TROPICAL CYCLONE PRECIPITATION ESTIMATION AND REGULARITY ANALYSIS OF CHINA MAINLAND FROM 1951-2008

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Tropical Cyclone (TC) activity is an important feature of China’s climate that can have important impacts on precipitation and cause extensive property damage. In particular, precipitation from TCs contributes a significant portion of overall precipitation in China. This study deals with TCs that influenced China and focus on TC precipitation’s temporal and spatial regularity analysis. Surface TC precipitation datasets were generated by interpolation of precipitation contour maps based on station-observed precipitation from Typhoon Yearbook\textsuperscript{10} compiled by Shanghai Typhoon Institute of China Meteorological Administration (CMA_STI), and the interpolation results were verified by satellite-based derived precipitation data products from Fengyun(FY-2C)\textsuperscript{11} geostationary Meteorological Satellite. Based on the interpolated precipitation data (STI), two aspects were found in this research. Firstly, the TC precipitation gradually decreased from the southeast to the northwest of China, and the main area of TC precipitation concentrated in the southeast of China, including Hainan, Fujian, Zhejiang and Guangdong, while the most significant TC precipitation fluctuations arise in Shanxi, Henan and Hebei provinces. Secondly, there is no trend that was detected to pass 95% confidence level in annual TC precipitation and maximum TC precipitation from 1951 to 2008 in China, but a cycle of 5.43 years based on 95% confidence level was detected to be existing for annual maximum TC precipitation in China.

**Key Words**: Tropical Cyclone, Precipitation, Spatial Distribution, Temporal Distribution, Trend, Cycle

1. **INTRODUCTION**

Tropical cyclones (TCs) constitute one of the most destructive natural disasters that affect many countries around the world and lead to tremendous annual losses in human casualties and property. Every year, nearly 7-8 Typhoons (severe TC) would land china\textsuperscript{3}. According to the statistics from Chinese government, there are 4315 death and 45.06 million hectares of farmland flooded by tropical cyclone in Zhejiang province from 1949 to 1990, China\textsuperscript{4}.

The precipitation brought by tropical cyclone is one of the most significant causes of economy and life losses. In the report of IPCC Workshop on Changes in Extreme Weather and Climate Events (2002), the limitation that observed climatological records of tropical cyclone activity are of limited duration was pointed out\textsuperscript{5}. For example, spatial duration limitation for lack of complete coverage of basins in the pre-satellite era and temporal duration limitation for satellite data for limited historical satellite records. In addition, analysis of tropical cyclone climatological records for evidence of long-term trends are also emphasized as one of a three related topics of tropical cyclones and global climate change in the IPCC Report of 2002. Namely, the trend analysis of tropical precipitation based on a long time series is of great significance.

Steps to analyze the temporal and spatial regularity of TC precipitation can be concluded as follows in this research. Firstly, surface precipitation datasets (STI) were generated by inverse distance weighted interpolation based on TC precipitation contour data (STI_0) from Shanghai Typhoon Institute. Secondly, the satellite-based derived TC precipitation estimation products (FY) from FY-2C satellite, managed by China Meteorological Administration, verified the interpolated precipitation data (STI). Finally, the temporal and
spatial regularity were estimated based on the interpolated precipitation datasets (STI) from 1951 to 2008.

2. DATA AND ANALYSIS

The TC precipitation data used in this study includes two datasets. The first dataset is from Typhoon Yearbook compiled by Shanghai Typhoon Institute of the China Meteorological Administration (CMA_STI), which contains cumulative precipitation of each typhoon case mainly by rain gauges during 1951/05/12-2008/10/15 in contour maps. The second dataset, 1-hour full disk precipitation estimation products, is from Fengyun geostationary Meteorological Satellite (FY-2C), which contains hourly TC precipitation estimation with resolution of 0.1°×0.1° latitude-longitude grids from 2007/10/24-2010/01/19.

Rain gauges provide a direct measurement of rainfall, which can accurately reflect the rainfall of points. Satellite-derived rainfall is less direct, less accurate and limited records than gauges but has the advantage of complete coverage over river basins, mountainous regions, and sparsely populated areas where rain gauges are not available. Therefore Satellite-derived data can more efficiently reflect the spatial distribution and changes than rain gauges. Thus surface precipitation data (STI) with longer historical records, generated by isohyet data (STI_0), was verified by satellite-derived data (FY) with records of complete coverage of basins.

