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Evolution characteristics of the precipitation in the Yangtze River delta based on the probability density*

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In this paper the dryness/wetness (DW) grade data of the Yangtze River delta is transformed into the temporal evolution of precipitation probability (PP), and its hierarchically distributive characters are revealed. Research results show that the precipitation of the Yangtze River delta displays the interannual, interdecadal, as well as longer quasi-periodic changes than a century, and all the periods have a confidence level of more than 0.05. In the DW grade series of 530 years, although the frequency of the small probability events (SPEs) of drought/flood in each area of the Yangtze River delta is different, the frequency of the SPEs triggered by the climatic background state is yet the same. This research result fully shows the significant impact of the climatic evolution as a background state upon the occurrence of SPEs, which will be instructive in climatic prediction theory and in raising the accuracy of the climatic prediction.

Keywords: drought/flood, small probability events, Yangtze River delta, probability evolution
PACC: 9260X, 9260Y

1. Introduction

The influences induced by the global climate change on the development of economy and social conditions have become an important topic concerned by governments and scientists in the world. Among them, the climate change on the interannual–interdecadal timescale has even greatly impacted on the normal lives of human beings, which is one of research objects of the International Climate Variability (CLIVAR) Project.[1−4] Therefore, the research on the intrinsic variability and predictability of the climate is important for the prediction of short-term climatic changes.[5,6]

China is situated in the monsoon climate area with a maximum variability of precipitation in the world as well as the frequent occurrences of the drought and flood,[7] consequently, the research on the impact of the climatic variability of the precipitation upon social development and economic construction is of great importance. For the Yangtze River delta, which is one of the distinct areas where the population is densest and the economy grows most rapidly in China, anomalous precipitation not only restricts the economic growth, but also endangers the ecological environment. For example, the floods in 1991 and 1998 induced a large loss in the delta. Therefore, the discovery of the mechanisms for the interannual and interdecadal variability of the precipitation in the delta is a matter very urgent and of strategic importance. Meanwhile, although the climatically extreme events of the precipitation (severe drought/ flood) resulted in the huge loss, up to now their mechanisms and intrinsic origins are still not clear.[8]

In this paper, the drought and flood are brought into the unified framework of the small probability events (SPEs), and the temporally evolutional laws of the SPEs is explored from a global point of view based on the temporal distributions of precipitation proba-

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bility (PP). The time series in the climate system are non-linear, and possess the multi-scale property and singularity. How to process and analyse the meteorological data so as to better reveal and predict the essence and intrinsic law of object phenomena embedded in the data has always been an open problem.[9] In this paper the data of dryness-wetness (DW) grade series in the Yangtze River delta are transformed into the temporal evolution of PP. In comparison with traditional rainfall analysis method, the PP analysis method possesses the three advantages. Firstly, the transformation partly removes the spatial-temporal limitation of the precipitation process itself; secondly, its smoothing effect on the time series differs from that of the traditional methods, namely the temporal evolution of the PP fully contains the evolutional information of the historical data and inherits the self-memory evolutional characters of the climatic change itself; and thirdly, after the transformation of the time series for the precipitation into the temporal evolution of PP, the two opposite extreme events of the drought and flood are organically joined together and the evolution laws of the SPEs can be globally analysed.

2. Data

The DW grade data used are based on documents of drought and water logging atlas of China in the past 500 years.[10] The research area selected is the Yangtze River delta including Yangzhou, Nanjing, Suzhou, and Shanghai, and the length of time series is 530 years (1470–1999). Five grades of dryness/wetness are used to present the size of annual rainfall. First grade represents a flood year, second grade a flood-biased year, third grade a normal year, fourth grade a drought-biased year, and fifth grade a drought year. If σ denotes the standard deviation of regionally averaged annual rainfall, then the anomaly of the rainfall of the third grade is within $\pm 0.33\sigma$, the anomaly of the first grade is $>1.17\sigma$, the anomaly of the fifth grade $\leq -1.17\sigma$, and the anomalies of the second and fourth grade are between the first and the third, and between the third and the fifth, respectively. The DW grades from 1980 to 1999 were supplemented based on "Monthly Mean Rainfall at 160 Stations in China" compiled by China Meteorological Administration.[11] The method by which the literal description of historical document was transformed into the 500-year DW grade, the scientific basis of transformation were addressed, and the reliability of the grade series was also verified in terms of statistical analysis.[12]

