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Analysis of precipitation cycles based on MEM in the Yellow River basin

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Abstract Using the monthly precipitation series of 32 meteorological stations in the Yellow River basin from 1951 to 2003, the precipitation cycles were discussed using the Maximum Entropy Method (MEM), the spatial distribution of the precipitation cycles were analysed, and the possible driving factors of the cycles investigated. The results show that the precipitation in the Yellow River has decadal (60a), inter-decadal (25a and 14a) and inter-annual cycles (9a and 3a). The main oscillations over the whole basin are 3a and 9a. There are clearer inter-decadal variations in the riverhead area with much greater water resources, and north of the region of LanHe main stream. The decadal signals are detected in the inner area with less precipitation and Wei River basin. These differences are possibly related to some physical processes, such as the mutual action of sea and atmosphere, and solar activities.

Key words maximum entropy method; precipitation; cycles; Yellow River basin

1 INTRODUCTION

Climatic and hydrological phenomena have periodic and random characteristics over time scales. Precipitation periodicity has been a main focus of hydrology research. (Hao *et al.* 2008; Martino *et al.* 2013). The Yellow River basin is the second largest river basin in China, and the precipitation is the fundamental source of basin water resources. Analysing the precipitation cycle is essential for predicting the change trend of future precipitation and promoting the utilization and management of water resources in the basin.

Many methods are used to analyse the cycles of climatic and hydrological time series (Xu *et al.* 2002; Hanson *et al.* 2004; Li *et al.* 2010). The traditional cycle analysis methods, including the discrete periodogram, Harmonic cycle analysis and variance analysis, are limited by the fact that they are mainly in the time domain to analyse the periodic oscillation of time series, which has been regarded as the sine wave. In addition, determining the parameters of these methods is quite difficult (Sang 2009). In recent years, wavelet analysis has becoming a common mathematical measurement tool to determine time series cycles (Kang *et al.* 2007; Labat 2008), which can realize the flexible conversion of time series between the time domain and frequency domain. However, the outcome relies on the proper selection of the wavelet function. Also, the edge effect of wavelet analysis cannot be ignored (Wang *et al.* 2006).

Comparison of all the methods mentioned indicates that the Maximum Entropy Method (MEM) overcomes the weaknesses of low resolution, subjective choice of autocorrelation function maximum delay, unreality to extend data. This method has the advantages of a short and smooth frequency spectrum and high resolution, with which we can analyse the cycle of time series exceeding its sample length (Nicolas *et al.* 1989; Wang *et al.* 2004; Pardo-Igúzquiza *et al.* 2005). In this paper, MEM will be used to conduct cycle analysis of the precipitation series in the Yellow River basin, and the spatial distribution of the precipitation cycles of the basin will also be explored.

2 STUDY AREA AND DATA

The Yellow River, regarded as the Mother River of China, is the second longest river in China. Originating from the eastern Qinghai-Tibet Plateau at an elevation higher than 5000 m, the Yellow River flows eastward through northwestern China over a total length of 5464 km^2 through nine provinces, before discharging into the Bohai Sea (Fig. 1). It has a drainage area of more than 750 000 km^2 with 35 main tributaries, and exhibits a variety of geological and climatic features, with humid climate in the southeast, semi-arid in the central region and dry climate in the northwest. The average annual temperature of the basin ranges from 4°C to 14°C. The mean annual precipitation is highly heterogeneous across the basin, increasing from 368 mm in the upper reaches to 530 mm in the middle reaches and 670 mm in the lower reaches. The Yellow River is well known not only for its history and large drainage area, but also for its high sand content, frequent floods, and scarcity of water resources. Recently, affected by climatic change and human activities, the characteristics of the hydrological processes have changed, as reflected by the aggravation of soil erosion, and more frequent zero-flow events in the Yellow River basin during recent decades (Zhang *et al.*, 2009; Wang *et al.*, 2012).

The monthly precipitation data of 32 National Meteorological Observatory (NMO) stations from 1951 to 2003 were chosen in this study and provided by China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). The location of the meteorological stations over the Yellow River basin is shown in Fig. 1.

