mean TC precipitation calculated from station networks of differing density. Units: mm. Blue line is 50 mm isoline and dark red line is 200 mm isoline. a. Scheme A (1,416 stations); b. Scheme D (983 stations); c. Scheme E (821 stations); d. Scheme F (645 stations).

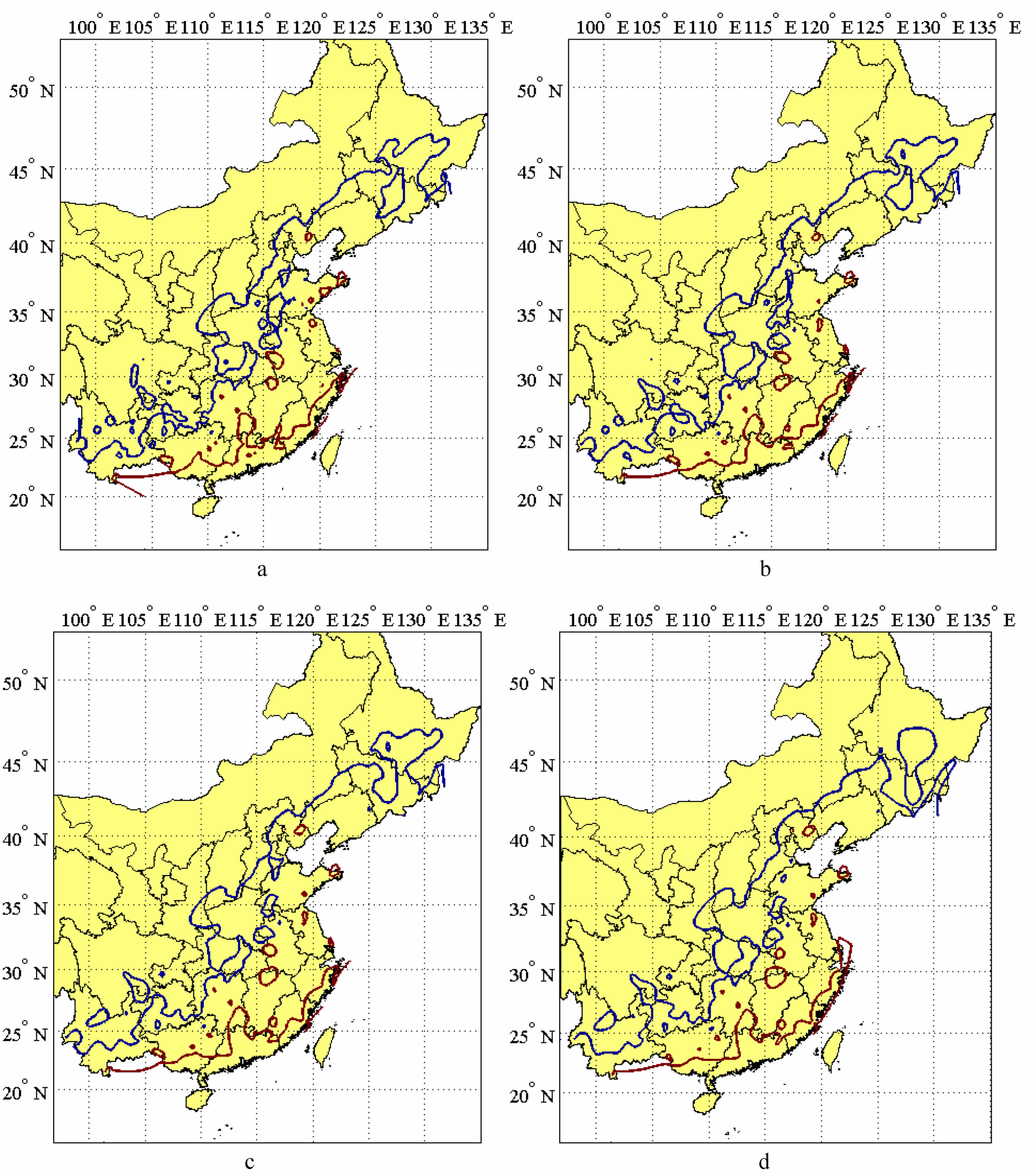