The concrete procedures of transforming the DW grade data into the time series of PP are as follows: Taking the first grade (flood) and fifth grade (drought) as extreme events, the third grade as normal states, the second grade (flood-biased) and the fourth grade (drought-biased) as a transition state, counting the ratio of each grade in 530 years in each region, and replacing the grade of each year with corresponding ratio value yield the time series of PP in each region. For instance, for Yangzhou DW grade data, the five grades (from the first to the fifth) account for 8.7%, 29.1%, 34.3%, 21.9% and 6.0% respectively in the length of 530 years. Then replace the grade of each year by the corresponding ratio value. For example, the grade value in 1978 is 5, transformed PP value is 0.06; and the grade value in 1999 (the value being 1) is transformed to 0.087 in the corresponding PP value. Thus the PP evolution with time is obtained for Yangzhou. And the DW grade data in other regions are dealt with similarly as that in Yangzhou.

It is especially emphasized that in the present paper the flood and drought are combined statistically as a whole, so for the PP evolution, the images for the independent flood or drought are not directly visualized, which is dominated by the property of the statistics, but can be well understood in association with the original data; and the PP can reveal the evolution law of the SPEs of drought/flood. Hence, the circumstance of PP evolution here is completely suitable for the global study of the SPEs mentioned above, i.e. the statistical combination of the flood and the drought.

The following analysis is based on the time series of PP, except when specially declared.

3. Analysis methods

Filtering and wavelet transform are used in the data analysis process.

The filter used was put forth by Zheng and Dong,[13] and it is a multi-stage filter with a very narrow filtering band. The filter was used to separate the slow-varying mean value from the climatic element fields (atmospheric temperature, precipitation, and sea surface temperature etc), and the length of the filtered series is the same as that of the original series.[14−16]

The wavelet analysis (wavelet transform) is a breakthrough of Fourier analysis method, and it is generally used in seismological data analysis, signal processing, turbulence, atmospheric and oceano-

graphic sciences, and so on. In comparison with traditional mathematical methods, it possesses great superiority.[3,6,17,18] The discrete form of wavelet transform is

$$W_f(a,b) = |a|^{-1/2}\,\Delta t \sum_{i=1}^{n} f(\mathrm{i}\Delta t)\, g\left(\frac{\mathrm{i}\Delta t - b}{a}\right), \quad (1)$$

where $f(x)$ denotes an arbitrary function of time or space, and g the basic wavelet or generating wavelet, which is a double-window function with one being time window and the other being frequency-spectrum window. a is a frequency parameter and b is a time parameter, representing the temporal transition of waves. Δt is the sample interval, and n the number of samples.

The wavelet transform can objectively separate structures of different wavelengths, and clearly exhibit the amplitude of waves. At the same time, it reveals the temporally evolutional characters which enable us to see the perturbation features of different scales, thus to judge the significant periods existing in the time series. Besides, the wavelet transform can analyse the local singularities of oscillation for wavelet coefficients on a certain timescale, determine the time position of different scale variations, and give the signal of abrupt changes. The real part signals of Morlet wavelet transform coefficients are analysed in the following part of this paper.