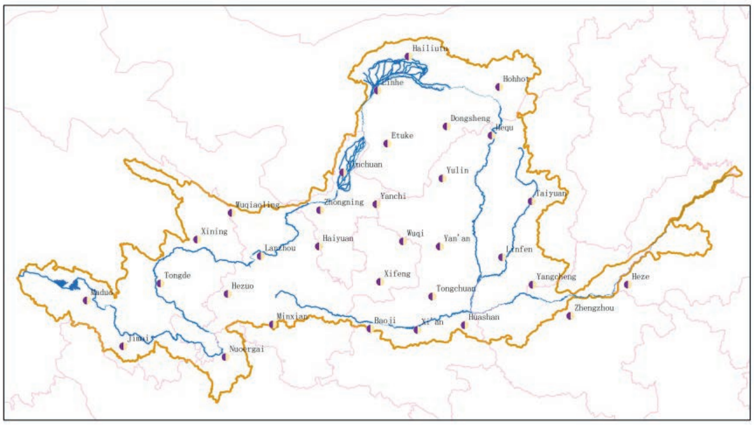

Fig. 1 Location of the meteorological stations in the Yellow River basin.

3 METHODOLOGY

MEM was introduced for the first time by Burg in 1967 (Wei, 1999) when using the maximum entropy principle in spectral analysis. The process of maximum entropy spectral estimation is substantially to estimate the power spectrum of the time series with the methods of lag correlation or auto-regression under the principle of maximum entropy. Due to the extended series length of correlation functions, the spectral estimation error is reduced and the resolution is greatly improved. The expression of time series X_k is set as follows:

$$X_k = -\sum_{i=1}^{m} b_i X_{k-i} + n_k \tag{1}$$

where X_k is the observed time series data, n_k is the steady white noise independent of X_l ($l < k$), m is the closing order (i.e. the running times) of the auto-regressive model, b_i is the auto-regressive coefficients for order m.

The time series can be considered to be a group of regular waves of different frequencies, the greater the variance of waves of different frequencies, the greater the power spectrum and the entropy value as well. The entropy value H of the series is defined as:

$$H = \int \log s(j) dj \tag{2}$$

where $s(j)$ is the frequency spectrum of the series, and the integration interval is the entire frequency domain. Using the formula of Wiener-Khinchine (Wei, 1999), the expression for MEM is deduced to be:

$$s(\mathrm{j}) = \frac{\sigma_m^2 \Delta t}{|1 - \sum_{j=1}^{\mathrm{m}} b_{j,m} \mathrm{e}^{-2ij\pi\Delta t}|^2} \quad (3)$$

where j is the frequency $f_k = k/T$ (k = 1,2 ..., m; T = 2 m;), Δt is the time interval of the discrete series, and Δt = 1 in equal interval series, i is an imaginary number, σ_{m}^2 is the variance of the forecast error.

It is crucial for MEM to determinate the closing order m. Any of a number of criteria could be used for selecting order m, Akaike information criterion (AIC), final prediction error (FPE), etc., as reported elsewhere (Brockwell and Davis, 1991). Nonetheless, in most applications m is chosen empirically between $N/5$ and $N/3$ with reliable results (N being the number of observations) (Weedom, 2003).

In this study, precipitation cycles in the Yellow River basin are examined over four time scales: the short-term (1 to 10a), the medium-term (10 to 20a), the middle-long term (20 to 50a) and the long-term (50 to 100a). To better illustrate the spatial distribution of the precipitation cycles, the basin is divided into seven sub-regions according to the water resources characteristics (Fig. 2).

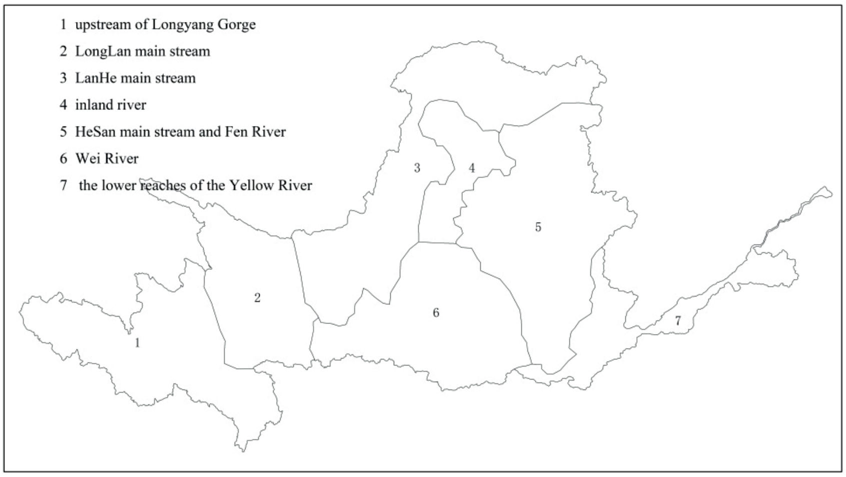

Fig. 2 The sub-regions of the Yellow River basin.