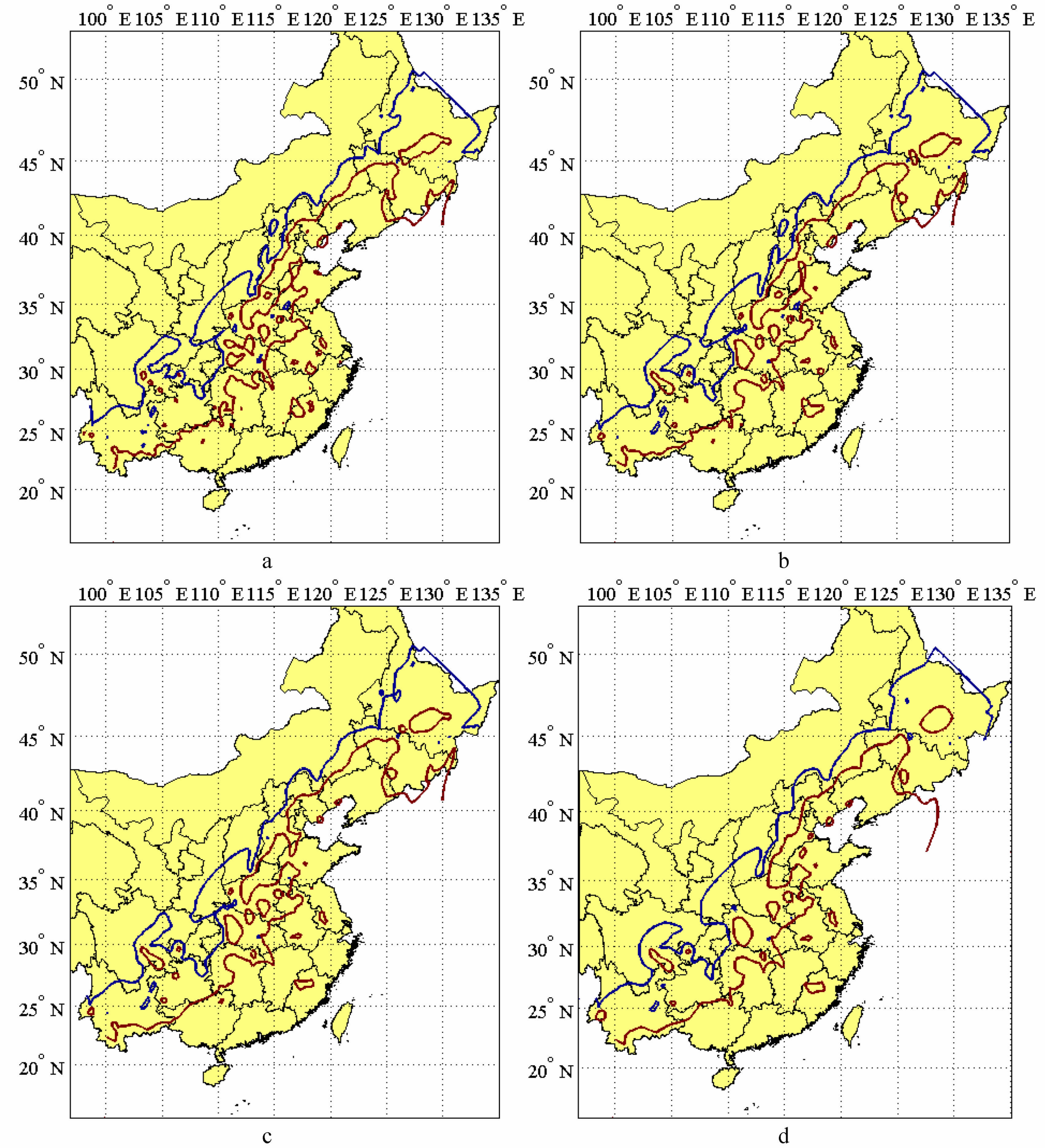
Figure 2. Maximum total precipitation generated by TCs calculated from different station schemes. Blue line is 100 mm isoline and dark red line is 300 mm isoline. Units: mm. a. Scheme A (1,416 stations), b. Scheme D (983 stations), c. Scheme E (821 stations), and d. Scheme F (645 stations).

