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Probabilistic trend of anomalous summer rainfall in Beijing: Role of interdecadal variability

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[1] The interdecadal variability of summer precipitation in Beijing from 1724 to 2005 is analyzed using a filter, keeping the true trends at time series ends. A probability distribution, Pearson type III, was applied to the summer precipitation series to estimate the probability of anomalous rainfall. This study includes the correlation between the interdecadal variations of the summer precipitation in Beijing and those of the indices of Northern Atlantic Oscillation (NAO), Southern Oscillation (SOI), Pacific Decadal Oscillation (PDO), and summer monsoon (SMS) of East Asia indices are computed. A methodology is thus developed to forecast the probable distribution of precipitation intensities in Beijing. Results show that the probability of drought in Beijing has greatly increased since the middle of the 1960s. The interdecadal variability of NAO, PDO, and SMS are extremely important for the low-frequency forecast of anomalous summer rainfall in Beijing. The method developed here seems appropriate to estimate the probability of future anomalous summer rainfall.

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1. Introduction

[2] Interdecadal climate variability, a fluctuation added to long-term climatic trends, is the background information influencing interannual climate variability [*Nakamura et al.*, 1997; *Moron et al.*, 1998; *Minobe and Mantua*, 1999]. Observational evidence for the interdecadal variability of the atmosphere-ocean system has attracted more and more attention over the past decade [*Trenberth*, 1990; *Mann and Park*, 1993; *Graham et al.*, 1994; *Latif and Barnett*, 1994; *Trenberth and Hurrell*, 1994; *Tourre et al.*, 1999a, 1999b]. The impact of the interdecadal variability of the atmosphere-ocean system on climate variability in the regions surrounding the North Pacific has been increasingly documented [*Latif and Barnett*, 1994; *Mantua et al.*, 1997]. Therefore the study on interdecadal climate variability becomes a mainstream issue within the climatic community where the investigation of regional precipitation variability on an interdecadal scale and its prediction is important. Some previous studies, e.g., that of *Chen et al.* [2004], indicate that the fluctuation of amplitude of annual precipitation in China has been extremely large during the last 100 years, particularly during the last 50 years [*Houghton et al.*, 2001; *Ding et al.*, 2006]. The differences in annual precipitation among various regions are obvious. North China, including Beijing, has been experiencing an apparently decreasing amount of precipitation since the middle of the 1960s [*Lu*, 2003; *Wei*, 2007]. The droughts caused by decreased precipitation are becoming more intense and have greatly influenced the economy, environment, water resources, and the livelihood of people in Beijing. Thus the investigation of the interdecadal variability, influencing factors and trend prediction of precipitation in Beijing has become crucial.

[3] Both dynamical and statistical methods are employed to produce climate prediction. In the last two decades, climatic numerical models are used to make long-term forecasts on a period of 10 years or longer. Statistical methods are based on historical data and identifying relationships between predictors and predictands. However, climatic anomalous change is the result of interaction among different spatiotemporal physical processes within the atmosphere-ocean system [*Mysak and Venegas*, 1998]. The interactions within the components of the climate system usually include feedbacks that act on different timescales [*Venegas and Mysak*, 2000].

[4] The intent of this study is to investigate the features of interdecadal precipitation variations based on summer precipitation data in Beijing during the 1724–2005 period. It is also to analyze the correlation between the interdecadal variation of the precipitation and a few climate indices. A statistical method has been developed to predict the probabilities for various precipitation intensities. It was hypothesized that the physical factors controlling interdecadal and interannual variations for the summer precipitation in Beijing might be different. The interannual variability of precipitation is generally a radical change, while interdeca-

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dal precipitation exhibits a gentle variation because of the long-term information of influence from interdecadal variation of external forcings, e.g., Pacific Decadal Oscillation (PDO) and solar cycle. With the use of these features for interdecadal and interannual precipitation variations, it is possible to forecast long-term climatic trend probability of summer precipitation.

2. Data

[5] It is well known that the rainfall in Beijing is concentrated in summer. The precipitation during June, July, and August (JJA) accounts for 74.5% of the entire year, while the winter precipitation is small, accounting for merely 2% of the whole year. Therefore the emphasis of this article is on summer precipitation in Beijing from 1724 to 2005. The JJA precipitation data from 1724 to 1840 was collected and organized by the former meteorological institute, the Central Meteorological Bureau of China, from the hourly rainfall records in the "*Records of Rain and Fairness*" which was founded in the Forbidden City of China. The data during 1841–2005 is from instrumental observations. We compared the two sets of data from the "*Records of Rain and Fairness*" and instrumental observations during the overlapped period from 1841 to 1903 and found the correlation coefficient was 0.75 with a confidence level greater than 99.9%.