4. Results analysis

4.1. Multi-timescale distribution characters of the PP evolution of the Yangtze River delta

A lot of works have been done on climatic changes of DW in China in the last 500 years and abundant results have been obtained.[19−21] For example, Zhang *et al*[19] have reconstructed the DW grade series of 1033 years with a resolution of one year in North China, East China etc., all together six regions in the east part of China. Meanwhile, they have discussed the quasi-periodic property existing in the 1000 years in those regions, and pointed out that the quasi-periodic property of about 3-year and 11-year is remarkable, and periods of 25-year and 36-year exist in part of the regions. Zhu and Wang[21] have calculated the correlation of the precipitation time series of representative stations with those in Eastern China, and determined the correlation area, yielding the prominent 80-year oscillations existing in North China, the south part of Northeast China, the middle and lower reaches of the Yangtze River, and the region south of the Yangtze River. Viewing from another angle, and using the time series of the PP of the Yangtze River delta, this paper studies the overall distribution characters and evolution laws of drought and flood treated as SPEs. Because the grade value of DW of a certain year in an area indicates the extent of precipitation abundance of this year in the area, the temporal evolution of PP transformed from the grade data represents the temporal distribution of precipitation.

The statistical analysis results indicate that the probability distribution transformed from DW grade data of the Yangtze River delta has a quasi-normal distribution (figure omitted).[22] Meanwhile it is found from the analysis of power spectrum that prominent interannual (3–7 years), interdecadal (20–30 years), 60–70 years, and 120 years quasi-periodic oscillations exist in the climatic precipitation series of Yangzhou region, and those quasi-periods all pass the significance test of the 0.05 level (Fig.1). In addition, the multi-timescale distribution characters of the PP evolution of Nanjing, Suzhou, and Shanghai region are similar to those of Yangzhou, therefore, the time series of PP of each region in the Yangtze River delta unexceptionally exhibits the multiple timescale distributive character (Table 1).

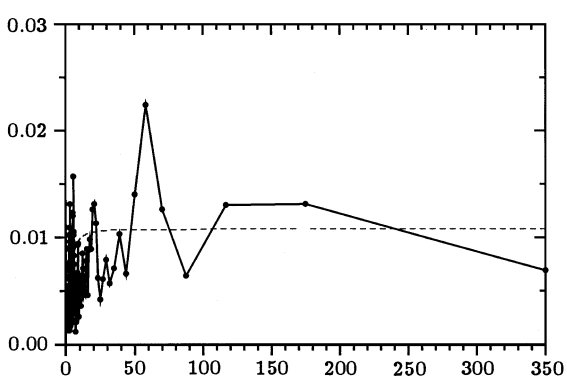


Fig.1. Power spectrum of the PP evolutional series of Yangzhou.

Table 1. Multi-timescale distribution of the PP evolution of the Yangtze River delta.

	Multi-level timescales (* y denotes year)		
Yangzhou	Inter-annual (3–7y)	quasi-20–30y*	quasi-60–70y, 120y
Nanjing	Inter-annual (3–7y)	quasi-40y	quasi-120y
Suzhou	Inter-annual (3–7y)	quasi-20–30y	quasi-120y
Shanghai	Inter-annual (3–7y)	quasi-20–30y	quasi-60–70y, 170y

The origins of the multiple timescales of precipitation and the contribution of each timescale to the precipitation are still not very clear up to now. Research results show that the area where the interannual change of climate is most distinctly affected by Elniño-Southern Oscillation (ENSO) is the Changjiang–Huaihe River valley, and the variance contribution of ENSO to the summer precipitation of China is about 25%.[23] After studying the influence of ENSO on the anomaly of the Asian summer monsoon and on precipitation in China, Zou and Ni[24] pointed out that the summer precipitation over the eastern part of China is greatly affected by ENSO, its impact concentrates on the first four modes of precipitation anomaly Empirical Orthogonal Functions (EOFs), and its variance contribution accounts for 52 % of the total. That is to say, more than one half of the anomaly of summer precipitation in the east part of China is related with ENSO. Furthermore, ENSO mainly affects the middle and lower reaches of the Yangtze River, and South China. In view of the above circumstance, this paper focuses on studying the evolution character of the climatic background precipitation and on exploring the contribution of the climatic background precipitation field to the occurrence of SPEs.

