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A graded index for evaluating precipitation heterogeneity in China

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Abstract: Precipitation heterogeneity has a nontrivial influence on human life. Many studies have analyzed precipitation heterogeneity but none have proposed a systematic graded index for its evaluation, and therefore, its true characteristics have not been expressed. After comparisons of various methods, the precipitation concentration degree (PCD) method was selected to study precipitation heterogeneity. In addition to the PCD, normal distribution functions, cumulative frequencies, and percentiles were used to establish a graded index for evaluating precipitation heterogeneity. A comprehensive evaluation of precipitation heterogeneity was performed, and its spatiotemporal variation in China from 1960 to 2013 was analyzed. The results indicated that (1) seven categories of precipitation heterogeneity were identified (high centralization, moderate centralization, mild centralization, normal, mild dispersion, moderate dispersion, and high dispersion) and (2) during the study period, the precipitation in more parts of China tended to be normal or dispersed, which is beneficial to human activities.

Keywords: heterogeneity; precipitation concentration degree; evaluation index; comprehensive evaluation; China

1 Introduction

The uneven distribution of precipitation has an important impact on agricultural production, flood control, drought relief, human life and other activities. When the precipitation is too concentrated, flooding may occur, and droughts may occur during the rest of the year. Droughts occur in areas that lack precipitation because it is too spatially concentrated. No matter which water diversion measures are taken over time or space, a significant investment is required. The more even the precipitation is, the more favorable an area is for life. For

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example, southern areas were growing three crops per year; the more evenly the precipitation is distributed in a year, the more suitable the region is for growing crops. If the precipitation is too concentrated in summer, the availability of sufficient water for spring and autumn crops cannot be ensured.

Tang *et al*. (1982b) discussed the non-uniform coefficient of the annual runoff distribution and created a contour map of the national non-uniform coefficient. Non-uniform coefficient was introduced into the study of precipitation heterogeneity and has been widely used (Feng *et al*., 2000; Zheng *et al*., 2003; Gu *et al*., 2010). The concept of a non-uniform coefficient has a clear and general use (Feng *et al*., 2000), but simple data cannot reflect the concentration of annual runoff in different periods of a year or the period that has the most runoff (Tang *et al*., 1982a). Tang *et al.* (1982a) used a vector method of determining the annual precipitation distribution as a reference and adopted vector synthesis to calculate concentration degrees and concentration periods of river runoff; this method has a higher resolution than the runoff distributive uniformity coefficient for a period of one year. Yang (1984) has improved this formula. Based on the runoff concentration degree and period (Wang *et al*., 2007), Zhang and Qian (2003, 2004) improved and redefined the precipitation concentration degree (PCD) and the precipitation concentration period (PCP), which were widely used (Cao *et al*., 2013; Li *et al*., 2011; Liu *et al*., 2013; Lu *et al*., 2012; Qin *et al*., 2010; Wang *et al*., 2013; Zou *et al*., 2013). In addition, some scholars have used a complete adjustment coefficient (Feng *et al*., 1994; Zheng *et al*., 2003), a Gini coefficient (Liu *et al*., 2007; Shi *et al*., 2012, 2013) or an apportionment entropy disorder index (Deng *et al*., 2014; Mishra A K *et al*., 2009; Singh V P, 1997; Wang *et al*., 2007) to study the heterogeneity of runoff and precipitation in detail.

Although the methods of studying precipitation heterogeneity are sundry and mature, a graded evaluation index has not been systematically developed. Several researchers have compared the calculated actual data and discussed the differences in heterogeneity of different areas and their spatiotemporal characteristics. A Gini coefficient can be divided into five general international sections and has some reference. However, because Gini coefficients are generally used in economics and the division of sections is primarily based on economic considerations, it obviously differs in a geographical and meteorological sense, and the four methods of estimating Gini coefficients have some disadvantages, such as being complex (Xiong, 2003), easily affected by deviations and inconvenient to use. The resolution and sensitivity of the PCD are higher (Tang *et al*., 1982a; Yang, 1984). Using original data in calculations avoids data distortion and allows free adjustment of the calculation's time scale. The method of calculation is simple, effective and less affected by deviations. It is dimensionless between 0 and 1 and very comparable. Therefore, our research tries to establish a graded index for evaluating precipitation heterogeneity based on the PCD and apply it in a comprehensive evaluation of the precipitation heterogeneity in China.

2 Materials and methods

2.1 Materials

Meteorological data were obtained from the observation data for the 56-year period from 1960 to 2013 in the Chinese Daily Terrestrial Climate Dataset collected by the China Meteorological Data Sharing Service Network. To ensure the integrity of the data (i.e., no more than 30 days of continuous missing data) and a uniform distribution, we removed observation stations with comparatively more outliers and selected data from 569 national observation stations (Figure 1) for further analysis. The missing data were imputed using the expectation-maximization algorithm (EM) in SPSS 21.0.

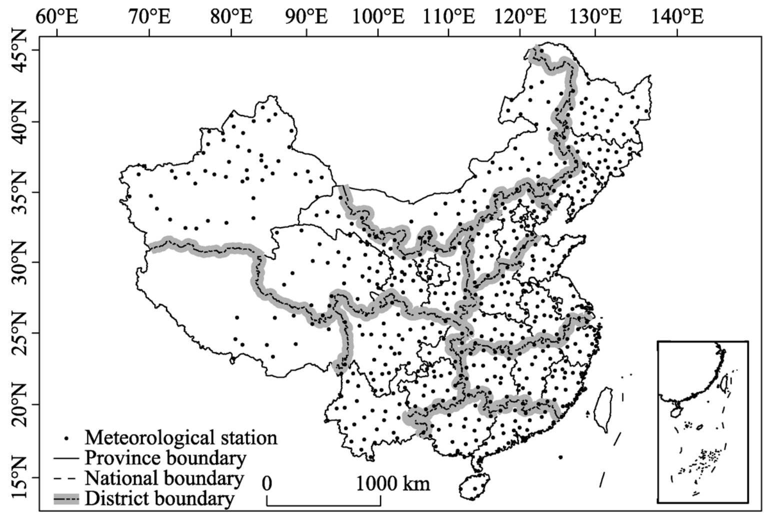

Figure 1 Distribution of meteorological stations in China

Our study defines 30 years as a climatic stage. There are 25 climatic stages from 1960 to 2013: 1960 to 1989, 1961 to 1990, ..., and 1984 to 2013.

Using Chinese meteorological geographical divisions (Wang *et al*., 2009), we simplified the geographical area into basic units of provinces and divided the country into 9 meteorological regions (Table 1). Because no data from Taiwan, Hong Kong and Macau were included, these regions were not included in the study.