4 RESULTS AND DISCUSSION

4.1 The precipitation cycle analysis

According to MEM, the calculated maximum entropy spectral density of different frequency-wave (can be converted to corresponding period) is represented. If there is sharp peak in the spectral density plot, the corresponding cycle is regarded as the significant cycle of the series (Fig. 3). Based on the monthly precipitation data from 1951 to 2003 of 32 weather stations in the Yellow River basin, the precipitation cycles on different scales are been calculated using MEM. The results are listed in Table 1.

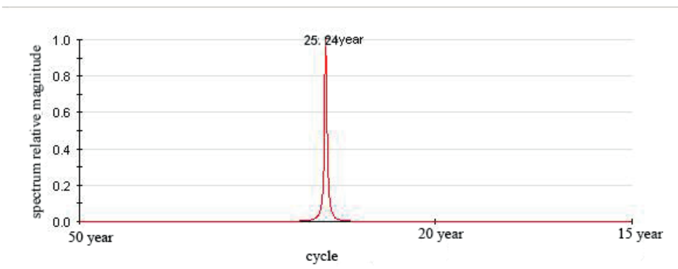

Fig. 3 The entropy spectrum of Xi'an station on the 20−50a scale.

As shown in Table 1, there exist 3a and 9a precipitation cycles on the short-term scale in the whole basin, a 13−15a cycle on the medium-term scale, a 25a cycle on the middle-long term scale, and an about 60a cycle on the long-term scale. After analysing all the data, it was found that 14a is the average primary cycle length on the medium-term scale, 25a on the middle-long-term scale and 60a on the long-term scale, respectively. In general, there are the decadal, inter-decadal and inter-annual precipitation cycles over the whole basin.

These results are consistent with many previous findings, which verify the applicability of MEM in studying the period features of the time series. Wang (1998) examined the hydrologic period in the upper and middle reaches of the Yellow River, and discovered a short period of 2a, a medium period of 20a, and a long period of 60a. Yang *et al.* (2005) pointed out that there was a 2−3a short cycle of the rainfall series in the source region of Yellow River. Hao *et al.* (2008) demonstrated that the rainfall in the middle and lower reaches of the Yellow River had a 2−4a inter-annual, 22a inter-decadal and 70−80a decadal cycle of four sub-regions during 1736−2000.

Table 1 Precipitation cycles of stations on different scales in the Yellow River basin (unit a).

Province	Station	1−10a	10–20a	20–50a	50–100a
Gansu	Wuqiaoling	2.5, 8.6	12.1	26.4	-
	Lanzhou	8.8	13.6	-	63.3
	Xifeng	2.5, 6.6	14	45.9	-
	Hezuo	2.9	15.5	-	60.2
	Minxian	3.0	-	21.0	55.5
Qinghai	Xining	2.8, 8.7	16.0	46.8	52.7
	Tongde	4.0	11.3	40.2	-
	Maduo	8.4, 3	18.5	47.5	-
	Jimai	3.5	15.1	22.3	-
Inner Mongolia	Hailiutu	3.0	12.6	25.2	-
	Hohhot	2.8	10.5	49.0	51.8
	Linhe	3.6, 8.7	16.7	-	59.3
	Etuke	8.6, 4	14.4	-	57.8
	Dongsheng	3.0	14.1	22.1	-
Shanxi	Hequ	9.6	14.1	-	56.0
	Linfen	6.6	10.0	-	69.6
	Yangcheng	5, 2.3		21.5	57.8
	Taiyuan	2, 6.7	14.3	-	61.8
Ningxia	Yinchuan	3,8	14.4	45.9	55.4
	Zhongning	4, 6	15.8	-	66.0
	Yanchi	4.2	-	34.8	-
	Haiyuan	6, 4	15.0	37.9	-
Shaanxi	Yulin	8.7, 3.4	15.9	48.0	50.9
	Wuqi	2.4	13.3	41.3	-
	Yan'an	2.0	12.9	22.2	62.5
	Tongchuan	6.3	-	20.3	-
	Baoji	2.8	-	25.1	60.7
	Xi'an	2.5	-	25.2	72.6
	Huashan	2.9	-	26.4	73.9
Sichuan	Nuoergai	2.8	15.3	20.7, 45.8	-
Henan	Zhengzhou	5, 9.4	12.9	26.5	63.3
Shandong	Heze	4.3, 7.3	12.1	-	61.0

“-” means there is no obvious cycle.