[6] Four physical factors were selected to investigate their possible influence on the climatic trends of summer precipitation in Beijing for a correspondingly long time. They are as follows:

[7] X_1: the index of the averaged North Atlantic Oscillation (NAO) from 1823 to 2005, which is defined as the difference of the Sea Level Pressures (SLPs) between stations at Gibraltor and Reykjavik [*Jones et al.*, 1997; *Li and Wang*, 2003]. The NAO is one of the most prominent teleconnection patterns in all seasons [*Barnston and Livezey*, 1987]. It exhibits considerable interseasonal, interannual and multidecadal variability. The wintertime NAO also exhibits significant interdecadal variability [*Hurrell*, 1995; *Thompson and Wallace*, 1998; *Chelliah and Bell*, 2004]. Recent studies have indicated that NAO has influence on the climate of China via the mechanism of teleconnection [*Wang and Li*, 2007].

[8] X_2: the index of the averaged Southern Oscillation (SOI) from 1866 to 2005, which is defined as the difference of the SLPs between stations at Tahiti and Darwin [*Walker and Bliss*, 1932]. It represents out-of-phase air pressure oscillations occurring around the Southeast Pacific and Indian Ocean. The negative phase of the SOI represents below-normal and above-normal air at Tahiti and Darwin, respectively. Observations have indicated that there are low-frequency variations in the SOI variability. For example, three strong variabilities are quite remarkable in about 1530–1550, 1740–1780, and 1855–1880. This shows that SOI fluctuates with apparently interdecadal variability [*Graham et al.*, 1994; *Minobe*, 1997, 1999, 2000; *Minobe and Mantua*, 1999].

[9] X_3: the index of the averaged Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997; *Minobe*, 1997; *Wolter and Timlin*, 1998; *Barnett et al.*, 1999], which is defined as the time coefficient of the first EOF component of the Sea Surface Temperature Anomaly (SSTA) in the Northern Pacific. The PDO, first defined by *Mantua et al.* [1997], is a climatic variability on the interdecadal scale in the Northern Pacific. It has a significant impact on the estimation of the climate of the Pacific and China [*Cane et al.*, 1986; *Hoerling and Kumar*, 2003; *McCabe et al.*, 2004].

[10] The three indices above (NAO, SOI and PDO) were downloaded from www.cru.uea.ac.uk/cru/data. They reflect the possible influences from the climatic interactions on the precipitation of Beijing.

[11] X_4: The intensity index of East Asia SMS, which is defined as the sea level pressure difference between longitude of 110°E and 160°E at 10°N–50°N [*Zhao and Zhang*, 1996]. The intensity of SMS is significantly related to the summer precipitation of North China [*Ding and Murakami*, 1994; *Huang et al.*, 2004].

3. Interdecadal Variability of Summer Precipitation in Beijing for the Last 282 Years

[12] Figure 1 shows the power spectrum of the summer precipitation series in Beijing during 1724–2005. It shows that three spectral peaks, 70.0, 31.11 and 20.0 year, are beyond the red noise null hypothesis with a 95% confidence limit on the interdecadal timescale. The multidecadal and interdecadal oscillation periods of summer precipitation in Beijing are 40–70 year and 20–30 year timescales, respectively. The timescales of multidecadal and interdecadal oscillation of summer precipitation in Beijing are similar to those of the multidecadal (65–70 year) and interdecadal (15–20 year) variation of the global climate system [*Mann and Park*, 1994; *Schlesinger and Ramankutty*, 1994].

[13] The interdecadal variability of summer precipitation in Beijing was investigated by using a new smoothing method introduced by *Mann* [2004]. This method avoids the missing of values at both ends of a time series, which is usually found in commonly used filtering methods. Hence it gives closer values to the actual trends at the ends of a time series. The first step of this method is to smooth the series of summer precipitation in Beijing by using a low-pass filter. Then the smoothing values at the ends of the series can be computed by employing three boundary conditions, i.e., norm, minimum slope and minimum roughness of the smoothed series [*Park*, 1992]. Finally, the mean square errors (MSEs) of these smoothing values are derived for each of the three boundary conditions. The smoothed series with the minimum MSE value is considered here as the most appropriate result. Figure 2 shows the summer precipitation in Beijing for 1724–2005 and the smoothed 10 years series with MSEs of 0.7440, 0.7381, and 0.7418, respectively, for taking the three boundary conditions, i.e., norm, minimum slope and minimum roughness of the smoothed series. The smoothed series with the boundary condition of minimum slope is then taken to be the interdecadal variability of precipitation in Beijing. It can be seen in Figure 2 that the summer precipitation of Beijing has experienced nine periods on the interdecadal scale during the last 282 years. The phases of 1724–1773, 1816–1839, 1853–1868, 1900–1947 and 1965–2005 are below the average annual precipitation. More specifically, the precipitation was extremely small during the two extremely long phases of 1724–1773 and 1965–2005. A