Table 1 Division of meteorological geography in China

Large scale region	Provincial administrative region
Northeast China	Liaoning, Jilin, Heilongjiang
Inner Mongolia	Inner Mongolia Autonomous Region
Northwest China	Shaanxi, Gansu, Ningxia Hui Autonomous Region, Qinghai, Xinjiang Uygur Autonomous Region
North China	Shanxi, Hebei, Beijing, Tianjin
East China	Shandong, Henan, Hubei, Anhui, Jiangsu, Shanghai
Jiangnan region	Hunan, Jiangxi, Fujian, Zhejiang
Southwest China	Sichuan, Chongqing, Yunnan, Guizhou
South China	Guangxi Zhuang Autonomous Region, Guangdong, Hainan, Hongkong Special Administrative Region, Macao Special Administrative Region, Taiwan
Tibet	Tibet Autonomous Region

2.2 Methods

2.2.1 The PCD and the PCP

The precipitation concentration degree (PCD) is a new parameter characterizing the precipitation time and distribution at a single station; it is calculated as follows (Zhang and Qian, 2003, 2004):

$$PCD_i = \sqrt{R_{xi}^2 + R_{yi}^2} / R_i, \tag{1}$$

where PCD_i is the precipitation concentration degree during the study period and R_i is the total amount of precipitation at a single station during the study period,

$$R_{xi} = \sum_{j=1}^{N} r_{ij} * \sin\theta_j \quad \text{and} \quad R_{yi} = \sum_{j=1}^{N} r_{ij} * \cos\theta_j . \tag{2}$$

where r_{ij} refers to 5-day total precipitation during the study period, θ_i refers to the corresponding azimuth (the azimuth for the study period was set to 360°), i refers to the year (i = 1960, 1961, ..., 2014), and j refers to the study order (j = 1, 2, ..., 72).

According to equations (1) and (2), the PCD reflects the degree of concentration of the annual precipitation concentrated on one of 5-day total precipitation. The PCD ranges from 0 to 1. A PCD closer to 1 indicates a more concentrated period of precipitation. A PCD closer to 0 indicates a more uniform distribution of precipitation (Zhang and Qian, 2004).

2.2.2 The Z-index

Because the precipitation does not follow a normal distribution in some periods, we suppose that the monthly or seasonal total precipitation follows a Γ distribution of Pearson III. Therefore, the probability density distribution is (Ju *et al.*, 1997)

$$P(x) = [\beta\,\Gamma(y)]^{-1} \left[\frac{x-\alpha}{\beta}\right]^{\gamma-1} e^{-(x-\alpha)/\beta}. \tag{3}$$

Normal processing of the precipitation, X, allows the probability density function to be changed from a Pearson III distribution to a standard normal distribution with Z as a variable. The transformation formula is (Ju *et al.*, 1997)

$$Z_i = \frac{6}{C_s}\left(\frac{C_s}{2}\varphi_i + 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6}, \tag{4}$$

where Z_i is the value of a meteorological factor after the transformation, C_s is the skewness coefficient, and φ_i is a criterion variable. All of these can be calculated based on the precipitation data as follows:

$$C_s = \frac{\sum_{i=1}^{n}(x_i - \overline{x})^3}{n\sigma^3} \quad \text{and} \quad \varphi_i = \frac{x_i - \overline{x}}{\sigma} \tag{5}$$

where $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}$, $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, and x_i is the value of meteorological factor i.

2.2.3 The variation coefficient

The variation coefficient is a dimensionless number that represents the data's degree of dispersion. It can be used to compare the dispersion degrees and stabilities of different dimensions and means. The larger C_v is, the higher the discrete degree and the data volatility are. In contrast, the smaller C_v is, the lower the discrete degree is or the more stable the data are. A value of C_v that is less than 1 represents an average variation range of estimated thresholds is less than average, and has the better and more stability. A value of C_v that is greater than 1 represents an average variation range of estimated thresholds is more than average, and less stability (Li and Huang, 2011).

$$C_v = \sigma / x = \frac{1}{\bar{x}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{6}$$

where n is the number of data points in the sample, σ is the standard deviation of the sample, x_i is the value of climatic element i, and $\bar{x}$ is the average of the climatic elements.

2.2.4 The station coverage rate

The station coverage rate is the ratio of the number of stations in each heterogeneity grade to the number of stations in all of the areas evaluated. It is used to evaluate the range over which of each heterogeneity grade occurs.

$$F_{ij} = (m / M) \times 100\% \tag{7}$$

where F_{ij} is the coverage rate of grade i at station j, M is the number of meteorological stations in the area evaluated, m is the number of stations with heterogeneity grade i.

2.3 Research process

This study consists of two parts: a definition of a graded index for evaluating precipitation heterogeneity and a comprehensive evaluation of the precipitation heterogeneity in China. No graded index for evaluating precipitation heterogeneity has been systematically defined or approved. Therefore, the first task is to choose reasonable thresholds and define a scientific graded index for evaluating precipitation heterogeneity. Our research group thinks that the scientific evaluation index should comply with the following principles.

(1) Symmetry. Generally speaking, the frequency of each grade should be symmetric. For example, the classification of a meteorological drought based on its Z-index (Ju *et al.*, 1997) and the frequency of each grade of drought or flood should be symmetric (Table 2).

Table 2 Graded division of drought and flood based on Z-index

Grade	Types	Z-index	Real frequency (%)	Cumulative frequency (%)
1	Severe flood	Z>1.645	5	100
2	Moderate flood	1.037<Z≤1.645	10	95
3	Mild flood	0.842<Z≤1.037	15	80
4	Normal	–0.842≤Z≤0.842	40	70
5	Mild drought	–1.037≤Z<–0.842	15	30
6	Moderate drought	–1.645≤Z<–1.037	10	15
7	Severe drought	Z<–1.645	5	5

(2) Dipartition. It should be able to distinguish between different events effectively. The more severe an event is, the small the frequency should be. Taking the graded divisions of droughts and floods based on the Z-index as an example (Table 2), when the climatic environment is stable, the probability and frequency of normal years should be the highest; therefore, that frequency takes up 40% of the distribution. As the severity of a drought and flood event increases, the frequency decreases. The frequency of a severe drought or flood is 5%; the index can effectively identify an extremely serious drought or flood.

(3) Ease of operation. It should be convenient for employees; therefore, the process of dividing events into grades should not be too complex. In addition, the number of decimal places should be neither to high nor too low. The calculated PCD values show that keeping two decimal places results in a difference between two values that is too small, making it impossible to distinguish between them effectively. However, when four decimal places are kept, the calculation requires too much accuracy. On the basis of the Z-index, one of the references (Zhang *et al*., 2006), and comparisons of calculated values, it is more appropriate to keep three decimal places.

(4) Stability. Meteorological elements do not undergo obvious changes, but there are certain differences between different climatic stages. To eliminate the differences, the thresholds for 25 climatic stages are calculated and the average value is selected as the threshold for the grade.

(5) Comparability. It should be widely applicable and comparable in different areas.

The main purpose of our research is to define a reasonable threshold for each grade using these features and principles. These thresholds can be used to establish a graded index for evaluating precipitation heterogeneity and applied to comprehensively evaluate the heterogeneity of precipitation in China (Figure 2).