Data preparation for TC regularity analysis has been conducted as following steps:

(1) Deriving surface precipitation

There are different methods of interpolation\(^6\). Spatial interpolation method can be divided into three categories: the overall interpolation method (trend surface analysis and multiple regression method, etc.), local interpolation method (Thiessen polygons, inverse distance weighted method, Kriging and Spline) and mixed interpolation method (overall interpolation and local interpolation integrated)\(^7\).

Thiessen polygon, inverse distance squared method (a kind of inverse distance weighted method), kriging interpolation method are the most commonly used in the interpolation of precipitation.\(^8\) Thiessen polygon assumes that the precipitation needed to be estimated is the same with the most closed known sites’ precipitation. It is adaptable for topography without rolling hills and not appropriate for gradually changed precipitation in space. Cokriging (kriging includes ordinary kriging, universal kriging, cokriging) was proved to be able to get better interpolation results than other methods in mountainous areas as the influence of elevation change into was also taken into consideration by kriging method\(^8\). As the areas affected by TCs in China is mainly plain along the east coastline, inverse distance squared method can improve the accuracy of the interpolation compared with Thiessen without elevation information like kriging\(^9\).

Thus Datasets (STI_0) were adjusted into surface precipitation data by Inverse Distance Weighted interpolation as

\[
P_j = \sum_{i=1}^{n} w_i P_i
\]

\[
w_i = \frac{r_i^{-b}}{\sum_{i=1}^{n} r_i^{-b}}
\]

Where \(P_j\) represents the precipitation (site \(j\)) need to be estimated. \(w_i\) is the weight of the known site \(i\). \(P_i\) is the precipitation of known site \(i\). \(r_i\) is the distance between known site \(i\) and interpolation target site \(j\). Here \(b\) equals 2.

(2) Adjusting spatial and temporal resolution to compare with Fengyun (FY) dataset.

For the difference of metadata (shown in Table 1) from each dataset spatially and temporally,

<table>
<thead>
<tr>
<th>Table 1 Data Quality of each Metadata Datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
</tr>
<tr>
<td>0.05°×0.05°</td>
</tr>
<tr>
<td>Temporal Resolution</td>
</tr>
<tr>
<td>Length</td>
</tr>
</tbody>
</table>

Homogeneity adjustments were done by temporal accumulation and spatial integration as shown in Table 2. Spatial integration was done by converting all datasets into 0.5°×0.5° latitude-longitude grids. Temporal accumulation was done by adding up FY_0 hourly precipitation maps in same TC case, to generate FY entire TC precipitation datasets.

<table>
<thead>
<tr>
<th>Table 2 Produced Datasets from Metadata</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution</td>
</tr>
<tr>
<td>Temporal Resolution</td>
</tr>
<tr>
<td>0.05°×0.05°</td>
</tr>
<tr>
<td>Hourly</td>
</tr>
<tr>
<td>FY</td>
</tr>
</tbody>
</table>
FY is generated from FY_0 by temporal accumulation. STI is obtained from STI_0 by spatial integration.

(3) Computing overall TC precipitation of each TC case
As a grid can also represent a trapezoid as shown in figure 1, it is easy to calculate the area represented by a given grid ABCD by looking the earth as a sphere for approximation as

\[ A_{\text{grid}} = (AB + CD) \times h/2 \]  
(3)

![Earth Grid](image)

Where \( h \approx AC = BD = R \times \theta \times \pi/180 \)  
(4)

\[ (AB + CD)/2 = r \times \theta \times \pi/180 \]  
(5)

\[ r = R \times \cos(\varphi + \theta/2) \]  
(6)

Where \( R \) is radius of the Earth, here equals 6372797.0m. \( \varphi \) is the bottom latitude of the grid, \( \theta \) is the latitude angle of the grid, \( r \) is the average radius of the grid. Then

\[ V_{\text{grid}} = A_{\text{grid}} \times P_{\text{grid}} \]

\[ V_{\text{grid}} = \cos(\varphi + \theta/2) \times (R \times \theta \times \pi/180)^2 \times P_{\text{grid}} \]  
(7)

where \( P_{\text{grid}} \) is precipitation of the grid.