Table 4. Daily precipitation statistics for TCs over the mainland of China.

Station density (number of stations)	Maximum daily TC precipitation/mm	Mean daily TC precipitation/mm	Standard deviation	Mean frequency of torrential rain (daily precipitation ≥50mm)
A(1,416)	645	22.8	31.9	14.2
B(1,380)	645	22.8	31.9	13.9
C(1,227)	645	22.5	31.6	13.1
D(983)	645	22.5	31.6	13.6
E(821)	634	22.6	31.5	12.2
F(645)	634	22.6	31.7	13.6
G(614)	634	22.6	31.7	14.0

Figure 4 shows the torrential rain frequency box-plot for the four station schemes A, D, E, and F (with density decreasing from A to F) over the mainland of China. The values at the third quartile, median, and first quartile of the torrential rain frequency from Schemes A, D, E, and F (from dense to sparse) are 13, 4, and 1 (A), 11, 3, and 1 (D), 10.75, 3, and 1(E), and 12, 4, and 1(F) respectively. This shows that when the stations are more widely separated, the frequency of TC torrential rain calculated from the observational dataset is slightly less than that calculated using the data from the denser station networks.

The above results show that the total precipitation, mean annual precipitation, mean daily precipitation, as well as their spatial characteristics, obtained from the seven different spatial density station schemes (A-G) are essentially the same. However, there is a slight difference in the maximum daily precipitation, its spatial distribution, and the torrential rain frequency. The maximum daily precipitation has a slightly different spatial distribution at the junction of the three provinces of northern Anhui, southwestern Shandong, and eastern Henan, and at the junction of the three provinces of southern Sichuan, northern Yunnan, and western Guizhou, but this is also related to the contour analysis and smoothing method. The variance analysis of the seven schemes shows that the difference is not significant. Therefore, in general, the characteristics of precipitation over the mainland of China generated by TCs and analyzed using the different schemes are the same; i.e., the overall conclusions drawn from these climatic statistics would not be affected by using observational datasets obtained from different spatial density station schemes.



a b c d

Figure 3. Maximum daily precipitation. Blue line is 40 mm isoline and dark red line is 100 mm isoline. Units: mm. a. Scheme A (1,416 stations), b. Scheme D (983 stations), c. Scheme E (821 stations), and d. Scheme F (645 stations).

