Spatial and Temporal Variation Characteristics of the Intensity of Landfall Tropical Cyclones in China

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Abstract. Based on the tropical cyclone data of the United States Joint Typhoon Center, this paper analyses the characteristics of the temporal and spatial changes of tropical cyclones that landed in China from 1951 to 2015. The conclusions are as follows: (1) The frequency of landings showed a slow upward trend from 1951 to the early 1990s, and showed a slow downward trend from the late 1990s to 2015. In 1988, it changed from a low period to a high period. (2) Tropical cyclones are mainly distributed in the range of 130-140°E, 10-15°N east of the Philippine Islands, and the northeastern part of the South China Sea. The spatial distribution of the first eigenvector of the source frequency EOF is basically the same as the multi-year spatial distribution. From the time coefficient of the first mode, the change trend of the concentrated distribution has undergone a process of strengthening-weakening. From the perspective of the spatial distribution of the second mode, the source frequencies in the Northwest Pacific and the South China Sea have opposite spatial distribution characteristics in the latitude direction. (3) One of the main tracks of landfall tropical cyclones is westward from the tropical Pacific to the Philippine Sea and South China Sea, and the other from the tropical Pacific to the northwest to South Korea and Japan, affecting the area near the coast of East Asia. The spatial distribution of the first eigenvector of the track frequency EOF is basically the same as that of the multi-year spatial distribution, and the spatial distribution of the second mode has a positive-negative opposite spatial distribution characteristic in the meridian direction.

1. Introduction
Tropical cyclones are the product of air-sea interaction, one of the most harmful natural disaster weather systems, and the focus of international research projects. The relationship between changes in tropical cyclone activity and global warming has attracted widespread public attention, and has become a focus and hot issue in the international tropical cyclone climate community[1-3]. Due to limitations of data or technology, most early studies focused on individual case studies of tropical cyclones. It was not until the 1970s that the international community began to pay attention to the research on the characteristics of interannual and interdecadal changes of tropical cyclones, Vecchi and Knutson[4] believe that in the past 100 years, the tropical cyclone activity in the eastern part of the North Atlantic has shown an increasing trend, while the western tropical cyclone activity has shown a decreasing trend. In the research on the relationship between tropical cyclone activity and global climate change, most of the focus is on the relationship between climate change and the intensity and frequency of tropical cyclones [5-8], some scholars pointed out that there are obvious temporal and spatial differences in tropical cyclone activity in the Northwest Pacific[9,10]. These studies reveal that there are obvious interannual and interdecadal changes in tropical cyclone activity in the tropical
northwest Pacific. However, this connection may be inconsistent in different regions of the Northwest Pacific. This article is based on tropical cyclone data released by the United States Joint Typhoon Center. Discuss the temporal and spatial characteristics of tropical cyclone activities (landing frequency, landing location, source, track) in China under the background of global warming, so as to provide scientific basis for regional marine environmental forecasting and short-term climate prediction, and promote and improve my country The level of ocean and climate monitoring and forecasting.

2. Data and methodology
Tropical cyclone data comes from the United States Joint Typhoon Warning Center (JTWC) (https://metoc.ndbc.noaa.gov/en/web/guest/jtwc/products-and-services-notice) the best tropical cyclones of 1951-2015 Track data set. The data set mainly includes the spatial position of the tropical cyclone center, the central pressure, and the maximum wind speed (1 minute central observation) every 6 hours. The empirical orthogonal function analysis method (EOF) method is used to analyse the time and space changes of the source and the track meter, and the t-test method is used to test the significance of the difference of the conclusions.

EOF (empirical orthogonal function, abbreviated as EOF), also known as eigenvector analysis (eigenvector analysis), or principal component analysis (PCA), is a way to analyse the structural features in matrix data and extract the main data features One way. Lorenz first introduced it to meteorology and climate research in the 1950s, and it is now widely used in geosciences and other disciplines. In geoscience data analysis, feature vectors usually correspond to spatial samples, so they are also called spatial feature vectors or spatial modes; principal components correspond to temporal changes, also called temporal coefficients. Therefore, EOF analysis is also called spatiotemporal decomposition in geosciences.