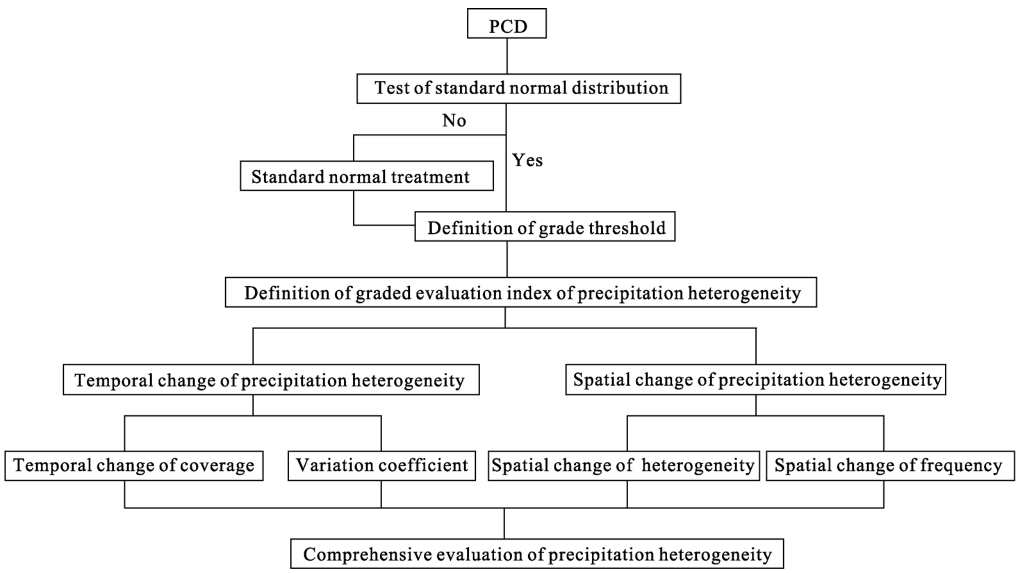

Figure 2 Comprehensive evaluation process of precipitation heterogeneity

3 Definition of the graded index for evaluating precipitation heterogeneity

3.1 Testing the normal distribution

Before defining a threshold, it is necessary to test the normal distribution of the variance. The main reasons are as follows:

(1) Random variables are generally assumed to follow normal distributions in meteorological statistics. To satisfy this condition when using this method, we should test the distribution of the variance (Huang, 2007).

(2) The probability density function of a normal distribution is symmetric around the av-

erage (μ). When a value is closer to μ, its probability is higher; when a value is farther away, its probability is lower. This feature is in accordance with the partition principles behind thresholds. A standard normal distribution is symmetric about μ=0; a negative value can be seen as less or dispersed precipitation, and a positive value can be seen as more or concentrated precipitation.

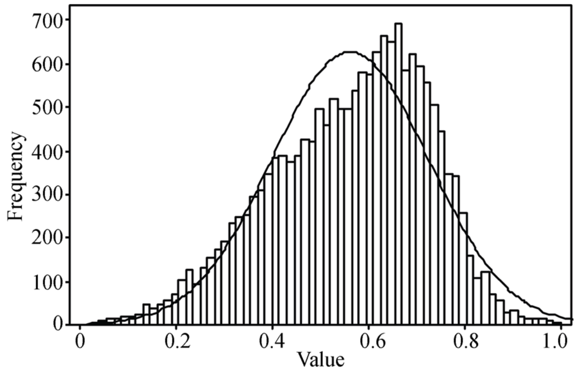

Figure 3 Histogram of precipitation concentration degree (PCD) (1960–1989)

We can judge whether the PCD follows a normal distribution by observing a histogram of it and testing its skewness and kurtosis. SPSS 21.0 can be used to obtain a histogram and the skewness and kurtosis coefficients. The histograms of the PCD of different climatic stages differ little. For the climatic stage that lasts from 1960 to 1989 (Figure 3), we observe the PCD has a negatively skewed distribution.

Assuming that the estimated variance follows a normal distribution, the coefficients of skewness and kurtosis are calculated for one sample. If the result is significant (α=0.05),

$$|g_1| > 1.96\sqrt{\frac{6(n-2)}{(n+1)(n+3)}} \qquad |g_2| > 1.96\sqrt{\frac{24n(n-2)(n-3)}{(n+1)^2(n+3)(n+5)}} \tag{8}$$

then, the hypothesis is rejected; the variance does not have a normal distribution. Otherwise, the variance has a normal distribution (Huang, 2007). The number of data points in one climatic stage is 17,070. If $|g_1| > 0.04$ and $|g_2| > 0.07$, then, the variance does not have a normal distribution. It can be shown using the calculated skewness and kurtosis coefficients of the PCD for each climatic stage that the variance does not have a normal distribution; its distribution is negatively skewed (Table 3).

Table 3 Skewness and kurtosis of precipitation concentration degree (PCD) in various climatic stages

Climatic stage	Skewness coefficient	Kurtosis coefficient	Climatic stage	Skewness coefficient	Kurtosis coefficient
1960–1989	–0.426	–0.282	1973–2002	–0.419	–0.284
1961–1990	–0.419	–0.301	1974–2003	–0.416	–0.281
1962–1991	–0.424	–0.264	1975–2004	–0.424	–0.246
1963–1992	–0.414	–0.267	1976–2005	–0.446	–0.218
1964–1993	–0.398	–0.294	1977–2006	–0.453	–0.222
1965–1994	–0.396	–0.318	1978–2007	–0.450	–0.206
1966–1995	–0.410	–0.292	1979–2008	–0.447	–0.196
1967–1996	–0.405	–0.268	1980–2009	–0.439	–0.224
1968–1997	–0.405	–0.285	1981–2010	–0.441	–0.228
1969–1998	–0.420	–0.292	1982–2011	–0.443	–0.204
1970–1999	–0.424	–0.259	1983–2012	–0.450	–0.193
1971–2000	–0.428	–0.253	1984–2013	–0.446	–0.213
1972–2001	–0.439	–0.254			

3.2 Standard normal treatment

Because the PCD is not normally distributed in each climatic stage, we need to apply the standard normal treatment to it. The application of exponential, logarithmic, arcsine, square root arcsine and Z-index transformations still can not allow the skewness and kurtosis coefficients of the PCD in each climatic stage to pass the normal test, but the arcsine transformation has a significant effect, and the results have an approximately normal distribution. Excessive emphasis on a normal distribution may result in data that are not true to their original values; therefore, we use the results of the arcsine transformation.

For the climatic stage that lasts from 1960 to 1989 (Table 4), the original PCD sequence is denoted by X_i and the new transformed sequence is denoted by Y_i. Then, the effects of different transformation methods are comprehensively compared. The arcsine transformation is the best; the skewness and kurtosis coefficients decrease significantly (α=0.01) after it is applied. The results can be seen as having a normal distribution.

Table 4 Coefficient of skewness and kurtosis of precipitation concentration degree (PCD) after normal transformation (1960–1989)

Transforationr method	Square	Cubic	Square root	Cube root	Reciprocal	Logarithm	arcsine	Square root arcsine	Z-index
Skewness coefficient	0.24	0.81	–0.92	–1.15	87.16	–1.91	–0.07	–0.39	–0.10
Kurtosis coefficient	–0.47	0.60	0.98	1.97	9640.34	8.03	–0.18	0.16	–0.40

After the arcsine transformation, the data do not have a standard normal distribution. Therefore, we take the results of the standardized treatment and denote the new sequence by Z_i.

3.3 Defining the graded threshold and evaluation index

The first task in defining the evaluation index is to choose the threshold. The parameter method and a non-parametric method were used in the threshold definition process. The parameter method, which is based on extreme value theory (Dong *et al*., 2011; Li *et al*., 2013; Zhang *et al*., 2010), is used to calculate the marginal value of the gamma distribution function to define the threshold. The calculation is complex and involves a heavy workload due to the large amount of data. The non-parametric method, which is mainly based on percentiles (Gong and Han, 2004; Li *et al*., 2010; Alexander *et al*., 2006; Zhai and Pan, 2003; Zhang *et al*., 2005), is used to arrange the sample data in ascending or descending order and to define a threshold based on the correspondences between numerical values and percentiles. This method is easy to use because of its comparatively light workload, but it requires a certain level of subjective experience.