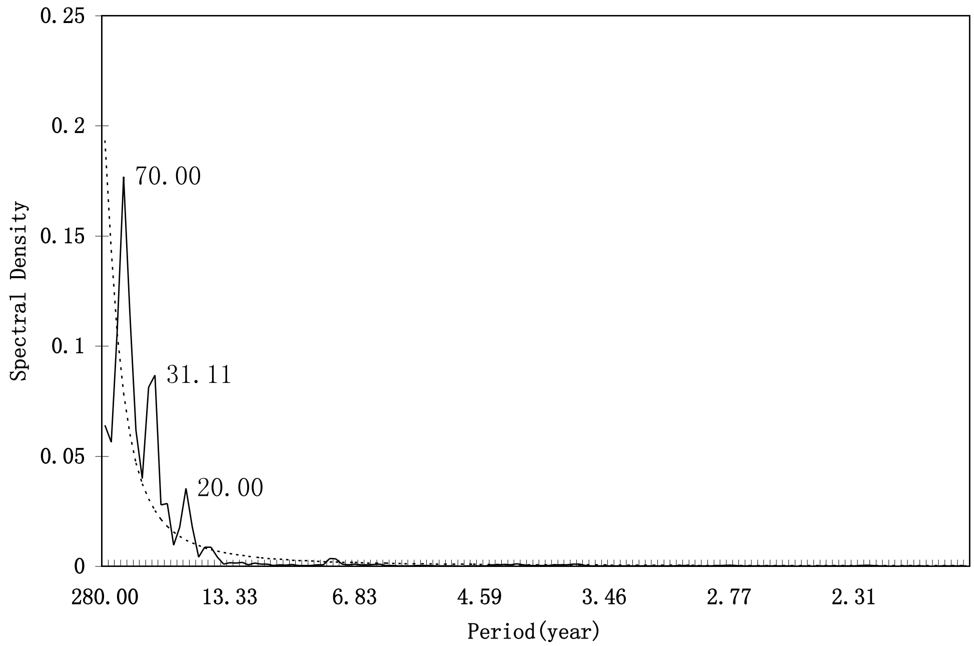

Figure 1. Power spectrum of the summer precipitation series in the last 282 years (dotted line shows 95% confidence level when compared with red noise).