4.2. Evolution character of the climatic background PP of the Yangtze River delta

In order to reveal the mechanism of interannual precipitation changes, the influence of century-scale and interdecadal-scale climatic precipitation could not be neglected. The time series of PP for the Yangtze River delta is filtered, and separated into two different time-scale series of more than 40-year background field (climatic basic state) and the relatively higher frequency component of less than 40-year. The character and evolution laws of climatic basic state need to be revealed and to be studied, because the slow-frequency component as a background state may greatly affect high-frequency changes, and interannual variation is only a high frequency oscillation superimposed on the background state.[16,25,26]

The character and evolution laws of precipitation on climatic background state in Yangzhou region are at first investigated. Fig.2(a) displays the temporal evolution of the PP of climatic basic state, and small solid circles in the vicinity of the minimum value of probability distribution denote the extreme events corresponding to the first and fifth grade in the original data. Fig.2(b) exhibits the temporal evolution of the climatic basic state of DW grade series. It can be seen from Fig.2(a) that the evolution of Yangzhou PP on climatic basic state temporally exhibits the distinct fluctuation, whereon the wave crest denotes the normal state of precipitation, and the wave trough the SPEs. The concrete character is as follows: 1480–1500, 1550–1575, 1610–1630, 1725–1750, and 1880–1920 are the periods for normal precipitation; within 1510–1540, 1575–1590, 1640–1660, 1690–1710, 1815–1860, and 1950–1975 do exist the frequent SPEs (drought or flood). It is known from comparing Fig.2(a) with Fig.2(b) that 1525–1550, 1640–1660, 1910–1930 etc. are relatively dry periods, while 1510–1530, 1575–1590, 1690–1710, 1810–1850, and 1950–1970 are rainy periods. That is to say, the relative dry and rainy periods in Fig.2(b) basically correspond to the distribution intervals of SPEs in Fig.2(a), while the normal precipitation years correspond to the intervals of PP maximum values.

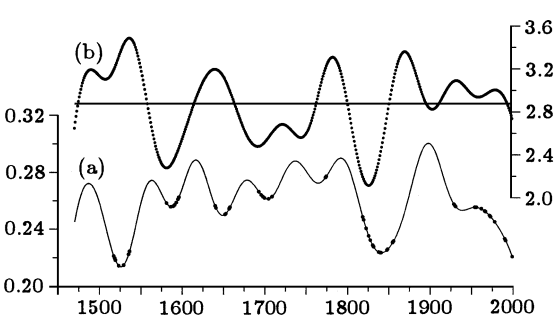


Fig.2. Temporal evolution of Yangzhou precipitation on climatic basic state. (a) PP series; (b) DW grade series. Small solid circles in the vicinity of the minimum value of probability distribution in (a) denote the extreme events corresponding to the first and fifth grade in the original data.

There are totally 78 times of drought or flood in the 530-year DW grade series of Yangzhou region,

and those SPEs account for 14.7% of the total samples. Among them 57 times (small solid circles in Fig.2(a)) occur in the vicinity of the minimum value (wave trough) of probability distribution on climatic state scale, and account for 73.1% of the total number of SPEs. The above important fact clearly shows that the climatic basic state plays a deterministic role in the occurrence of SPEs, or at least, the climatic basic state provides an important background field for the occurrence of SPEs.

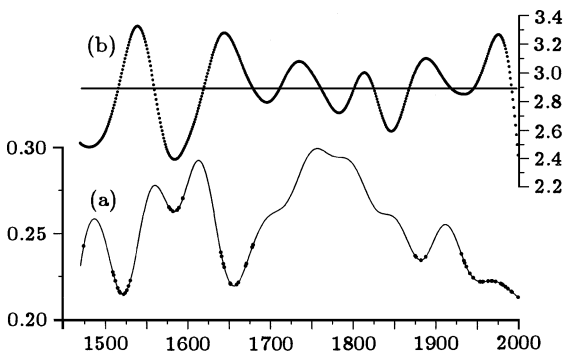


Fig.3. Same as Fig.2 but for Shanghai.