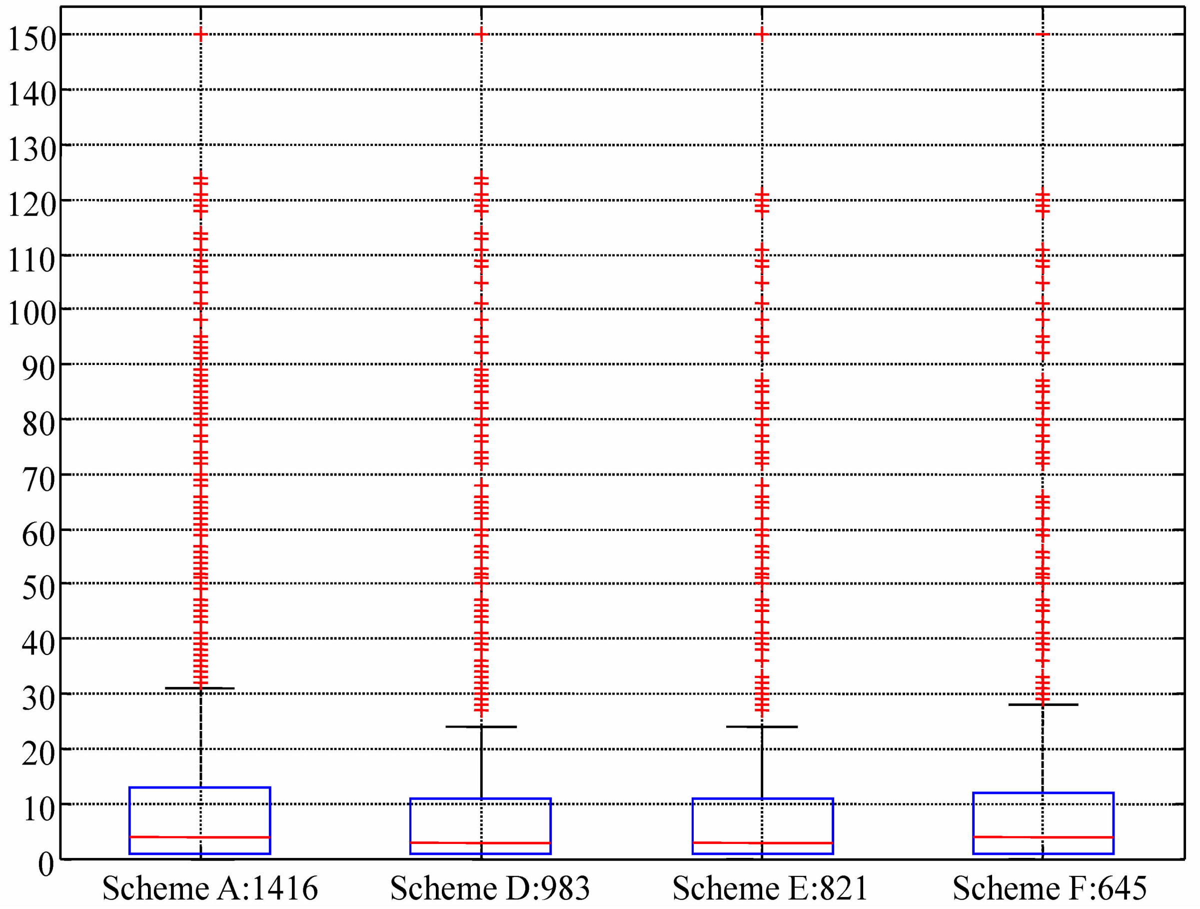


Figure 4. The torrential rain frequency box-plot for different spatial density station schemes on the mainland of China. The upper boundary of the rectangular box is the third quartile line of the sample, the lower boundary is the first quartile line, and the middle red line is the median line. The vertical axis is the torrential rain frequency and the horizontal axis is different spatial density station schemes showing the selected station numbers.

A comparison of the torrential rain frequency distribution over the mainland of China from this study with that in the *Climatological Atlas of Tropical Cyclones over the Western North Pacific* (*1951–2000*) (Xu [16]) demonstrates that the trends and distributions of the isolines for frequencies of 20 and 50 are basically the same. However, there is a difference for the zero frequency isoline. In this study, there is a zero isoline region in eastern Sichuan, Chongqing, and western Hubei. At the same time, the zero isoline is disconnected between Shanxi and Shaanxi. Despite the differing analysis periods and station densities used across the regions, a consistent trend in torrential rain frequency is evident. This shows that the statistical analysis based on different spatial density station schemes has no influence on the basic climate characteristics identified.

4.2 *Statistical results from different regions*

Focusing on east China and south China, we next analyzed the regional difference in the statistical results calculated from the TC climatology data obtained from the various station schemes. Table 5 shows that the mean daily precipitation differs little across south and east China for the seven schemes and the maximum does not exceed 1.2 mm. The maximum daily precipitation for east China was reduced by 33 mm from Scheme D onward (where the minimum distance R between stations used for rarefaction was 40 km) and the maximum daily precipitation in south China was reduced by 11 mm from Scheme E onward (where the minimum distance R between stations used for rarefaction was 50 km). There were also some slight differences in the torrential rain frequency, but these were not significant.