Principle and algorithm: The data to be analysed is selected and preprocessed, usually in the form of anomalies. You get a data matrix. The cross product of X and its transpose matrix is calculated to obtain the square matrix $X_{m \times n}$ :

$$C_{m \times n} = \frac{1}{n} X \times X^T$$

If X has been processed into anomalies, then C is called the covariance matrix; if X has been standardized (that is, the mean value of each row of data in C is 0 and the standard deviation is 1), then C is called the correlation coefficient matrix. Calculate the eigenvalue and eigenvector of square matrix C, which meet the following requirements:

$$C_{m \times n} \times V_{m \times n} = V_{m \times n} \times \Lambda_{m \times n}$$

Where: is dimensional diagonal matrix, that is

$$\Lambda = \begin{bmatrix}
\lambda_1 & 0 & \cdots & 0 \\
0 & \lambda_2 & \cdots & 0 \\
\cdots & \cdots & \cdots & \cdots \\
0 & 0 & \cdots & \lambda_m 
\end{bmatrix}$$

Generally, put the characteristic roots in order from the largest to the smallest, that is $\lambda_1 > \lambda_2 > \cdots > \lambda_m$. Since the data X is a true observation, it should be greater than or equal to 0.

Each non-zero feature root corresponds to a column of eigenvector values, also known as EOF. For example, the eigenvector value corresponding to 1 is called the first EOF mode, that is, the first column of V is $EOF_1 = (1,1)$; The eigenvector corresponding to k is the KTH column of V is $EOF_k = (1,k)$. Calculate the principal component. Projection of EOF onto the original data matrix X can obtain the time coefficient (namely, principal component) corresponding to all space eigenvectors, which is
\[ PC_{\text{mean}} = V_{\text{mean}}^T \times X_{\text{mean}} \]

Where, each row of data in PC is the time coefficient corresponding to each eigenvector. The first line \( PC (1,:) \) is the time coefficient of the first EOF, and so on. Above are the EOF and principal component (PC) obtained by computing the data matrix \( X \). Therefore, the original data matrix \( X \) can also be completely recovered by using EOF and PC, which is

\[ X = \text{EOF} \times \text{PC} \]

Sometimes the most prominent EOF modes can be used to fit the main characteristics of the matrix \( X \). In addition, both EOF and PC have the characteristics of orthogonality, which can prove

\[ \frac{1}{n} \sum_{i=1}^{n} PC_{\text{mean}} \times PC^T = \Lambda \]

That is, the correlation between different PCs is zero. \( E \times E^T = I \), \( I \) is the diagonal identity matrix, that is, the value on the diagonal is 1, and the other elements are all 0. This shows that the correlation between the various modes is 0 and is independent. It can be seen from the above calculation process that the core of EOF analysis is to calculate the eigenvalue and eigenvector of matrix \( C \).

3. Temporal characteristics of the intensity of landfall tropical cyclones in China

3.1 Monthly variation characteristics of landing frequency

The generation of tropical cyclones (TC) is mainly concentrated from May to December, which are: 69, 117, 249, 355, 321, 245, 157, and 60. There are fewer tropical cyclones from January to April; landfall from TC In terms of the monthly changes in frequency, tropical cyclones landed from April to December of the year, but they were mainly concentrated in May to November. They were: 16, 56, 132, 129, 109, 38, and 12, accounting for the total about 99% of the number of logins (Figure 1). Therefore, the time range of landfall tropical cyclones selected in this article is May-November 1951-2015.