3. RESULTS

With datasets derived from metadata (STI_0, FY_0), the applicability of interpolated dataset (STI) was evaluated by comparing with satellite-based dataset (FY). Moreover TC precipitation regularity was also analyzed with interpolated surface observation datasets (STI) based on rain gauges. Results are explained below in details.

(1) Comparison between STI and FY
Interpolation could produce error, therefore the applicability of STI should be evaluated. The comparison between FY and STI (surface observation) was conducted by Absolute Error (A), Relative Error (B), Mean Absolute Error (A1), Mean Relative Error (B1), Maximum Absolute Error (A2), Maximum Relative Error (B2), Absolute Error Variance (A3), and Relative Error Variance (B3).

\[ A^k_{(i,j)} = \text{abs}(\text{grid}_{FY}^k_{(i,j)} - \text{grid}_{STI}^k_{(i,j)}) \]  
(8)

\[ B^k_{(i,j)} = \frac{\text{abs}(\text{grid}_{FY}^k_{(i,j)} - \text{grid}_{STI}^k_{(i,j)})}{\text{grid}_{FY}^k_{(i,j)}} \]  
(9)

\[ A1_{(i,j)} = \frac{\sum_{k=0}^{n} A^k_{(i,j)}}{n} \]  
(10)

\[ A2_{(i,j)} = \max[A^k_{(i,j)}]_{k=0}^{n} \]  
(11)

\[ A3_{(i,j)} = \sum_{k=0}^{n} A^2_{(i,j)} - A1_{(i,j)}^2/n \]  
(12)

\[ B1_{(i,j)} = \frac{\sum_{k=0}^{n} B^2_{(i,j)}}{n} \]  
(13)

\[ B2_{(i,j)} = \max[B^2_{(i,j)}]_{k=0}^{n} \]  
(14)

\[ B3_{(i,j)} = \sum_{k=0}^{n} (B^2_{(i,j)} - B1_{(i,j)})^2/n \]  
(15)

Where \( i, j \) is column and row number of each grid in a TC image, \( k \) is ID number of TC case. These indices were used to conduct the accuracy of spatial distribution of interpolated surface precipitation (STI) (see in Fig.2). 808 TC cases of STI from 1951-2008 were calculated in this research, while the application for verification was just 14 cases for the limited records of FY as FY-2C was working from 2004-2008. The comparison between FY and surface observation (Fig.2) shows that

I. From A1 and A2 in Fig.2, the difference between FY and STI evaluated by absolute error occurs in Hainan, Guangdong, Fujian, Zhejiang province of China. This is because such areas are the main TC-affected zones. The frequency and intensity of such areas are much more serious than other zones.

II. From B1, B2 and B3, there are two zones with obvious spatial difference; one is the area that extends to the northwest along Jiangxi, Anhui, Hubei and Henan province from the junction of Fujian and Zhejiang Province. Yangtze river flow through such provinces. And Dai had tested the precipitation estimation products of Fengyun, pointing that FY satellite-derived data reveals good quality in eastern areas with high frequency of rain but relatively not good quality along rivers. Another obvious spatial difference appears to be the junction of Jilin and Liaoning province.

Besides the spatial comparison, the comparison of TC precipitation volume between satellite-derived datasets (FY) and interpolated datasets based on observation (STI) was also conducted, shown in (Fig.3).

As shown in Fig.3, FY=1.0407×STI+18.659 with correlation coefficient \( R^2 = 0.94383 \), which reveals that interpolated surface precipitation (STI) are highly consistent to FY precipitation estimation data products, verifying the accuracy of STI for trend and cycle analysis. Moreover, average Tropical Cyclone precipitation is nearly 23 billion cubic meters (seen in temporal distribution below). The difference between regression line and 45-degree diagonal line, showing the difference between satellite-derived data and interpolated rain gauge data, is 1.8659 billion cubic meters as shown in Fig.3.
Fig. 2 Comparison between FY and surface observation. (Taiwan without data)
Therefore the difference between STI and FY is about \( \frac{1.87}{23} \approx 8\% \). The interpolated surface precipitation data (STI) was considered to be applicable for the following TC regularity analysis.

(2) Regularity Analysis of TC precipitation based on Surface Observation datasets

There were 808 TC cases that influenced China during 1951-2008 based on rain gauges from Shanghai Typhoon Institute. As regularity Analysis needs long-term time series, the records of satellite-derived precipitation data in China were limited. Thus the regularity analysis in this paper was based on historical records of observation after interpolation (STI).

a) Spatial Distribution

Four indices were used to evaluate the spatial distribution of historical TC precipitation in this study. They were mean value (Fig. 4a), maximum value (Fig.4b), absolute variance (Fig.4c) and relative variance (Fig. 4d) of 808 TC cases in gridded data.