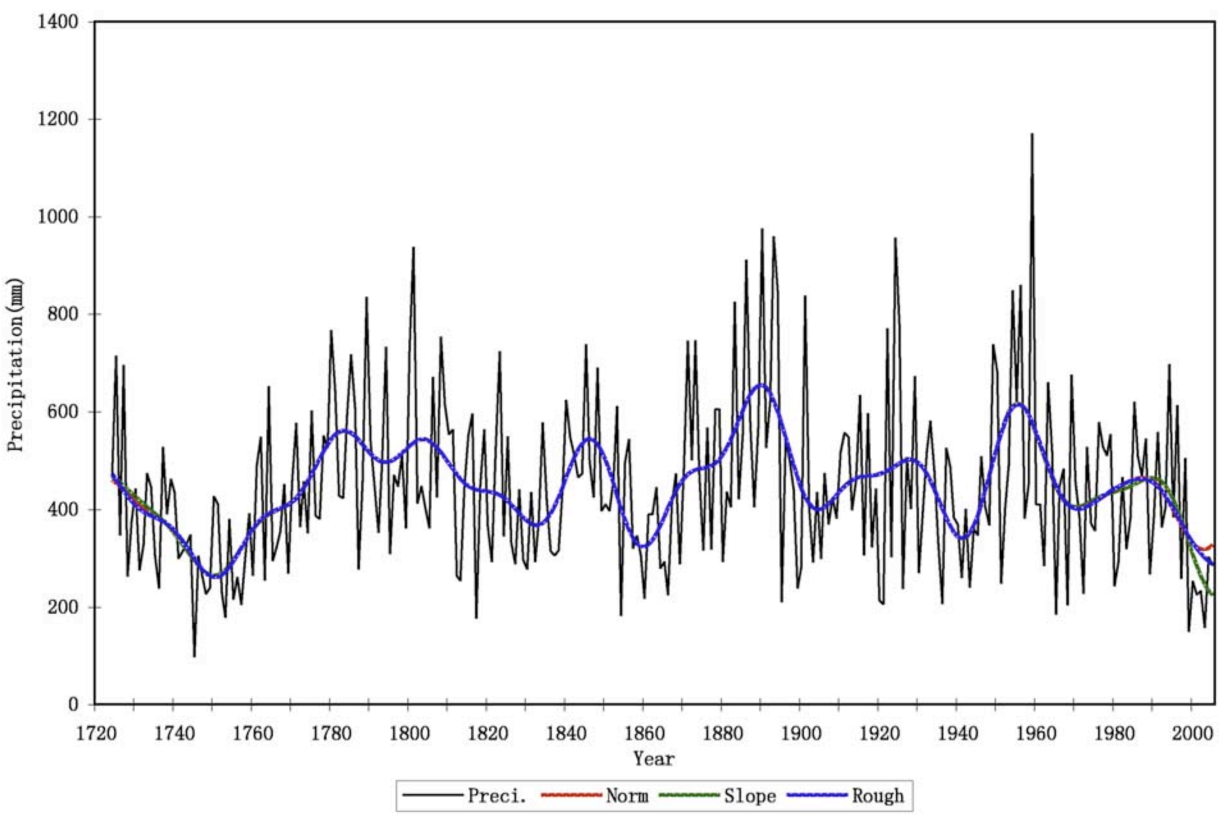

Figure 2. Summer precipitation in Beijing for 1724–2005 and 10 years smoothed series using three boundary conditions, i.e., norm of the smoothed series, minimum slope, and minimum roughness (black line: summer precipitation; red line: norm of the smoothed series; green line: minimum slope; blue line: minimum roughness).

Table 1. Averages of Summer Precipitations Over Each Phase and Statistical Value ($u_{\alpha=0.05}$ = 1.96)

Phases	1724–1773	1774–1815	1816–1839	1840–1852	1853–1868	1869–1899	1900–1947	1948–1964	1965–2005
Trends	Below	Above	Below	Above	Below	Above	Below	Above	Below
Average (mm)	366	512	409	510	370	553	436	555	402
$\|u\|$ Values	4.77	3.28	3.14	4.53	5.00	4.11	2.03	5.62	

significant decrease in precipitation was found around 1965, which agrees well with some previous studies based on the investigation of precipitation for North China in the last 50 years [*Ma*, 2005]. It was also found that the summer precipitation of Beijing was above normal during 1774–1815, 1840–1852, 1869–1899 and 1948–1964. Table 1 gives the average values for each phase and the statistic u test values between every sequent pair of phases. The u-test (similar to Student's t-test) is used to compare means between summer precipitation of Beijing in two phases. All of the u tests exceed the 95% confidence level ($u_{0.05}$ = 1.96) which suggests that the differences in average precipitation are significant between any sequent pair of phases [*Sneyers*, 1990].

4. Probability Distribution of Anomalous Summer Rainfall in Beijing

[14] The summer precipitation in Beijing is a non-normal distribution with left-eccentricity where the minimum value is limited to be larger or equal to zero but the maximum value has no limitation. The probability distribution, Pearson type III, is used to estimate the distribution for summer precipitation R in Beijing. From the probability function of Pearson type III [*Abramowitz and Stegun*, 1972], we obtain

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

where C_s is the eccentricity coefficient, φ_i (i = 1, 2,. . ., n. n is sample numbers of summer precipitation series in Beijing) is the standardized deviation of the summer precipitation R. The C_s and φ_i can be given by

$$C_s = \frac{\sum_{i=1}^{n}\left(R_i - \overline{R}\right)^3}{n\sigma^3}, \qquad (2)$$

$$\varphi_i = \frac{R_i - \overline{R}}{\sigma}, \qquad (3)$$

where

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(R_i - \overline{R}\right)^2},$$