![Figure 1](image)

**Figure 1.** Monthly formation of tropical cyclones in the Northwest Pacific Ocean from 1951-2015.

3.2 Long-term trends of tropical cyclones of different levels

According to the National standard of Tropical Cyclone Classification (2006), tropical cyclones are classified into six categories: tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), strong typhoon (STY) and super typhoon (SuperTY). It is shown in Figure 2 that the frequency of TD, TS, STS, TY, STY and SuperTY from 1951 to 2015 has strong interannual and decadal characteristics.
Figure 2a shows the frequency of TD, which showed a slow upward trend from 1951 to the end of the 1990s, and a rapid downward trend from the early 2000s to 2015 (red fitting curve). However, from the perspective of long-term change trend (green trend line), the frequency of tropical depression showed an upward trend from 1951-2015, which passed the 0.05 significance level test. Figure 2b shows that the frequency of TS showed a slow decline from 1951 to the late 1960s, and a slow rise from the early 1970s to 2015. From the long-term trend, the frequency of tropical storms showed an upward trend from 1951-2015, but failed to pass the 0.05 significant level test. Figure 2c shows that the frequency of STS showed an upward trend from 1951 to the late 1970s, and a downward trend from the early 1980s to 2015. In terms of long-term trend, the frequency of severe tropical storms showed a slow upward trend from 1951-2015, but failed to pass the 0.05 significant level test. Figure 2d shows that the frequency of TY showed an upward trend from 1951 to the late 1970s, and a downward trend from the early 1980s to 2015. In terms of long-term trend, the frequency of typhoons showed a slow upward trend from 1951-2015, but failed to pass the 0.05 significant level test. Figure 2e shows that the frequency of STY did not change significantly from 1951 to the late 1990s, but showed a downward trend from the early 2000s to 2015. From the long-term trend, the frequency of strong typhoons showed a slow decline from 1951-2015, but failed to pass the 0.05 significant level test. Figure 2f reflects the changing trend of SuperTY. The landing frequency showed a slow decline from 1951 to the late 1970s, and a slow rise from the late 1980s to 2015. From the long-term trend, the frequency of super typhoons landed from 1951 to 2015 showed a trend of slow weakening, but failed to pass the 0.05 significance level test (P =0.15).

3.3 Long-term change trend of landing location
From 1951 to 2015, a total of 498 tropical cyclones (excluding tropical depressions) generated over the Northwest Pacific Ocean (including the South China Sea) made landfall in China. Figure 3 shows
that the landing latitude from 1951 to 2015 has strong interannual and interdecadal changes. There was an upward trend from 1951 to the late 1960s, a downward trend from the early 1960s to the early 1980s, and a slow upward trend from the late 1980s to the late 2000s. From the long-term trend (green trend line), there is no obvious upward or downward trend.

![Figure 3. Time change of tropical cyclone latitude from 1951-2015.](image)

**Figure 3. Time change of tropical cyclone latitude from 1951-2015.**

### 4. Spatial and temporal variation characteristics of tropical cyclone landfall in China

#### 4.1 Spatial and temporal variation characteristics of tropical cyclone origin

Figure 4 depicts the spatial distribution of the locations where tropical cyclones are generated from 1951-2015. The geographic distribution of tropical cyclone frequencies is mainly distributed in two regions, one is in the Northwest Pacific (130-140°E, 10-15°N), the other is in the northeastern part of the South China Sea (115°E, 15-20°N), and the center value of the South China Sea is slightly higher than the center value of the Northwest Pacific, which means it landed The most active source of tropical cyclones in China is in the South China Sea. This conclusion is basically consistent with the research results of other scholars [11-13].

![Figure 4. Spatial distribution characteristics of tropical cyclone Sources (every 10 years).](image)

**Figure 4. Spatial distribution characteristics of tropical cyclone Sources (every 10 years).**

From the spatial distribution of the first feature vector of the source frequency EOF (Figure 5a), it can be seen that the feature vectors are all positive in the key area. The two positive centers are in the 130-140°E, 10-15°N range of the Northwest Pacific Ocean (east of the Philippine Islands) and the northeast South China Sea (115°E, 15-20°N). This is basically the same as the multi-year spatial distribution characteristics (Figure 4). The spatial distribution of the first eigenvector of the source frequency EOF is essentially the spatial distribution of the tropical cyclone source. The sliding T test of the time coefficient of the first mode did not find a jump phenomenon (Figure 5b).