- Mean Value
  \[ C_{1(i,j)} = \frac{\sum_{k=0}^{n} C_{k(i,j)}}{n} \]  
  \( i,j \) is column and row number of each grid in a TC case, \( k \) is TC case number. \( n \) is total number

- Maximum Value
  \[ C_{2(i,j)} = \max \{ C_{k(i,j)} \} \]  

- Absolute Variance
  \[ C_{3(i,j)} = \sum_{k=0}^{n} (C_{k(i,j)} - C_{1(i,j)})^2/n \]  

- Relative Variance
  \[ C_{4(i,j)} = \sum_{k=0}^{n} (C_{k(i,j)}/C_{1(i,j)} - 1)^2/n \]  

Fig.3. Comparison between FY and interpolated surface precipitation (STI)
of TC case, here 808. The spatial distribution of precipitation (Fig. 4) shows that

I. TC precipitation decreases from southeast to northwest, and the most influenced area by TC was Hainan, Guangdong, Fujian, Zhejiang, southern Guangxi province. (Fig. 4a)

II. Although intense TC precipitation generally happened in the southeast coast of China mainland (Fig. 4a), North China, especially Northern Shanxi, Henan and Hebei province, also appeared to be intense TC precipitation (Fig. 4b). This conclusion can also be seen in Zhang’s paper about the influence of El Niño on Shanxi province. But such regions showed high variance of precipitation (Fig. 4d), revealing that precipitation spread out around the mean precipitation of TC event series in such areas. Namely, intense TC precipitation appeared to be occasionally in such areas.

**b) Temporal Distribution**

The number of TC cases and total precipitation from 1951-2008 were presented in Fig. 5. There were 808 TC events affected China from 1951 to 2008, with single TC precipitation from 0.3345 billion cubic meters to 151.508 billion cubic meters. Average TC precipitation reached 22.9406 billion cubic meters, namely nearly 20 billion tons.

Analysis of tropical cyclone climatological records for evidence of long-term trends was emphasized in the IPCC Report of 2002. Cycle and Trend detection are two most important research tasks of TC precipitation analysis for TC precipitation prediction in this study. Power Spectrum Analysis was used to detect the cycle of TC precipitation. The point that the curve of Power Spectrum Density (PSD) exceeds the 95% significance line reveals the cycle of TC precipitation.

As shown in Fig. 6a&6b, there was no cycle detected to pass 95% confidence level for annual TC precipitation, but a 5.43 years’ cycle for annual maximum TC precipitation was detected.

The trend of TC precipitation was conducted by Mann-Kendall rank statistics in this study as Fig. 7 shows. C1 is a normalized sequence of TC precipitation in natural time series from 1951 to 2008, and C2 is a normalized retrograde sequence in adverse time series from 2008 to 1951. The theory and procedures can be found in Wang’s paper on Mann-Kendall rank statistics. When C1 or C2 curve exceeds the significance dashed line, it proves that an abrupt change has been detected.
intersection of two curves (C1 and C2) lies within the two-side 95% confidence level localized the abrupt change point. As Fig. 7a&7b show, there is no abrupt change for annual TC precipitation or annual maximum TC precipitation, which means no trend had been detected to pass 95% confidence level in this study based on 58 years’ surface observation TC precipitation data.

4. CONCLUSIONS

The main objectives of this study, as stated in the introduction, are spatial and temporal regularity analysis of TC precipitation. From all of the results shown in this study, two main conclusions can be drawn.

a) TC precipitation gradually reduced from southeast to northwest in China. The typhoon rainfall mainly concentrated in the regions of Hainan, Fujian, Zhejiang and Guangdong as these regions are the mostly frequently affected by tropical Cyclones. But the most significant Typhoon precipitation fluctuations arise in Shanxi, Henan and Hebei provinces.

b) There is no trend that was detected to pass 95% confidence level in annual typhoon precipitation and maximum typhoon precipitation from 1951 to 2008 in China, but a cycle of 5.43 years based on 95% confidence level was proved to exist for annual maximum TC precipitation in China.

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