$$\overline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i.$$

[15] The Z indices of summer precipitation during 1724–2005 in Beijing were first computed from equation (1). Then the precipitation became a normalized variable Z. Furthermore, the Z indices of summer precipitation were classified into 7 grades (severe, flood, weak flood, normal, weak drought, drought, and severe drought) according to the criteria in the standard normal distribution of the Z index which is shown in the third column of Table 2. The fourth and fifth columns of Table 2 list the theoretical probability and the computed probability in percentages for each grade, respectively. The theoretical probability can be obtained from a standard normal distribution table. The computed probability is the percentage of frequency for each grade. It was found that the computed probability was near theoretical probability in all 7 grades, which indicated that the probability function, Pearson III, could well represent the actual distribution of summer precipitation in Beijing. Thus this grade-classification was used to study the probability distributions of abnormal precipitation in Beijing under different climate periods. Table 3 lists the frequencies of every precipitation grade in the 9 interdecadal climate phases of Beijing for 1724–2005. The last two rows demonstrate that the summation of precipitation frequencies in grades of weak drought, drought and severe drought, reached up to 41.3% in the interdecadal climate phases for precipitation below average. In the same phases, the precipitation frequencies for the grades of weak flood, flood, and severe flood were only 20.3%, far below the average values during the last 282 years. In the interdecadal phases for precipitation above normal, the summations of precipitation frequencies for flood, normal, and dry, were 48.7%, 41.2%, and 10.2%, respectively. It was concluded that the precipitation frequencies were significantly different in each interdecadal climate phase. Beijing usually suffers droughts in the below normal interdecadal phases with the frequency of normal and more precipitation being largely reduced. On the other hand, the frequency of normal and more precipitation was increased in the interdecadal phases for above normal. Moreover, it can be also found from Table 3 that the frequency of extreme drought and flood in Beijing remark-

Table 2. Seven Grades of Summer Precipitation and Probability Distributions

Grade	Type	Z Value	Theoretical Problem (%)	Actual Problem (%)
1	Severe Flood	Z ≥ 1.645	5.0	5.3
2	Flood	1.0367 ≤ Z < 1.645	10.0	8.2
3	Weak Flood	0.5244 < Z < 1.0367	15.0	16.3
4	Normal	−0.5244 ≤ Z ≤ 0.5244	40.0	41.1
5	Weak Drought	−1.0367 < Z < −0.5244	15.0	13.8
6	Drought	−1.645 < Z ≤ −1.0367	10.0	10.6
7	Severe Drought	Z ≤ −1.645	5.0	4.6

Table 3. Frequencies of Each Precipitation Grade in the Nine Interdecadal Climate Phases of Beijing (%)

Phase	Trend	Severe Flood	Flood	Weak Flood	Normal	Weak Drought	Drought	Severe Drought
1724–1773	Below	0.0	6.0	6.0	40.0	18.0	24.0	6.0
1774–1815	Above	7.2	14.3	23.8	45.2	2.4	7.2	0.0
1816–1839	Below	0.0	4.2	20.8	33.3	37.5	0.0	4.2
1840–1852	Above	0.0	23.1	27.7	49.2	0.0	0.0	0.0
1853–1868	Below	0.0	0.0	12.5	43.8	25.0	12.5	6.3
1869–1899	Above	16.5	6.5	29.0	29.0	13.0	3.2	3.2
1900–1947	Below	8.3	4.2	14.6	43.8	14.6	8.3	6.3
1948–1964	Above	17.6	23.5	5.9	41.2	5.9	5.9	0.0
1965–2005	Below	0.0	4.9	19.5	39.0	9.8	17.1	9.8
Average of Below		1.7	3.9	14.7	39.9	21.0	12.5	7.8
Average of Above		10.2	16.9	21.6	41.2	5.3	4.1	0.8

ably increased in the last 50–60 years. The frequency of severe floods during 1948–1964 was 17.6%, while the frequency of severe drought was 9.8% during 1965–2005. These are the highest of the above normal climate phases and below normal climate phases, respectively, in the last 282 years.

5. Forecasts of Probabilistic Trend of Anomalous Summer Rainfall in Beijing

[16] NAO, SOI, PDO and SMS, are smoothed out on 10-year scales for 1900–2005 by using the aforementioned smooth filtering method. The smoothed series with the minimum MSE was selected as the interdecadal component series. Then the interannual component series was obtained by subtracting the interdecadal component series from the original time series. By using this interannual component series, we computed the correlation coefficients of the interdecadal components for the prediction factor and precipitation with 0–10 year lags. It is seen in Figure 3 that the interdecadal variations of NAO, SOI and SMS have positive correlations with those of precipitation, while the interdecadal variations of PDO show a negative correlation with those of precipitation. Precipitation is strongly correlated