With regard to the characters and evolution laws of precipitation on climatic basic state of Shanghai region, it can be observed from Fig.3 that on climatic mean timescale, whether the PP distribution or the DW grade distribution accord generally with those of Yangzhou region. The temporal evolution of Shanghai PP also exhibits distinct oscillations. The concrete character is displayed as follows: during the periods of 1510–1540, 1570–1590, 1640–1675, 1870–1890, 1925–1945, and 1960–1980 the SPEs (drought and flood) happened frequently (Fig.3(a)); while 1480–1500, 1550–1570, 1600–1625, 1725–1825, and 1900–1925 are the periods of normal precipitation. As known from comparison of Fig.3(a) and (b), 1525–1550, 1640–1660, 1725–1750, 1875–1900, and 1960–1980, etc, are the relatively dry periods with the severe draught periods in 1525–1550, 1640–1660, and 1960–1980; while 1570–1590, 1680–1710, 1770–1790, 1830–1860, and 1910–1940 are the rainy periods with the most abundant rainfall period in 1570–1590 on climatic basic state. As known from the above analysis, the relatively dry and wet periods in Fig.3(b) also accord with the distribution intervals of SPEs in Fig.3(a). The characters and evolution laws of precipitation of Nanjing and Suzhou on climatic basic state are generally consistent with those of Yangzhou and Shanghai (figures omitted). Table 2 lists the correlation coefficients of the PP time series on climatic basic state among four regions in the Yangtze River delta, and those correlation coefficients indicate that Shanghai, Suzhou, Nanjing, and Yangzhou have basically the same climatic background field of precipitation. Values in brackets are the correlation coefficients of the DW grade series among the four regions, and the starred correlation coefficients are higher than the corresponding correlation coefficients of the PP time series on climatic basic state. Precipitation is limited spatially and temporally, and its prediction is also a very difficult research topic. However, viewing from the angle of the temporal evolution of PP, this paper reveals a fundamental fact that the climatic basic state has the same evolution law in the Yangtze River delta. This discovery may provide a new train of thought for precipitation forecast.

Table 2. Correlation coefficients of the PP evolution on climate basic state among four regions in the Yangtze River delta.

	Yangzhou	Nanjing	Suzhou	Shanghai
Yangzhou	1.00			
Nanjing	0.60(0.49)	1.00		
Suzhou	0.47(0.38)	0.50(0.51)*	1.00	
Shanghai	0.57(0.36)	0.63(0.42)	0.48(0.70)*	1.00

Note: * denotes the values in brackets higher than the corresponding values out of brackets.

Table 3. Frequencies of SPEs (drought/flood) in various regions in the Yangtze River delta.

	Drought/flood events	SPEs under climatic basic state	Percentage/%
Yangzhou	78	57	73.1
Nanjing	84	58	69.0
Suzhou	111	58	52.3
Shanghai	102	57	55.9

Table 3 gives the frequency of SPEs (drought or flood) in each region in the Yangtze River delta, and the importance of climatic background field is clearly seen. In the 530-year DW grade series, although the number of droughts or floods in various regions is not the same (numbers of SPEs in Yangzhou, Nanjing, Suzhou, and Shanghai are 78, 84, 111, and 102, respectively), and the numbers of SPEs in a certain time period are also different, the number of the SPEs occurred under climatic background state is basically the same, i.e. 57 times or 58 times. The times of the SPEs on climatic basic state in the Yangtze River delta account for 62.6% of the total number of SPEs: that is to say, the contribution of the SPEs under climatic background to the total extreme events occurred in the recent 530 years is about 60%. According to the distribution of severe droughts and floods in the middle and lower reaches of the Yangtze River,[27] it is also found that the genesis of at least 50% of SPEs is related with climatic basic state.