According to the spatial distribution of the second mode (Figure 5b), the latitudinal direction of the South China Sea is positive-negative, while the latitudinal direction of the Northwest Pacific Ocean is negative-positive. This characteristic indicates that the frequency of landfall tropical cyclone in the Northwest Pacific Ocean and the south China Sea often show the opposite trend. The sliding T-test of the time coefficient of the second mode found that the mutation from high value to low value occurred
around 1980, indicating that the variation trend of the South China Sea contrary to that of the Northwest Pacific Ocean began to weaken in the early 1980s (Figure 5d).

Figure 5. EOF decomposition of the generation frequency of tropical cyclone source area. (a) The spatial distribution of the first mode; (b) The time coefficient of the first mode; (c) The spatial distribution of the second mode; (d) The time coefficient of the second mode

4.2 Spatial and temporal variation characteristics of the frequency of tropical cyclone tracks
The track of tropical cyclones can be described by the frequency of occurrence of tropical cyclones. The frequency of occurrence is calculated by calculating the number of tropical cyclones passing in a grid of 5º × 5º latitude and longitude. The calculation is based on the tropical cyclone position data every 6 hours. Enter the same grid only once, and the result can reflect the chance of an area being affected by tropical cyclones[14].

Figure 6 depicts the spatial distribution characteristics of the track frequency from 1951-2015. One main track is from the tropical Pacific to the west to the Philippine Sea and the South China Sea, and the other is from the tropical Pacific to the northwest to South Korea, Japan affects the area near the coast of the East Asian continent; the maximum passing frequency of tropical cyclones occurs in the annex area centered at 115-125ºE and 15-25ºN.

Figure 6. Spatial Distribution characteristics of tropical cyclone Track Frequency (every 10 years)

From the spatial distribution of the first feature vector of the track frequency EOF (Figure 7a), it can be seen that the feature vectors are all positive in the critical region. The center is distributed in the
range of 110-130°E and 15-25°N in the east of the South China Sea, which is basically the same as the multi-year spatial distribution characteristics (Figure 5). The spatial distribution of the first eigenvector of the track frequency EOF is essentially the spatial distribution characteristics of the tropical cyclone track frequency. A sliding T test was performed on the time coefficient of the first mode, and it was found that there were two more changes in 1986 and 1996 (Figure 7b), indicating that this centralized distribution trend showed a weakening trend after 1986, until 1996. The trend of annual concentrated distribution is rapidly strengthening.

From the spatial distribution of the second mode (Figure 7b), the positive center mainly appears in the northern part of Taiwan Island (115-125°E, 20-30°N), and the negative center is mainly distributed in the South China Sea. In the east (110-120°E, 15-25°N), the meridional direction is positive-negative. The time coefficient of the second mode indicates that the frequency of the tropical cyclone landing in the northern part of Taiwan Island and the eastern part of the South China Sea often shows opposite trends. The sliding T test of the time coefficient of the second mode found that abrupt changes occurred around 2000, indicating that the opposite trend of track frequency between the northern part of Taiwan Island and the eastern part of the South China Sea began to strengthen in the early 2000s (Figure 8d).

Figure 7. EOF decomposition of tropical cyclone track frequency. (a) The spatial distribution of the first mode; (b) The time coefficient of the first mode; (c) The spatial distribution of the second mode; (d) The time coefficient of the second mode.

5. Conclusions
Based on the tropical cyclone data of the United States Joint Typhoon Center, this paper analyses the characteristics of the temporal and spatial changes of tropical cyclones that landed in China from 1951 to 2015. The conclusions are as follows: (1) The frequency of landings showed a slow upward trend from 1951 to the early 1990s, and showed a slow downward trend from the late 1990s to 2015. In 1988, it changed from a low period to a high period. (2) Tropical cyclones are mainly distributed in the range of 130-140°E, 10-15°N east of the Philippine Islands, and the northeastern part of the South China Sea. The spatial distribution of the first eigenvector of the source frequency EOF is basically the same as the multi-year spatial distribution. From the time coefficient of the first mode, the change trend of the concentrated distribution has undergone a process of strengthening-weakening. From the perspective of the spatial distribution of the second mode, the source frequencies in the Northwest Pacific and the South China Sea have opposite spatial distribution characteristics in the latitude...
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