Figure 5 shows the torrential rain frequency box-plot obtained from the various schemes for east China (left) and south China (right). For east China, there is no significant difference among the seven torrential rain frequency schemes, and the values corresponding to the third quartile and the first quartile are all 19 and 6, respectively. The difference in the median value among the seven schemes is very small. For south China, the differences are slightly greater among the seven schemes. For Schemes A, B, C, F, and G, the values of the third quartile, median, and first quartile are all near 82.5, 40.5, and 18, respectively, whereas for Schemes D and E, the values of the third quartile, median, and first quartile are 86 and 84.25, 41 and 43, and 16.5 and 18 respectively; i.e., the difference is greater than that of other schemes. Therefore, for the torrential rain frequency, the choice of different spatial density station schemes has no effect on the results for east China and little effect for south China, and the obvious changes in torrential rain frequency begin to appear in the scheme with station spacing between 40 and 50 km. For regional experiments, the mean precipitation calculated using observational data from the different density station networks is basically the same; for the daily precipitation extreme value and frequency, the statistical results are different, and the quartiles of the different schemes also differ. The difference in south China is significantly greater than that in east China, which may have a small effect on the conclusion of the overall statistical analysis of TCs. However, the same variance analysis showed that there was no significant difference between various schemes.

Table 5. Statistical characteristics of regional daily precipitation generated by TCs.

Station density	Maximum daily precipitation/mm	Mean daily precipitation/mm	Standard deviation	Mean frequency of torrential rain (daily precipitation ≥50)
east China A	493	22.7	31.3	18.0
east China B	493	22.6	31.3	18.0
east China C	493	21.9	30.0	17.0
east China D	460	21.5	29.3	17.0
east China E	460	21.9	30.2	17.0
east China F	460	22.2	30.5	17.0
east China G	460	22.2	30.5	17.0
south China A	645	24.7	34.8	49.9
south China B	645	24.7	34.9	50.3
south China C	645	24.8	35.4	50.5
south China D	645	25.1	35.8	51.7
south China E	634	25.1	35.3	52.0
south China F	634	24.7	35.0	51.0
south China G	634	24.7	35.0	51.0

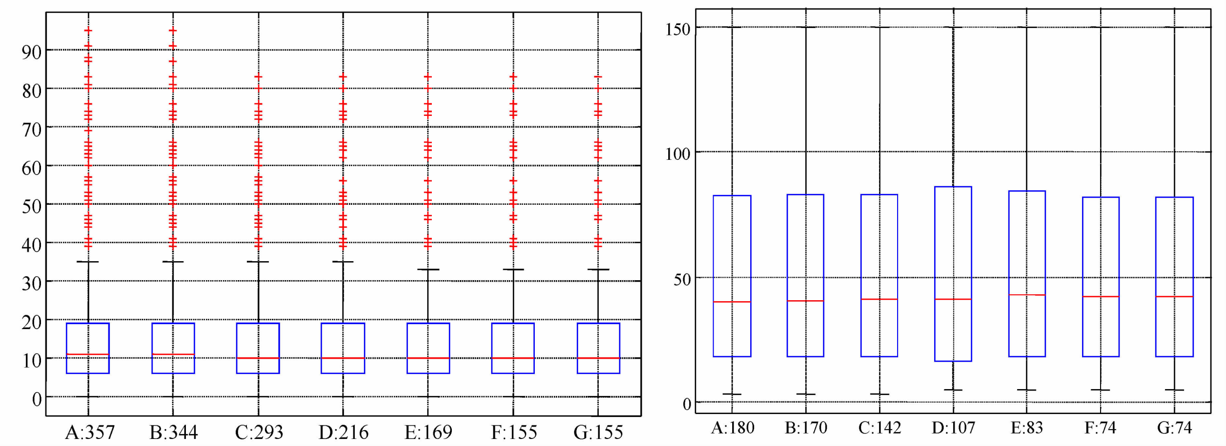


Figure 5. The same as Fig.4 but for the torrential rain frequencies from different schemes in east China (left) and south China (right).