For the purpose of more succinctly and explicitly exhibiting the time-frequency characters of precipitation on climatic basic state of the Yangtze River delta, the wavelet transform of the PP time series is performed. For example, Fig.4 gives the wavelet transform coefficients of Yangzhou PP evolution on climatic basic state. In Fig.4 the abscissa displays time and the ordinate represents timescale, and a positive closed center alternating with a negative one on a certain timescale suggests the existence of a prominent cycle. The zero contours represent the abrupt change point, the positive and negative contours the normal state and extreme state (SPEs) of precipitation on a certain timescale in some period of time respectively. The PP evolution of Yangzhou on climatic basic state exhibited a prominent cycle of quasi-150 years, as well as a quasi-cycle of 60–70 years in the period of 1470–1780 and after 1920 but with a weaker intensity. On the 150-year timescale, the intensity is relatively weak in the period of 1500–1720, and increases after the middle of the eighteenth century; do exist abrupt changes in 1500, 1575, 1650, 1720, 1800, 1875, and 1955 or so. Among them, the positive-negative abrupt change happened around 1500, 1650, 1800, and 1955 respectively, indicating the transition of precipitation on this timescale from the period of normal state to the period of frequent drought or flood; and the negative-positive abrupt change occurred in about 1575, 1720, and 1875 respectively, indicating the conversion of precipitation from the period of frequent drought or flood to the period of normal state. Time-frequency characters of precipitation on climatic basic state for the other three regions are similar with that of Yangzhou, and unnecessary details are not given here.

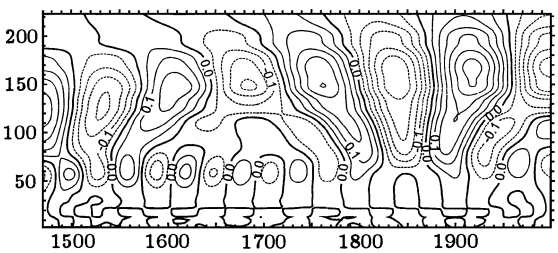


Fig.4. Wavelet transform coefficients of Yangzhou PP evolution on climatic basic state. The abscissa: time; the ordinate: timescale.

On the 150-year timescale, the Yangtze River delta now is experiencing the frequent SPEs (near the negative centre), which may be confirmed by the frequent drought/flood, especially flood events occurred in the lower reach of the Yangtze River since the 1980s. Based on the above, we may predict that on climatic background scale, the Yangtze River delta will still experience frequent SPEs in the coming 20–30 years, and, afterwards, the precipitation will gradually return to the normal state (positive contour area). Besides, on the 60–70-year timescale, the delta is also within the period of frequent SPEs (weaker intensity), and this may maintain for ten and odd years. Based on the above two timescales with the same phase (the frequent SPEs), this situation may lead to the frequent occurrence of extreme climate events in the coming 20 years.

5. Conclusion

Based on the idea of transforming the time series of meteorological elements into the temporal evolution of probability, in terms of power spectrum analysis and wavelet transform methods, etc, using the DW grade data of the Yangtze River delta, this paper studies the multi-timescale distribution of PP evolution in Yangtze River delta, and the evolution character of precipitation on climatic basic state and its contribution to the occurrence of SPEs. Results show:

1. The PP evolutional series of various regions in the Yangtze River delta all exhibit the multi-timescale character; the quasi-cycles of interannual, interdecadal and more than a century are remarkable, and those quasi-cycles all pass the significance test of the 0.05 level.

2. Evolution characters of the PP on the climatic

basic state of various regions in the Yangtze River delta are basically the same, and 60% of occurrences of SPEs in the past 530 years are related to climatic background field. The discovery of this fact provides a new train of thought and approach for effectively predicting the climate precipitation in the delta.

3. In the 530-year DW grade series, although the numbers of droughts or floods in various regions are not the same, and the numbers of SPEs in a certain period of time are also different, the numbers of the SPEs occurred under climatic basic state are basically the same, i.e. 57 times or 58 times. This result suggests that the climatic basic state has a very important or even decisive impact on the occurrence of the SPEs (drought/flood), thus deeply manifesting the importance of climatic background field.

4. Judging by the climatic background field, we conclude that the delta will still be in the period of frequent SPEs, which may lead to frequent occurrences of climatic extreme events in the coming ten and odd years. This predication may provide a useful scientific basis for the reduction and prevention of natural disasters, and for the future development program of society and economy in the delta.

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