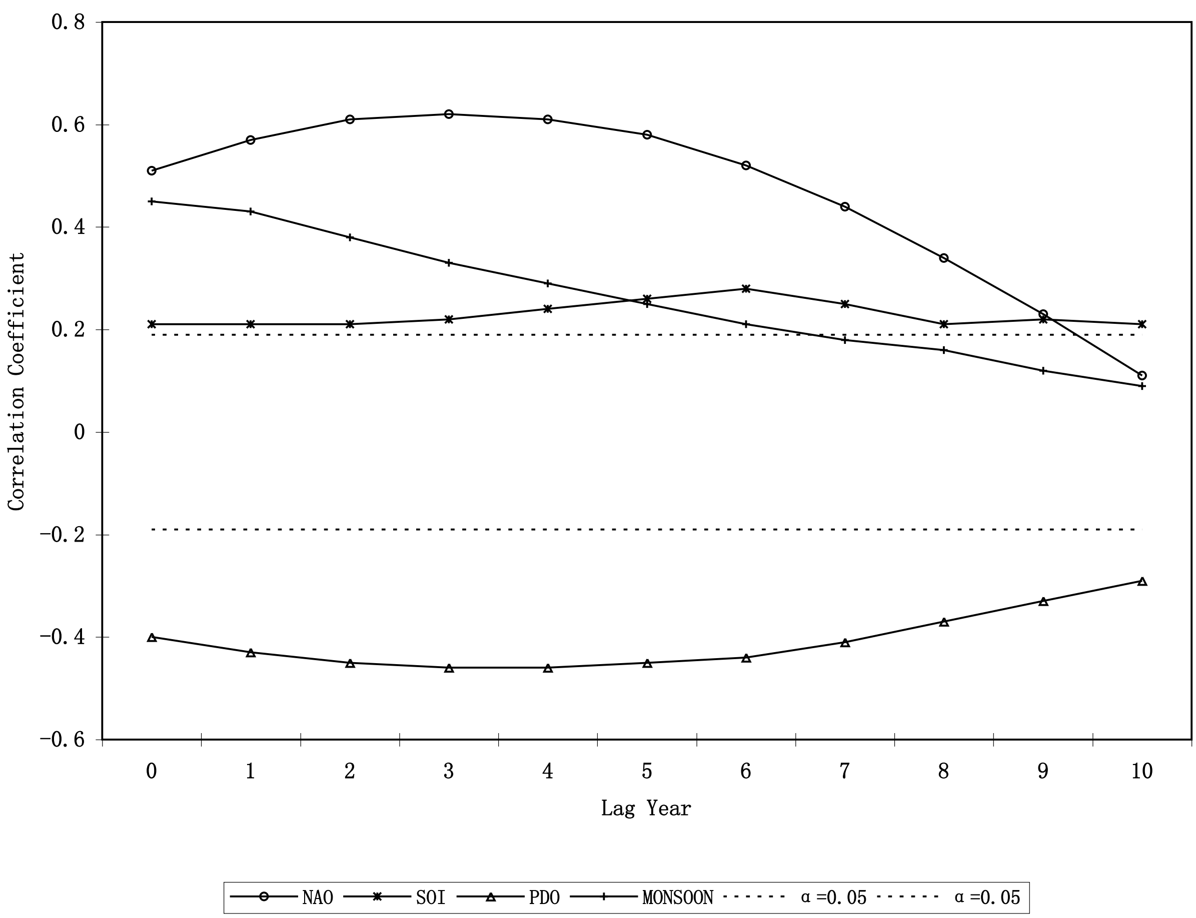

Figure 3. Correlations of the interdecadal variations of NAO, SOI, PDO, and SMS and interdecadal components of annual precipitation in Beijing.