On the long-term (50a to 100a) scale, 20 of the 32 stations in the river basin have cycles in their precipitation series, which verifies the advantages of MEM in the analysis of the climatic series cycles.

4.2 Spatial distribution of precipitation cycles

According to the geographic location of the stations (Fig. 1), the basin sub-regions (Fig. 2) and the corresponding cycles of each station (Table 1), using GIS spatial interpolation techniques, the spatial distribution of the different temporal scales were analysed. The results show that the spatial differences of the precipitation cycles are significant. On the short-term scale, there generally exist cycles of about 3a and 9a over the whole basin. On the medium-term scale, the trend of cycle distribution is for longer cycles in the northwest and shorter cycles in the southeast and 12–16a is the main cycle component. There are more than 16a cycles in the upstream of Longyang Gorge, LongLan main stream and LanHe main stream. There are 12–16a cycles in the inland river, HeSan main stream and most parts of Fen River. Most parts of the Wei River and the lower reaches of Yellow River shows periods of less than 12 years. The spatial distribution of the medium-long term precipitation cycle is similar to the medium-term cycle. The spatial distribution is generally as follows: in the upper reach, there is a more than 36a cycle in the upstream of Longyang Gorge, the northeast regions of LanHe main stream and north regions of Fen River. Wei River basin, southwest regions of HeSan main stream and small parts of the northwest regions in the upper reach of Yellow River have a cycle of about 28a. On the long-term scale, the spatial distribution is different from the others. In the upstream of Longyang Gorge and north region of LanHe main stream there is no obvious cycle. Very long cycles of more than 60a are shown in Longlan main stream, the lower reach of Wei River basin and lower reach of Fen River basin. Other regions have cycle of about 50–60a.

4.3 Factors influencing precipitation cycles

Precipitation change is considered as an expression of climate change, which can be influenced by combinations of exterior factors including solar activity, the Earth and celestial motion, crustal movement, and interior factors of the climate system, such as atmospheric circulation. Moreover, other factors such as topography and human activities may also affect precipitation change.

4.3.1 Solar activities Solar radiation is the fundamental energy source of the Earth's climate system operation and climate change. The solar activities may affect precipitation in the Yellow River basin. Li *et al.* (2005) found that solar activities have a certain influence on the rainfall of the Yellow River basin. On the 9a time scale, there is a certain degree of negative correlation between the rainfall of the basin and the macula, and the rainfall shows 1–2a hysteresis.

4.3.2 Atmospheric circulation Atmospheric circulation is the most direct cause of climate change. Studies (Brázdil, 1995; Kalimeris, 2012) have shown that 2–3a cycle is the most fundamental cycle of the change of meteorological elements on Earth. It is also a very important change rule of the process of atmospheric circulation and meteorological elements. The 3a precipitation cycle is consistent with the 3a cycle of the subtropical ridge line which is an important system that influences the rainfall in western regions of China.

4.3.3 Sea surface temperature (SST) Ocean thermal conditions change and air–sea interactions have been considered to be important factors in the causes of climate change. SST has an important effect on the atmospheric circulation, weather and climate change. Research has shown (Wang, 1993) that there was significant correlation in the 20.7 month cycle between precipitation in the middle reaches of the Yellow River and the equatorial West, East Pacific and North Pacific monthly SST, which were in the same phase.

There are precipitation cycles on four time scales in the Yellow River basin, which are related to the result of interaction of multiple factors. Hao *et al*. (2008) discovered that the inter-annual and inter-decadal oscillating cycles of rainfall in the middle and lower reaches of the Yellow River region may be influenced by the combined effects of the solar activity, El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

5 CONCLUSION

The multi-temporal and spatial distribution of precipitation cycles have been investigated in the Yellow River basin by using MEM and GIS. The results show that the precipitation in the Yellow River has decadal (60a), inter-decadal (25a and 14a) and inter-annual cycles (9a and 3a). Meanwhile, the spatial difference of precipitation cycles is significant. The results demonstrate that the MEM method is applicable to calculate the time series cycle.