4.3 *Statistical results from different provinces*

To investigate the differences in TC precipitation climatology among the provinces, we analyzed data from Guangdong (a coastal province frequently affected by TCs), Hainan (an island province frequently affected by TCs) and Jiangxi (an inland province frequently affected by TCs), and our statistical results are shown in Table 6. The maximum daily precipitation in Guangdong and Jiangxi is the same for the seven schemes, whereas the maximum for Hainan is slightly different in Scheme E and the lower density schemes, and the difference is 11 mm. The mean daily precipitation in the seven schemes for the three provinces is essentially the same, with a difference of no more than 1 mm. The torrential rain frequency box-plot obtained from the various schemes shows that the selection of different density station schemes has little effect on the results from Guangdong and Jiangxi but has a more obvious effect for Hainan. This may be because the spatial scale of Hainan Island is small (the island covers only 2.5° of latitude at its width), it is severely affected by TCs throughout the year, and the number of stations across the province is relatively small; therefore, the changes in the number of stations used in the climatic analysis will have a greater effect on the statistical results. In the three provinces, the most obvious change occurred for Scheme D or E, where the station spacing is 40-50km.

Table 6. Statistical characteristics of daily precipitation generated by TCs in various provinces.

Station density	Maximum daily precipitation/mm	Mean daily precipitation/mm	Standard deviation	Mean frequency of torrential rain (daily precipitation ≥50mm)
Guangdong A	560	24.8	33.9	63.1
Guangdong B	560	24.6	33.6	62.0
Guangdong C	560	24.4	33.6	61.0
Guangdong D	560	24.6	33.9	62.5
Guangdong E	560	24.9	34.4	64.3
Guangdong F	560	24.6	33.9	62.6
Guangdong G	560	24.6	33.9	62.6
Hainan A	645	31.5	45.7	108.3
Hainan B	645	31.5	45.7	108.3
Hainan C	645	31.7	46.1	108.6
Hainan D	645	32.4	46.9	114.4
Hainan E	634	32.4	46.1	115.6
Hainan F	634	32.0	45.3	119.9
Hainan G	634	32.0	45.3	119.9
Jiangxi A	351	18.6	24.1	12.9
Jiangxi B	351	18.5	24.0	12.9
Jiangxi C	351	18.5	24.1	13.0
Jiangxi D	351	18.0	23.6	11.9
Jiangxi E	351	18.4	24.5	12.6
Jiangxi F	351	18.4	24.9	12.8
Jiangxi G	351	18.4	24.9	12.8

The basic variance analysis of the statistical results showed that there is no significant difference between different schemes for the various regions and provinces, indicating that station selection is the main reason for different statistical results of TC precipitation. As a result, the datasets derived from the lower-density station network sometimes generate larger mean precipitation amounts or torrential rain frequencies, and this may be due to the specific characteristics of the TC precipitation observed at the stations selected. At the same time, because the spatial DAM was used for parsing the stations, after determining the R between stations for a set of 1,416 stations, a set of fixed stations was obtained in each scheme. However, the stations were randomly selected in different schemes and this can also lead to the statistically insignificant differences in the statistical climatic characteristics among different schemes.

5 STATISTICAL DIFFERENCES IN AREAL PRECIPITATION GENERATED BY TCS FROM DIFFERENT SCHEMES

Areal precipitation refers to the mean precipitation in an area, which is an important parameter in hydrology, particularly for flood forecasting (Yang et al.[17]; Wang[18]; Xu et al.[19]; Yu[20]), and compared with the traditional single point precipitation measurements, it can more objectively describe the actual precipitation status of a region[17]. Therefore, it is necessary to analyze whether the use of observational data from station networks of different spatial densities will affect the statistical characteristics of the areal precipitation generated by TCs.