After the standard arcsine transformation, the PCD has a standard normal distribution. Whether the precipitation is too concentrated or distributed is related to the frequency of floods and droughts. Therefore, its division based on graded thresholds can be made using the cumulative frequency of the Z-index. Our technique uses a combination of the normal distribution function, the cumulative frequency and the percentile method to divide the precipitation heterogeneity into 7 grades.

The PCD for all of the meteorological stations, which has been transformed using the standard arcsine transformation (that is, Z_i; the number of data points in one climatic stage is

17,070), is sorted in ascending order in the period under study. We can determine the corresponding values of Z_i using the cumulative frequency of the Z-index (Table 2) and then, use equation (9) to invert the transformation and calculate X_i.

$$X_i = \sin\left(Z_i\sigma + \bar{y}\right) \tag{9}$$

where $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}$, $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$, and $y_i = \sin^{-1} x_i$

During the operation process, a single value that exactly corresponds to the cumulative frequency rarely exists. For the climatic stage that lasts from 1960 to 1989, cumulative frequency when the PCD is –1.646 is 4.984% and the cumulative frequency when the PCD is –1.641 is 5.038%. Therefore, the PCD corresponding to a cumulative frequency of 5% is set to the average of the two values, –1.644.

Following this approach, the corresponding values of X for the cumulative frequencies of the 25 climatic stages are calculated (Table 5). The standard deviations of the estimated values for the 25 climatic stages are extremely small. The degree of dispersion of the estimated

Table 5 Value corresponding to cumulative frequency in various climatic stages

Climatic stage	5%	15%	30%	70%	85%	95%
1960–1989	0.275	0.390	0.482	0.654	0.729	0.806
1961–1990	0.269	0.385	0.477	0.651	0.725	0.804
1962–1991	0.272	0.388	0.479	0.652	0.726	0.804
1963–1992	0.272	0.386	0.478	0.650	0.724	0.802
1964–1993	0.271	0.385	0.477	0.648	0.723	0.800
1965–1994	0.268	0.383	0.475	0.648	0.723	0.802
1966–1995	0.273	0.387	0.479	0.651	0.725	0.803
1967–1996	0.273	0.387	0.479	0.651	0.725	0.803
1968–1997	0.270	0.385	0.478	0.651	0.725	0.804
1969–1998	0.270	0.385	0.477	0.650	0.725	0.803
1970–1999	0.271	0.386	0.478	0.650	0.724	0.803
1971–2000	0.268	0.383	0.476	0.649	0.723	0.802
1972–2001	0.266	0.382	0.474	0.648	0.723	0.802
1973–2002	0.269	0.385	0.477	0.649	0.723	0.801
1974–2003	0.269	0.383	0.475	0.648	0.722	0.800
1975–2004	0.271	0.384	0.475	0.647	0.720	0.798
1976–2005	0.272	0.386	0.477	0.647	0.720	0.799
1977–2006	0.271	0.384	0.475	0.646	0.719	0.798
1978–2007	0.271	0.384	0.475	0.646	0.719	0.797
1979–2008	0.271	0.383	0.474	0.645	0.718	0.796
1980–2009	0.269	0.382	0.472	0.643	0.717	0.795
1981–2010	0.267	0.381	0.471	0.642	0.716	0.794
1982–2011	0.269	0.382	0.471	0.642	0.715	0.793
1983–2012	0.268	0.381	0.471	0.641	0.714	0.793
1984–2013	0.267	0.381	0.472	0.643	0.717	0.795
Average	0.270	0.384	0.476	0.647	0.721	0.800
Standard deviation	0.002	0.002	0.003	0.003	0.004	0.004

and average values for each climatic stage is very low. It can be seen as stable. Therefore, the average of the values corresponding to each cumulative frequency is the threshold.

Using the averages of the estimated values for the 25 climatic stages, the graded index for evaluating precipitation heterogeneity is defined (Table 6). The centralization scale includes mild, moderate and high centralization. The dispersion scale includes mild, moderate and high dispersion.

Table 6 Graded evaluation index of precipitation heterogeneity

Grade	Types	PCD	Real frequency (%)	Cumulative frequency (%)
1	High centralization	PCD＞0.800	5	100
2	Moderate centralization	0.721＜PCD≤0.800	10	95
3	Mild centralization	0.647＜PCD≤0.721	15	80
4	Normal	0.476≤PCD≤0.647	40	70
5	Mild dispersion	0.384≤PCD＜0.476	15	30
6	Moderate dispersion	0.270≤PCD＜0.384	10	15
7	High dispersion	PCD＜0.270	5	5

4 Comprehensive evaluation of the precipitation heterogeneity in China

4.1 Temporal changes in the precipitation heterogeneity

Using the graded index for evaluating precipitation heterogeneity, the precipitation heterogeneity at 569 meteorological stations from 1960 to 2013 in China was graded, and the frequency of each grade at each station (Table omitted), the average frequency of each grade in China (Table 7) and the station coverage rate of each precipitation heterogeneity grade in each year (Figure 4) were calculated.

Table 7 Average frequency and variation coefficient in different grades of precipitation heterogeneity

Grade	Types	Real frequency (%)	Cumulative frequency (%)	Variation coefficient
1	High centralization	4	5	2.58
2	Moderate centralization	11	10	1.30
3	Mild centralization	17	15	0.89
4	Normal	38	40	0.58
5	Mild dispersion	14	15	0.98
6	Moderate dispersion	11	10	1.37
7	High dispersion	5	5	2.09

By comparing the actual and theoretical frequencies of each grade, it was found that the actual and theoretical frequencies of each grade were basically consistent (Table 7). The actual frequency of the centralization grade was 32%, which was 2% higher than the theoretical frequency. The actual frequency of normality was 38%, which was 2% less than the theoretical frequency. The actual frequency of the dispersion grade was 30%, which was equal to the theoretical frequency.

It can be seen from the variation coefficients of the different grades (Table 7) that the higher the centralization and dispersion grades are, the larger the regional differences.

The station coverage rate of the centralization grade significantly decreased by 1.55%/10a (α=0.01) in the nearly 54 years of the study period (Figure 4a). The station coverage rate of the dispersion grade significantly decreased by 0.24%/10a (α=0.05) (Figure 4a). The station coverage rate of the normal grade decreased by 1.31%/10a (which did not pass the significance test) (Figure 4b). This shows that the area in China in which the annual precipitation tends to be normal or dispersed increased in the nearly 54 years of the study period.