The precipitation cycles in the basin may be restricted and influenced by solar activities, atmospheric circulation and air–sea interaction. In addition, they may also be affected by other factors such as terrain features, human activities, and its specific impact mechanism remain to be further recognized.

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REFERENCES

Brázdil, R. and Zolotokrylin, A.N. (1995) The QBO signal in monthly precipitation fields over Europe. *Theor Appl Climatol.* 51, 3–12

Brockwell P.J. and Davis R.A. (1991) *Times Series: Theory and Methods*, Second ed. Springer, New York 577pp.

Burg J.P. (1967) Maximum entropy spectral analysis. In: *37th Annual International Meeting of the Society for the Exploration of Geophysics*. Oklahoma City, OK, pp. 34–41.

Hao Z.X., Zheng J.Y. and Ge Q.S. (2008) Precipitation cycles in the middle and lower reaches of the Yellow River (1736−2000). *J. Geogr. Sci.* 18, 17–25

Hanson R.T., Newhouse M.W. and Dettinger, M.D. (2004) A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States. *Journal of Hydrology* 287, 252–269.

Kang S.J. and Lin. H. (2007) Wavelet analysis of hydrological and water quality signals in an agricultural watershed. *Journal of Hydrology* 338, 1–14

Kalimeris A., *et al.* (2012) Long-term precipitation variability in the Ionian Islands, Greece (Central Mediterranean): climatic signal analysis and future projections. *Theor Appl Climatol*. 109, 51–72. doi: 10.1007/s00704-011-0550-5

Labat, D. (2008) Wavelet analysis of the annual discharge records of the world's largest rivers. *Advances in Water Resources* 31, 109–117.

Li, C.H. and Yang, Z.F. (2006) Relationship between solar activities and precipitation in the Yellow River Basin. *Meteorological Monthly* 31(11), 42−44 (in Chinese).

Li, Z.J. and Yu, J.S. (2010) Analysis on precipitation cycles in the Yellow River basin. *J. Beijing Normal University* (Natural Science) 46(3), 401−404 (in Chinese).

Martino G., *et al.* (2013) Variability and trend in seasonal precipitation in the Continental United States. *J. Hydrol. Eng*. 18(6), 630−640.

Nicolas R.D. and Panagiotis, A.T. (1989) Maximum entropy spectra for regional precipitation analysis and forecasting. *Journal of Hydrology* 109(1-2), 25−42.

Pardo-Igúzquiza, E. and Rodríguez-Tovar, F.J. (2005) MAXENPER: a program for maximum entropy spectral estimation with assessment of statistical significance by the permutation test. *Computers and Geosciences* 31(5), 555–567.

Sang, Y.F., *et al.* (2009) The relation between periods' identification and noises in hydrologic series data. *Journal of Hydrology* 368, 165−177.

Wang, D., *et al.* (2004) Maximum entropy spectral analysis for annual maximum tide levels time series of the Changjiang River Estuary. *Journal of Coastal Research* SI43, 101–108.

Wang H.R., *et al.* (2006) The problems in wavelet analysis of hydrologic series and its improvement. *Progress in Natural Science*. 16(8), 1002−1008 (in Chinese).

Wang, W., *et al.* (2012) Reference evapotranspiration change and the causes across the Yellow River Basin during 1957–2008 and their spatial and seasonal differences. *Water Resour. Res*., 48, W05530, doi:10.1029/2011WR010724.

Wang, S.H. and Chao H.L. (1993) The relationship between precipitation in the middle reaches of the Yellow River and Pacific SST, Southern Oscillation. *Meteorological Science* 13(1), 47–55 (in Chinese).

Weedom G.P. (2003) *Time-Series Analysis and Cyclostratigraphy: Examining Stratigraphic Records of Environmental Cycles*. Cambridge University Press, Cambridge, UK 259pp.

Wei, F.Y. (1999) *Modern statistical diagnosing and forecasting technology of climate.* China Meteorological Press, Beijing (in Chinese).

Xu, J.J. and Johnny, C.L., 2002. Interannual and interdecadal variability of winter precipitation over China in relation to global sea level pressure anomalies. *Advances in Atmospheric Sciences* 19(5), 915–926.

Zhang, Q., Xu, C.-Y. and Tao, Y. (2009) Variability of water resource in the Yellow River Basin of past 50 years, China. *Water Resour. Manage*. 23(6), 1157–1170.