In this research, the areal weight represented by the stations was our focus; therefore, the areal precipitation was calculated based on the Thiessen polygon method[17-20]:

$$P=\sum_{i=1}^{n}\frac{R_i S_i}{A i},$$

where P is the mean of areal precipitation in the study area (mm), R_i is the station precipitation in the current polygon area (mm), S_i is the current polygon area, A is the total area under consideration, and n is the total number of stations in the study area.

Our results show that, with the decrease in station density, there is no difference in total and daily areal precipitation across the mainland of China, in the two regions (east and south China), or in Hainan Province (taking Hainan frequently affected by TCs as a case) for Schemes A-C, and there was only a small change for Schemes D and E. For Schemes F and G, the mean areal precipitation increased by 5 to 28 mm. In other words, the station network schemes with different densities do affect the results of the statistical characteristics of areal precipitation, and the influence begins at a station spacing of around 40-50 km. When the station spacing reaches 100 or 200 km, the statistical results are completely different. This is related to the spatial distribution of the selected stations, the division method of Thiessen polygon, and the area calculation. In addition, the different areal precipitation calculation methods and terrains may also affect the results.

6 DISCUSSION AND CONCLUSIONS

Based on data from 1,416 conventional ground-based observation stations in the mainland of China, this paper analyzed the statistical differences in the climatic characteristics of TC precipitation between 1981 and 2010 caused by changing the spatial density of the station networks. Our main findings are as follows.

(1) For the mainland of China, the total precipitation, mean annual precipitation, mean daily precipitation, and their spatial characteristics for the seven different spatial station density schemes were essentially the same. However, the precipitation extreme values and their spatial characteristics were slightly different. In general, the different spatial station density schemes had no effect on the statistical properties of TC precipitation across the mainland of China.

(2) For the regions of east and south China, and the provinces of Guangdong, Hainan, and Jiangxi, the mean precipitation calculated for the different densities of station networks was the same, but there were differences in the extreme values and torrential rain frequencies. These changes emerged for Schemes D or E, that is, when the station spacing was 40–50 km, which is close to the mean spacing of the the mainland of China stations. The TC precipitation extreme values obtained using the data from the less-dense station networks were smaller than those obtained from the observation data with a higher-density station network, and the frequency box-plots were also different.

(3) In terms of the degree of influence, the difference between the various schemes in Hainan Province was significantly greater than that in Guangdong and Jiangxi, and similarly, it was more obvious in south China than east China. This will influence the conclusions derived from provincial or regional climate statistics. The variance analysis of the statistical characteristics showed that there was no significant difference in the various schemes for the regions and provinces, indicating that random station selection is the main reason for the difference.

In addition, our analysis of the influence of different spatial densities of the station networks on total and mean daily areal precipitation showed that the statistical values began to change when the station spacing was around 40 or 50 km, and when the station spacing reached 100 or 200 km, the differences in the results became larger. The results of Amani and Lebel's test[21] around the Niamey area (the capital of Niger) in 1988 showed that there is a linear relationship between the mean areal precipitation estimated using a dense station network and the mean areal precipitation estimated using a sparse station network; thus, the difference in the estimation of TC mean areal precipitation using different spatial density station schemes requires further research.

The above analysis demonstrates that, in the analysis of the climate characteristics of TC precipitation, a slightly sparser station network can be used for the total or mean daily precipitation to reduce the data analysis workload, but the station spacing cannot exceed 50 km. In addition, in this research the critical distance R (station spacing) used in the DAM was the same for all regions in each scheme and this was not so appropriate. In areas that are more frequently affected by TCs, the high precipitation intensity has a greater effect on climate statistics and a denser station network should be used than in areas that are less affected by (localized) high-precipitation events. Thus, different station spacings can be used in various provinces in future research to analyze their influence on the statistical characteristics of climate.

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