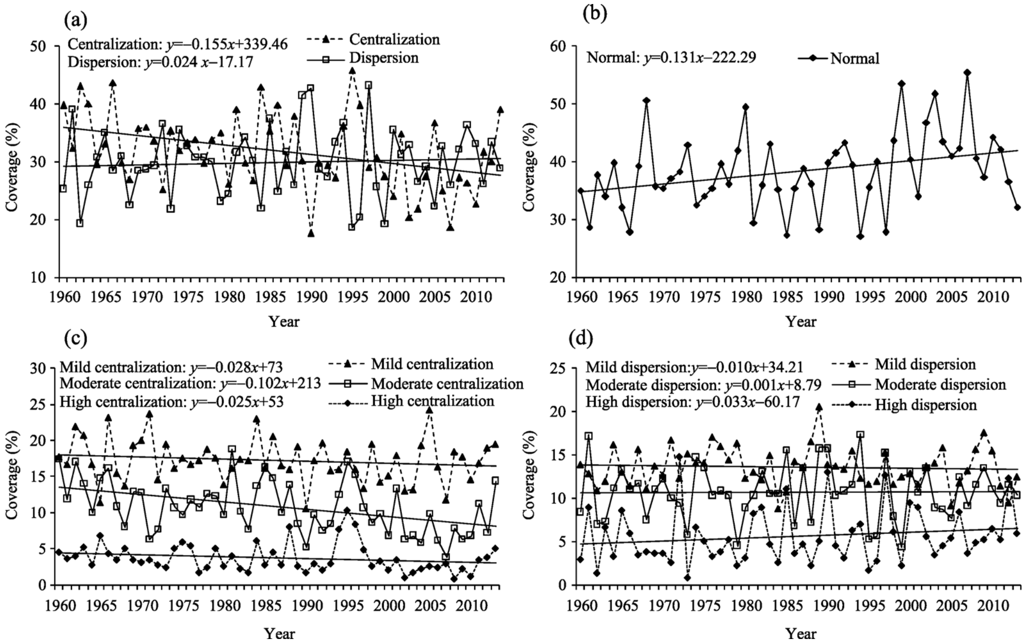

Figure 4 Station coverage in different grades of precipitation heterogeneity (1960–2013)

The station coverage rates of mild, moderate and high centralization all exhibited downward trends. The tendency rates were –0.28%/10a, –1.02%/10a and –0.25%/10a, respectively. The station coverage rate of moderate centralization decreased the fastest (Figure 4c).

The station coverage rate of mild dispersion exhibited a downward trend with a tendency rate of –0.10%/10a. The station coverage rate of moderate dispersion remained basically unchanged, but exhibited a slight increase. The tendency rate was –0.10%/10a. The station coverage rate of high dispersion exhibited an upward trend. The tendency rate was 0.33%/10a (Figure 4d).

According to the variation coefficients of the station coverage rate for each grade (Table 8), the higher the centralization and dispersion grades were, the larger the interannual fluctuations were. However, the degree of fluctuation was much less than the regional differences (α=0.01). This indicated that the higher the centralization and dispersion grades are, the larger the regional differences and annual fluctuations.

Table 8 Variation coefficient of station coverage in different grades of precipitation heterogeneity

Grade	High centralization	Moderate centralization	Mild centralization	Normal	Mild dispersion	Moderate dispersion	High dispersion
Variation coefficient	0.52	0.33	0.17	0.17	0.17	0.29	0.29

4.2 Spatial changes in the precipitation heterogeneity

4.2.1 Spatial changes in the precipitation heterogeneity

By analyzing the average grade of the precipitation heterogeneity at each meteorological station, we concluded that the precipitation heterogeneity showed the characteristics of spatial dispersion in the south and east and of centralization in the north and west (Figure 5).

In northwestern China, the distribution of the precipitation heterogeneity grade revealed three sections. That of the eastern section (Shaanxi, Ningxia and eastern Gansu) tended to be normal. The northern part of the middle section (western Gansu) was characterized as normal while the southern part of the middle section was characterized as mainly mildly or moderately centralized. The eastern section was divided into two parts by the Tianshan Mountains; its northern part (northern Xinjiang) was characterized by high dispersion and its southern part (southern Xinjiang) was characterized by mild or moderate centralization. The Tianshan area was normal.

The precipitation in northern China was generally mildly centralized. Within this region, the precipitation in Hebei, Beijing, Tianjin and northern Shanxi was mainly mildly centralized, that in eastern Hebei was moderately centralized and that in southern Shanxi was mainly normal.

The precipitation in Inner Mongolia was mainly mildly centralized, but at individual meteorological stations, it was mainly normal or moderately centralized.

There was a two-section "east-west" distribution in northeastern China. The precipitation in the east was generally normal, that in the west was generally mildly or moderately centralized and that in the area near the Greater Khingan Range was generally moderately centralized.

There was a two-section "south-north" distribution in eastern China in which the precipitation tended to be dispersive from north to south. The precipitation in the northern part (Henan and Shandong) was generally normal and that in northern Shandong tended to be mildly centralized; in the southern part (Hubei, Anhui, Jiangsu and Shanghai), the precipitation was generally mildly or moderately centralized.

The precipitation in the Jiangnan region (area south of the Yangtze River Basin) was generally moderately dispersed. In the eastern (Zhejiang and eastern Fujian) and western (Hunan and western Jiangxi) parts, the precipitation was generally moderately dispersed, and in the middle part (eastern Jiangxi and western Fujian), it was generally mildly dispersed.

In southern China, the precipitation was generally normal or mildly dispersed. In the middle part, it was generally mildly dispersed, but it was generally normal in the eastern and western parts.

In southwestern China, the precipitation was generally normal or mildly dispersed. In the eastern part (Chongqing and eastern Guizhou), it was generally mildly or moderately dispersed; in the middle part (eastern Sichuan) and Yunnan Province, it was generally moderately dispersed; in the Hengduan Mountains, it was generally moderately dispersed; and in western Sichuan, it was generally mildly centralized.

In Tibet, the precipitation was generally moderately or highly centralized. Due to incomplete meteorological data and the large area of Tibet, it was necessary to consider whether the data are representative by analyzing the spatial characteristics of the precipitation heterogeneity grades of individual meteorological stations. However, the results of performing the calculations using data from only 11 meteorological stations showed that the heterogeneity grades generally tended to be centralized. This consistency supports the result given above.

By analyzing the variation coefficients of the precipitation heterogeneity at various meteorological stations, the numerical stability of the precipitation heterogeneity was shown to have the following spatial characteristics: the "south and east were steady, but the north and west were fluctuant" (Figure 6). People living in the regions in which the precipitation homogeneity tended to fluctuate should pay more attention to the spatiotemporal regulation of water to respond to droughts and floods. The precipitation heterogeneity tended to fluctuate more in Inner Mongolia, the eastern part of northern China (Hebei, Beijing and Tianjin), the eastern part of northeastern China, the middle (western Qinghai and western Gansu) and western parts of northwestern China (southern Xinjiang) and Tibet.