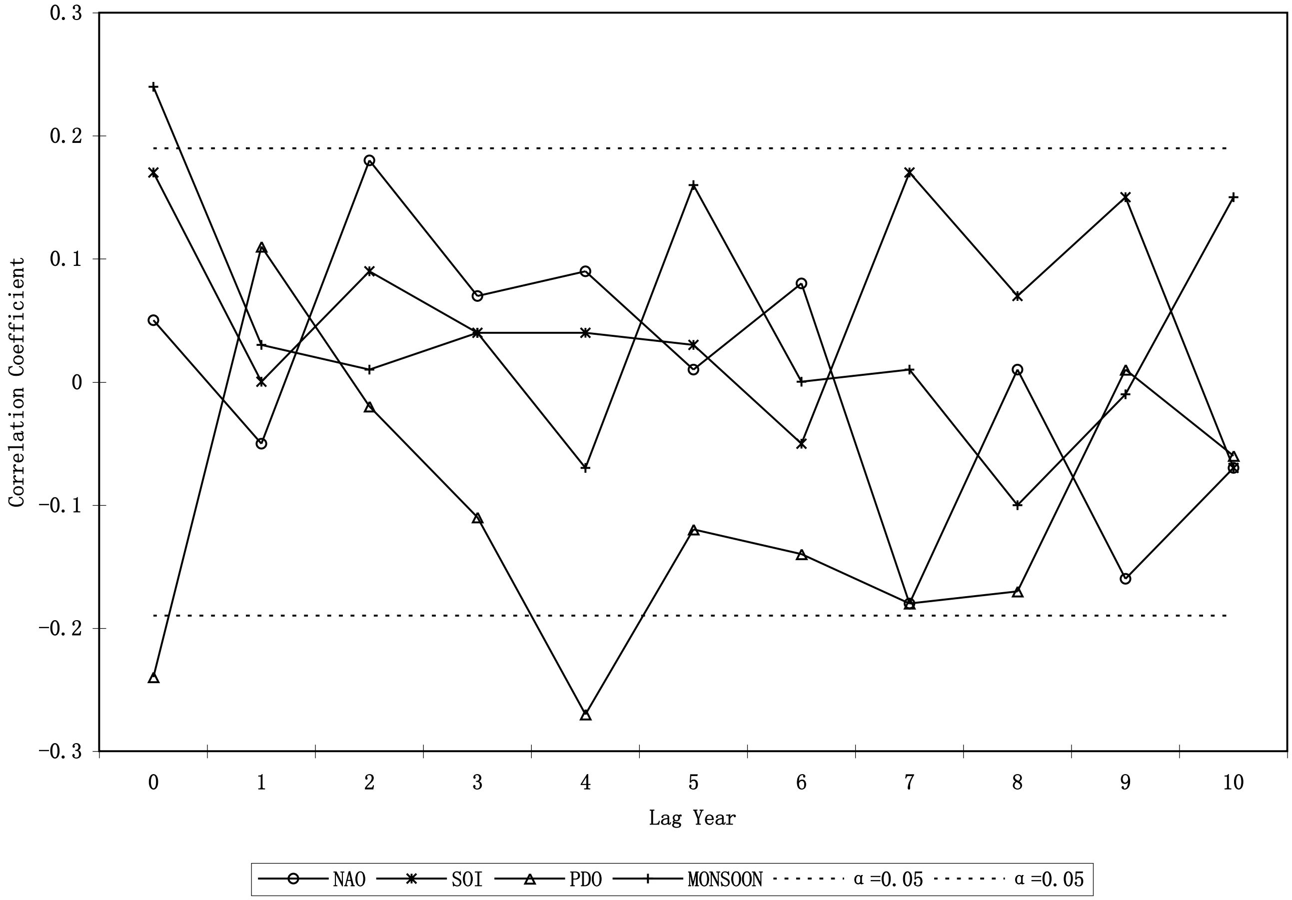

Figure 4. Correlations of the interdecadal variations of NAO, SOI, PDO, and SMS.

with NAO and PDO giving confidence greater than 99.9%. This characteristic can last a long time, so that the correlations with an 8–9 year lag can still be significant with confidences of greater than 95%. The duration of the relationship between SMS and interdecadal summer precipitation in Beijing is not as long as NAO and PDO; however, the relationship lag for 0–4 years may be beyond the confidence level of 99.9%. Although the relationship between SOI and precipitation arrives at the confidence level of 95%, it is not as distinct as the three indexes above. Using the long-term information of correlations between the interdecadal variabilities of NAO, PDO and SMS and the summer precipitation of Beijing, we can forecast precipitation trends for the next 10 years.

[17] The interannual components for prediction factor and precipitation with 0–10 year lags (see Figure 4) can be compared with Figure 3. In Figure 4, it is seen that the correlations between the interannual components of precipitation and prediction factor are neither significant nor persistent.

[18] Making a forecast before 1 year is extremely difficult (the standard deviation of the summer precipitation for 1900–2005 is 180.4 mm). However, the summer precipitation in Beijing has a good correlation with the selected factors on the interdecadal timescales. Thus we have introduced a new approach to predict precipitation by using the correlation between the precipitation and the factors on the interdecadal timescales. The probabilities of precipitations can then be derived from those in the similar periods of history.

[19] Summer precipitation R in Beijing can be given by

$$R = Rd(x_{di}) + Ra(x_{ai}) + e \tag{4}$$

where $Rd(x_{di})$ is the interdecadal component of precipitation, x_{di} is the interdecadal component of the atmospheric and oceanic factors which influence precipitation, $Ra(x_{ai})$ is the interannual component of precipitation, x_{ai} is the interannual component of the factors which influence precipitation. It is known that the significant and persistent correlations between the interdecadal components of NAO, PDO and SMS and precipitation can last a long time. Therefore, using the summer precipitation from 1900–2005 and the interdecadal component series of NAO, PDO and SMS, a statistical model for predicting the interdecadal component of summer precipitation was estimated as follows

$$Rd = 112.3180 + 203.6517x_{d1} - 60.1015x_{d3} + 321.1390x_{d4} \tag{5}$$

where x_{d1} is the interdecadal component of NAO, x_{d3} is the interdecadal component of PDO and x_{d4} is the interdecadal component of SMS. The multiple correlation coefficient of the model is 0.6416. A statistical test shows that the action of this forecasting model and the three factors on the model

Figure 5. Interdecadal components of summer precipitation in Beijing during 1900–2005. Solid line is measured data. Dashed line is simulated results. Circle line indicates predicted results.

are significant at a confidence level of 99.9%. From the values and signs of regression coefficients in the forecasting model, the SMS contributes most to the interdecadal variation of summer precipitation in Beijing. Furthermore, it has a positive phase relationship with the precipitation. NAO makes the second most significant contribution to the interdecadal variation of summer precipitation. It also has a positive phase relationship with precipitation while PDO has a negative phase relationship. Therefore, with the interdecadal variability of SMS and NAO being stronger, the negative phase of PDO becomes stronger and the tendency of summer precipitation in Beijing becomes greater. The interdecadal components of the summer precipitation in Beijing during 1900–2005 are simulated by using equation (5). It is evident that the interdecadal variation of NAO, PDO and SMS can well simulate the precipitation trends of less than average and more than average, respectively, in the phases of 1900–1947, 1965–2005 and 1948–1964. The MSE of the simulated values is 35.7 mm.

[20] In order to test the accuracy of our model, the interdecadal components of summer precipitation forecasts were made for 1971–2005 (Figure 5), where the interdecadal components of NAO, PDO and SMS during 1971–2005 were used. The MSE between prediction and observation is 63.69 mm, which is larger than that between the simulated values and observation. However, the abnormal declining tendency of summer precipitation in Beijing from the 1970s was well predicted. Thus the probabilities of precipitation grades could be deduced from the climate type of the prediction period.

[21] Because of the long-term correlation between precipitation and factors on the interdecadal scale, we extended the interdecadal series of three factors from 1900–2005 to 1900–2015. The summer precipitation trend for 2006–2015 can then be computed by employing equation (5). Our results show that the trends of summer precipitation in the next 10 years will be consistent with those during 1965–2005 in Beijing. From the probability of precipitation during the average of below period in Table 3, the estimated probabilities of precipitation grades in the next 10 years are 41.3%, 20.3% and 39.9%, respectively, for Drought, Flood and Normal.

6. Conclusions

[22] The multidecadal and interdecadal oscillation periods with 40–70 year and 20–30 year, respectively, in the summer precipitation series of Beijing have been found for the last 282 years; these are consistent with those in the global climate system. The physical mechanism of multidecadal and interdecadal oscillations of the summer precipitation of Beijing is complex and currently uncertain [*Versteegh*, 2005]. By employing a new approach to the smoothing of a time series, we divided the summer precipitation of Beijing into 9 interdecadal climate phases for the last 282 years. Our analysis demonstrates that the differences in the average precipitation are significantly different

between below normal and above normal phases. Moreover, the average probabilities of precipitation in the below normal phase are also found to be different from those in the above normal phase. We have examined the relationship between the summer precipitation series of Beijing and global annual temperature anomaly series [*Jones and Moberg*, 2003] during 1965–2005. The correlation coefficient of the two series is -0.22 with a confidence level greater than 99.9%. It should be noted that the probability of droughts in Beijing has greatly increased since the middle of the 1960s; this is closely related to the interdecadal variation of precipitation and global warming in the last 40 years. Furthermore, the probability distribution of abnormal droughts and floods in Beijing shows that the probability of extreme drought and flood events may increase remarkably with global warming, because the hydrological cycle process may have been aggravated by climate warming [*Houghton et al.*, 2001].

[23] On the basis of the long-term memory of the correlations between the interdecadal variation of NAO, PDO and SMS and the summer precipitation in Beijing, we developed a methodology to predict the probability of precipitation using interdecadal variability. Calibration and validation experiments with independent data indicate that our forecast model exhibits significant skill in estimating the trends of summer precipitation in below and above normal phases. These trends can then become a basis for forecasting precipitation probabilities.

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