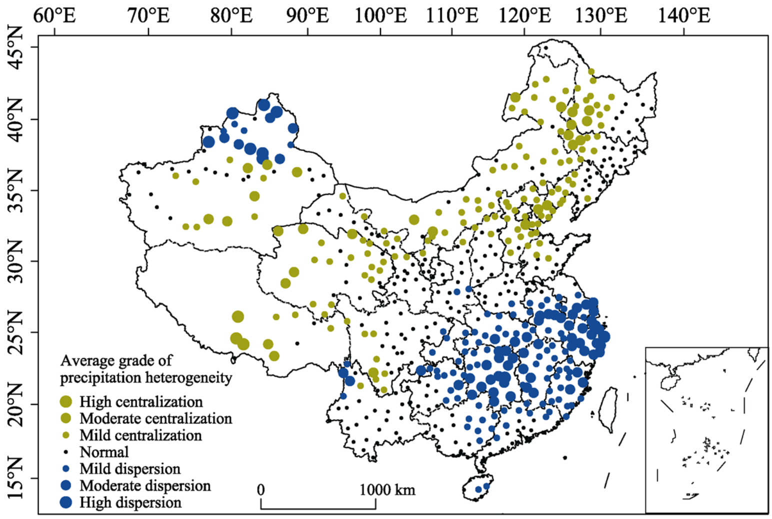

Figure 5 Spatial distribution of average grade of precipitation heterogeneity

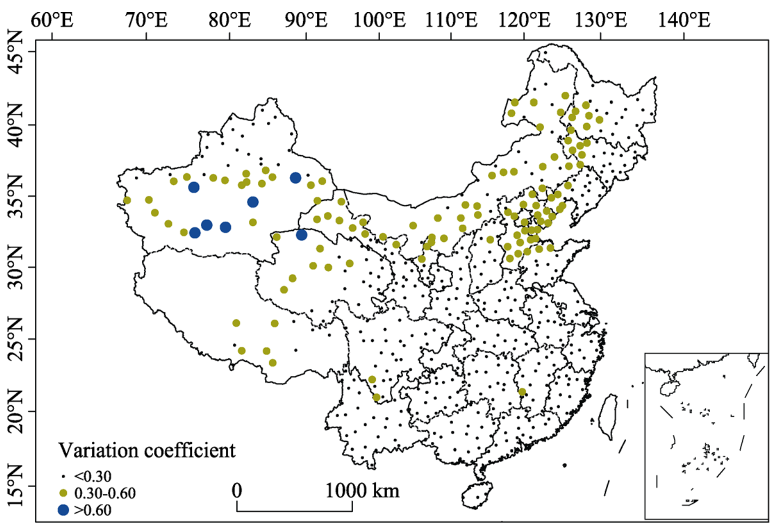

Figure 6 Spatial distribution of grade variation coefficient of precipitation heterogeneity

4.2.2 Spatial changes in the frequency of each precipitation heterogeneity grade

We analyzed the frequency of each precipitation heterogeneity grade at various meteorological stations in China. For the purpose of convenient description and understanding, we defined the frequency grades as follows: 0–20% is very low, 20%–40% is low, 40%–60% is moderate, 60%–80% is high, and 80%–100% is very high.

(1) The spatial distribution of the frequency of the centralization grade

In the nearly 54 years of the study period, the frequency of the centralization grade was generally low in the south and high in the north (Figure 7).

The frequency increased from east to west in northwestern China. Among these cities, the frequency was very low at Shaanxi, very low or moderate at Ningxia and Gansu, high at Qinghai, very low in northern Xinjiang, and moderate or high in southern Xinjiang.

The frequency was high in northern China, especially in the east, and the frequency gradually increased from west to east.

The frequency was high in the Inner Mongolia region and very high in the area near the Greater Khingan Range.

The frequency increased from east to west in northeastern China.

In southern China, the Jiangnan region, eastern China (except for Shandong Province) and the eastern part of southwestern China (Guizhou and Chongqing), the frequency was low, which showed that the precipitation in these areas was homogenous.

The frequency was low in southwestern China and tended to be low in the west and high in the east. It was low in the east (Guizhou and Chongqing) and the west (eastern Sichuan and eastern Yunnan). In addition, the frequency was high on the border between Yunnan and Sichuan.

The frequency was very high in Tibet.

(2) The spatial distribution of the frequency of the normal grade

The spatial distribution of the frequency of normal precipitation was complex during the 54 years of the study period, and the distribution was different in each region (Figure 8).

In northwestern China, the frequency was high in the east and low in the west. The frequency was high in Shaanxi, Ningxia, and eastern Gansu and very low or low in Qinghai, western Gansu and Xinjiang.

In northern China, the frequency exhibited the special characteristic of being low in the west and high in the east. It was very low or low in Hebei, Beijing and Tianjin and very high in Shanxi.

The frequency was low or moderate in the Inner Mongolia region.

The frequency was high in the east and low in the west of northeastern China. It was high in the east and low or moderate in west.

The spatial distribution of the frequency showed that it was high in the northern part and low in the southern part of northern China. The frequency was moderate or high in Shandong and Henan, but low or very low in Hubei, Anhui, Jiangsu, and Shanghai.

In the Jiangnan region, the frequency was low or very low, but it was higher in Fujian.

In southern China, the frequency was low or moderate.

On the whole, the frequency was high in southwestern China. It was low in eastern Chongqing and Guizhou but high or very high in western Guizhou, Sichuan and Yunnan.

There were some internal differences in Tibet, and the frequency was very low or low in

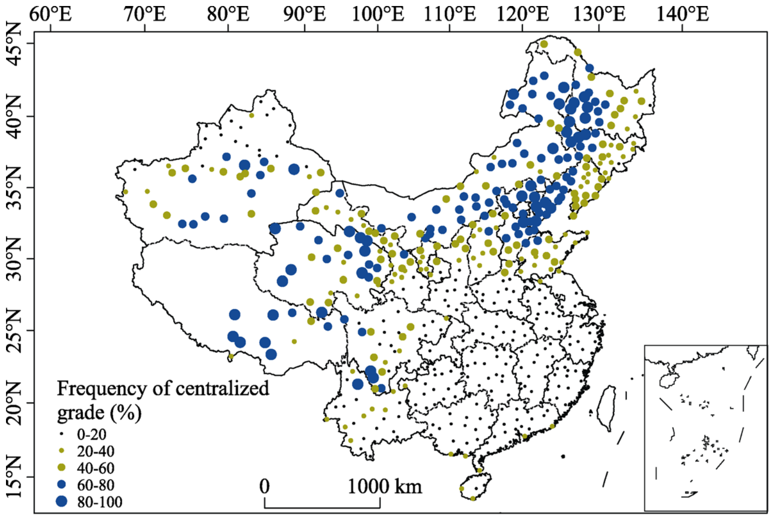

Figure 7 Spatial distribution of frequency of centralization grade (1960–2013)

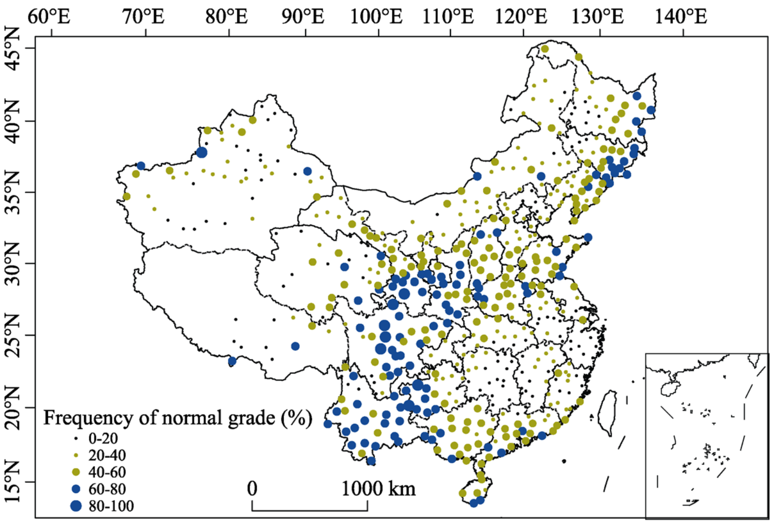

Figure 8 Spatial distribution of frequency of normal grade (1960–2013)

general.

(3) The spatial distribution of the frequency of the dispersion grade

The spatial pattern of the frequency of the dispersion grade in China was that it was high in the south and low in the north (Figure 9).

In northwestern China, the frequency was generally high in the west and low in the east. The frequency was low or moderate in southern Shaanxi and very low in northern Shaanxi, Gansu and Qinghai. The frequency was low or moderate in southern Xinjiang and very high in northern Xinjiang.

In northern China, the Inner Mongolia region, northeastern China and Tibet, the frequency was very low.

The frequency gradually increased from north to south in eastern China. The frequency was low in Henan and very low in Shandong and high or very high in Hubei, Anhui, Jiangsu and Shanghai.

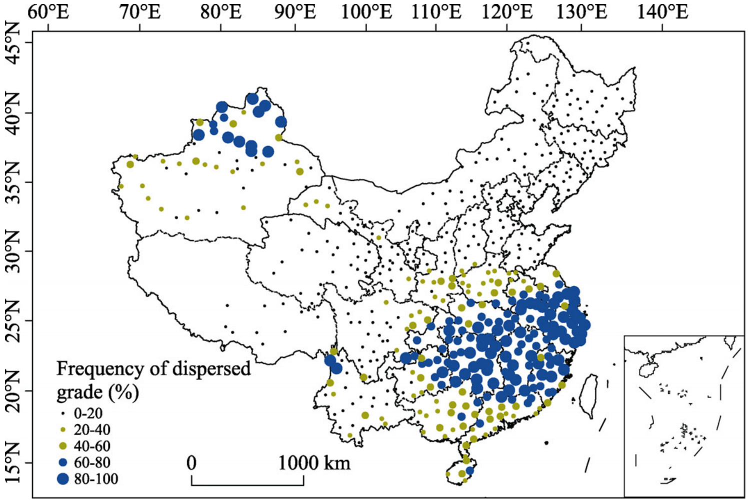

Figure 9 Spatial distribution of frequency of dispersed grade (1960–2013)

The frequency was high and generally characterized as extremely high in the Jiangnan region.

The frequency was low or moderate in southern China.

In view of the overall situation, the southwestern part exhibited a spatial distribution of the frequency that was high in the east and low in the west. The frequency in eastern Chongqing and Guizhou was high or very high, but it was very low or low in Sichuan, Yunnan and western Guizhou.

4.3 Comprehensive evaluation of the precipitation heterogeneity

Considering the spatiotemporal variations in the average grade, frequency and variation coefficients of the precipitation heterogeneity grade at each station, we comprehensively assessed and classified the precipitation heterogeneity using the GIS spatial overlay method (Figure 10).

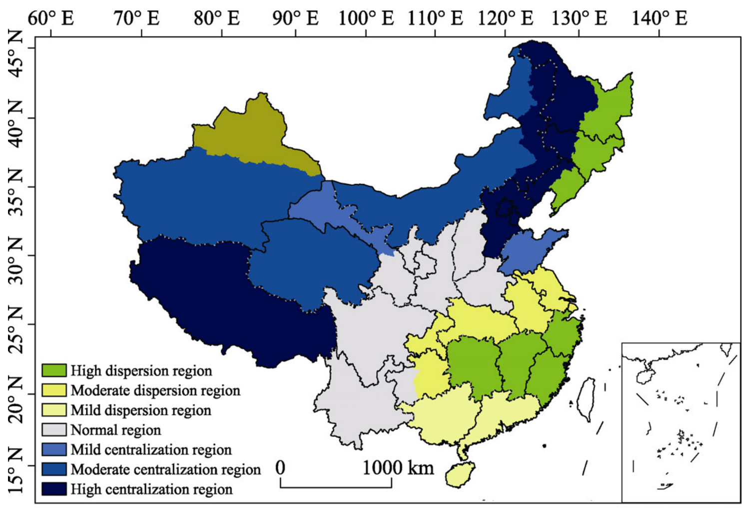

Figure 10 Comprehensive evaluation of precipitation heterogeneity in China

The precipitation was highly centralized in Tibet, the eastern part of northern China (Hebei, Beijing and Tianjin) and the Greater Khingan region (eastern Inner Mongolia and the western part of northeastern China). The precipitation was moderately centralized in southern Xinjiang, Qinghai and Inner Mongolia. It was mildly centralized in northern Gansu and Shandong.

The precipitation was normal in the western part of southwestern China (Sichuan, Yunnan and western Guizhou), the eastern part of northwestern China (Shaanxi, Ningxia and southern Gansu), Shanxi, Henan and the eastern part of northeastern China.

The precipitation was mildly dispersed in southern China. It was moderately dispersed in the eastern part of southwestern China (Chongqing and eastern Guizhou) and the southern part of eastern China (Hubei, Anhui, Jiangsu and Shanghai). It was highly dispersed in the Jiangnan region and northern Xinjiang.

To check the accuracy of the comprehensive evaluation and regionalization, we analyzed the temporal variations in the precipitation heterogeneity in each region (see Figure 11).

Normal region (Figure 11a): There were 52 normal years and 2 years with moderate degrees of centralization; therefore, normal years accounted for the overwhelming majority.

Mild dispersion region (Figure 11b): There were 26 years that were both normal and mild degrees of dispersion and 2 years with moderate degrees of dispersion. There were significantly more years with mild degrees of dispersion than there were in the normal region.

Moderate dispersion region (Figure 11c): There were 11 normal years, 28 years with mild degrees of dispersion and 15 years with moderate degrees of dispersion. There were significantly more years with moderate degrees of dispersion than there were in the mild dispersion region.

High dispersion region (Figure 11d): There were 11 years with mild degrees of dispersion, 28 years with moderate degrees of dispersion and 15 years with high degrees of dispersion. There were significantly more years with high degrees of dispersion than there were in the moderate dispersion region.

Mild centralization region (Figure 11e): There were 34 normal years, 18 years with mild degrees of centralization and 2 years with moderate degrees of centralization. There were significantly more years with mild degrees of centralization than there were in the normal region.

Moderate centralization region (Figure 11f): There were 11 normal years, 28 years with mild degrees of centralization and 15 years with moderate degrees of centralization. There were significantly more years with moderate degrees of centralization than there were in the mild centralization region.

High centralization region (Figure 11g): There were 14 normal years, 30 years with moderate degrees of centralization and 14 years with high degrees of centralization. There were significantly more years with high degrees of centralization than there were in the moderate centralization region.

Each category region of precipitation heterogeneity had obvious differences; therefore, the comprehensive evaluation of the precipitation heterogeneity and the climatic divisions were relatively accurate and efficient.

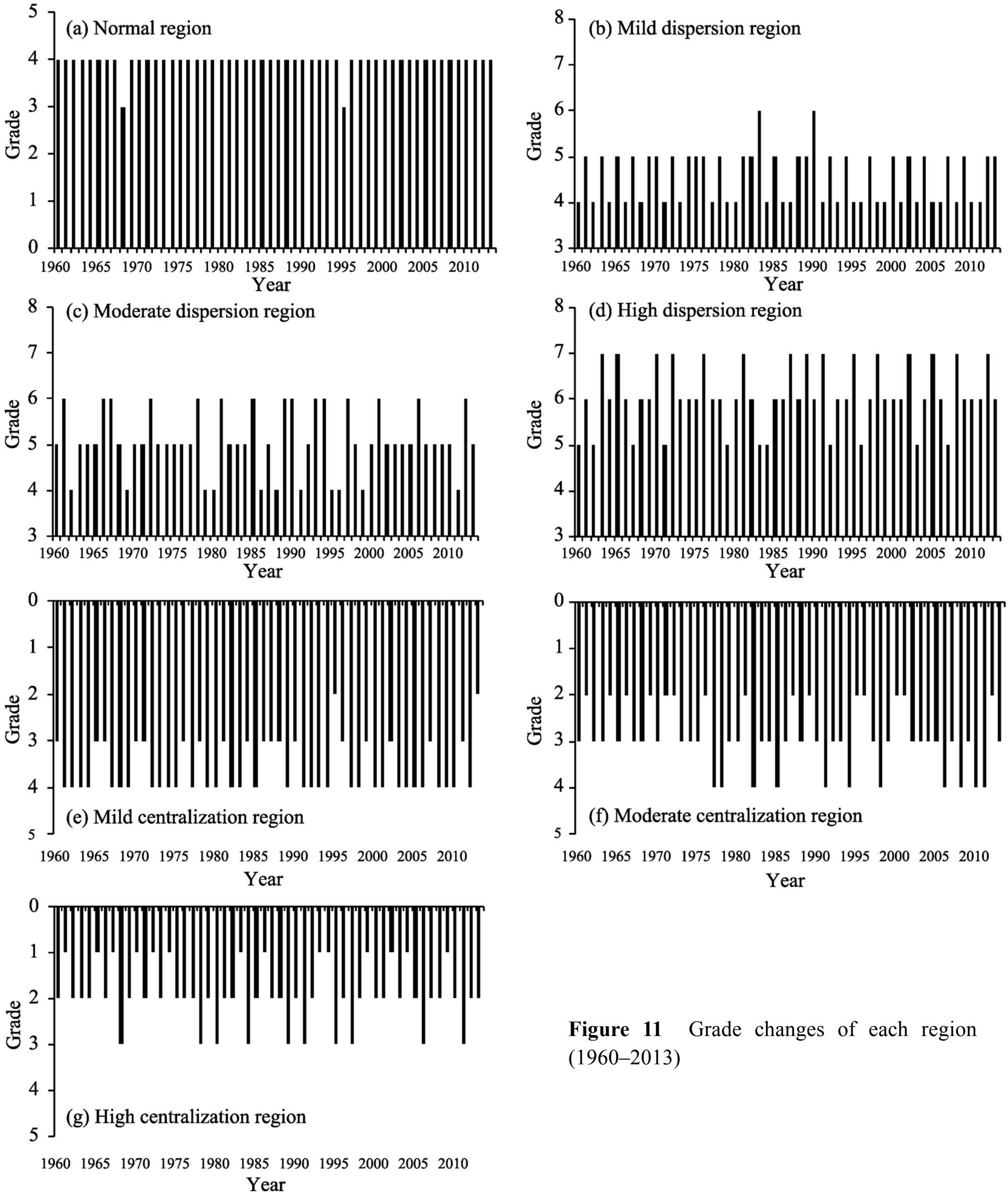

Figure 11 Grade changes of each region (1960–2013)

5 Discussion and conclusions

5.1 Discussion

(1) The problem of basic units

In this study, the provincial administrative area was taken as the basic unit of the analysis. In the comprehensive evaluation of the precipitation heterogeneity in China, it was found that the internal differences in each individual region are very obvious. Therefore, the county administrative areas in some regions were taken as basic units to refine the analysis, allowing it to reflect the regional differences in the precipitation in China more comprehensively. These regions are mainly the Greater Khingan Range area (eastern Inner Mongolia and the western part of northeastern China), northern Xinjiang, southern Gansu and western Guizhou.

(2) The problem of the evaluation index

The methods of studying the precipitation heterogeneity are varied. If we use a variety of methods to study and analyze this problem, it is easy to produce inconsistent or even opposing results. By comparing the advantages and disadvantages of various research methods, it was found that the precipitation concentration degree (PCD) method was the best in many ways. Therefore, the precipitation concentration degree method was used to analyze the precipitation heterogeneity in this study. The commonly used methods for studying precipitation heterogeneity are the non-uniform coefficient, precipitation concentration degree and Gini coefficient methods. The resolution and sensitivity of the precipitation concentration degree are higher than those of the heterogeneity coefficient (Tang *et al.*, 1982a; Yang, 1984), and Gini coefficients are based on the Lorenz curve, the estimation of which is complex. Therefore, the precipitation concentration degree method is optimal in many ways. In addition, the threshold values were determined on the basis of a normal distribution, cumulative frequencies and the percentile method, which had to be based on a certain level of subjective experience. To modify the frequency of each level's occurrence, the corresponding threshold must be determined. There is a certain degree of volatility, and we need to find the optimal frequency and set a fixed threshold in future applications of this method.

(3) The problem of the time scale

The time scale used in this paper has an important influence on the characteristics of the precipitation heterogeneity. According to the theoretical characteristics of the PCD method, the smaller the time scale and the azimuth distance are, the more they reflect the precipitation heterogeneity and the higher the accuracy is. This requires the data to be very accurate. However, the larger the time scale is, the greater the azimuthal distance is, which makes it impossible to reflect the characteristics of the precipitation heterogeneity very well. Precipitation is generally concentrated in the summer in most regions of China, and monthly or seasonal precipitation data are used in the analysis, it is impossible to distinguish the heterogeneity of each region. If daily precipitation data are used in the analysis, there is a small azimuthal range, a large workload, and higher requirements. Therefore, this study mainly uses 5-day total precipitation data to study the precipitation heterogeneity.

5.2 Conclusions

The aim of this study was to propose and establish a graded index for evaluating precipitation heterogeneity that can be used in all of China. Then, the graded index was used to perform a comprehensive evaluation of the precipitation heterogeneity in China from 1960 to 2013. The study reached the following conclusions:

(1) It proposed and established a graded index for evaluating precipitation heterogeneity that can be used in all of China. The precipitation concentration degree (PCD) at each meteorological station was calculated using daily precipitation data from 569 national observation stations for the period from 1960 to 2013. By comparisons made using normal distribution functions, cumulative frequencies and the percentile method, we used the averages of

estimated values for 25 climatic stages to define each grade's threshold, and then, established a graded index for evaluating precipitation heterogeneity (Table 6).

(2) The precipitation in more parts of China tended to be normal or dispersed. In these areas, the station coverage rates of mild centralization, moderate centralization and high centralization all exhibited downward trends. The station coverage rate of mild dispersion exhibited a downward trend. The station coverage rate of moderate dispersion remained basically unchanged and increased slightly. The station coverage rate of high dispersion exhibited an upward trend.

(3) Based on the spatiotemporal variation characteristics of the precipitation heterogeneity in China, all of China was divided into seven regions. Tibet, the eastern part of northern China and the Greater Khingan region comprised the high centralization region. Southern Xinjiang, Qinghai and Inner Mongolia comprised the moderate centralization region. Northern Gansu and Shandong comprised the mild centralization region. The western part of southwestern China, the eastern part of northwestern China, Shanxi, Henan and the eastern part of northeastern China comprised the normal region. The southern part of China comprised the mild dispersion region. The eastern part of southwestern China and the southern part of eastern China comprised the moderate dispersion region. The Jiangnan region and northern Xinjiang comprised the high dispersion region.

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