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On temporal evolution of precipitation probability of the Yangtze River delta in the last 50 years*

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The monthly precipitation observational data of the Yangtze River delta are transformed into the temporal evolution of precipitation probability (PP), and its hierarchically distributive characters have been revealed in this paper. Research results show that precipitation of the Yangtze River delta displays the interannual and interdecadal characters and the periods are all significant at a confidence level of more than 0.05. The interdecadal is an important time scale, because it is on the one hand a disturbance of long period changes, and on the other hand it is also the background for interannual change. The interdecadal and 3–7y oscillations have different motion laws in the data-based mechanism self-memory model (DAMSM). Meanwhile, this paper also provides a new train of thought for dynamic modelling. Because this method only involves a certain length of data series, it can be used in many fields, such as meteorology, hydrology, seismology, and economy etc, and thus has a bright perspective in practical applications.

Keywords: nonlinear time series, probability density; El Nino Southern Oscillation (ENSO), short-range climate changes

PACC: 9260X, 9260Y, 0340G

1. Introduction

Precipitation change is an important part of climate change.[1−7] Because China is located in the monsoon climate area with the maximum variability of precipitation in the world, research on the impact of the climatic variability of precipitation upon social development and economic construction is of great importance. The Yangtze River delta is one of the areas where the population is the densest and the growth of economy is the fastest in China. Anomalous precipitation not only retards the economic growth, but also endangers the ecological environment. For example, the 1991 floods incurred a grave loss in the delta. Therefore, the study of the interannual and interdecadal variations, and their formation mechanisms in the delta is an urgent affair and of strategic importance. Meanwhile, although the climatically extreme events of precipitation (severe drought/flood) resulted in grave loss, up to now their formation mechanisms and intrinsic causes are still not clear.[8] This paper brings drought and flood into a unified framework of small probability events (SPEs), and explores the spatial–temporal evolutional laws of SPEs from an overall point of view in terms of the temporal distribution of precipitation probability (PP).

The climatic data are nonlinear time series, and possess the multi-hierarchical property and singularity. How to process and analyse the meteorological data so as to better reveal and predict the essence and intrinsic law of underlying phenomena embedded in the data has always been a problem unsolved.[9−12] In this paper the monthly observational precipitation series in the middle and lower reaches of the Yangtze River are transformed into the temporal evolution of PP. In comparison with the traditional rainfall analysis method, the PP analysis possesses the following three advantages. First, the transformation partly removes the spatial–temporal limitation of the precipitation process itself. Second, its smoothing effect on the time series differs from that of traditional methods. The temporal evolution of PP contains the full evolutional information of history data, and inherits the

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self-memory evolutional characters of climatic change itself. Third, drought and flood are SPEs. After the transformation of the time series of precipitation into the temporal evolution of precipitation probability density (PPD), the two opposite extreme events of drought and flood are organically joined together, and the evolutional laws of SPEs can be overall analysed and studied in the whole spatial–temporal structure.

2. Laws of the temporal evolution of summer precipitation probability in the Yangtze Rive delta

The summer precipitation series of the Yangtze River delta consists of the regionally averaged value of June–August rainfall over 10 stations of Shanghai, Hangzhou, Nantong, Suzhou, and Nanjing etc from 1951 to 1998:[13]

{513, 447, 461, 764, 485, 601, 631, 356, 307, 508, 385, 519, 419, 320, 487, 323, 221, 290, 497, 474, 365, 423, 372, 556, 516, 408, 460, 169, 391, 717, 407, 517, 456, 488, 424, 511, 669, 403, 548, 413, 847, 382, 660, 361, 534, 622, 516, 469}, and the number of samples is 48.

Shown in Fig.1 is that the rainfall oscillated around 400mm in the years from 1960 to 1977; while in the period of 1980–98, it maintained around 450 mm and meanwhile exhibited an increase trend with frequent occurrence of SPEs (drought/flood), for example in 1980, 1987, 1991, 1993, 1996. No other obvious law was apparent.

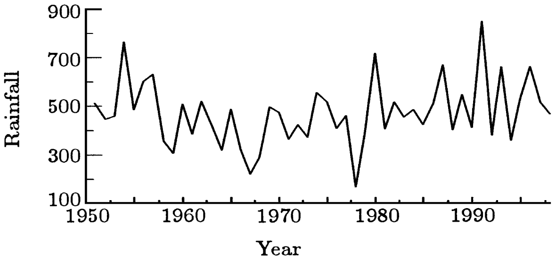

Fig.1. Summer flood-season precipitation of the Yangtze River delta from 1951-1998. The abscissa: year; the ordinate: rainfall (units: mm).

Among the 48 samples of rainfall, the minimum is 221mm in 1978, and the maximum 847mm in 1991. According to the amount of rainfall, the precipitation is divided into 5 grades: 219–319, 320–419, 420–519, 520–619 and more than 620mm. It can be seen that the variation of frequency against grade displays a quasi-Gaussian distribution, i.e. a pattern of middle-large-and-two-ends-small. The frequencies of grades 320–419 and 420–518 are 15 and 16, respectively, and their sum accounts for 64.58% of the total number of samples; the sum of frequencies (less than 4) of grades 219–319 and more than 720 accounts for 16.6% of the total.

This research method differs from the traditional one, and it can reflect the real situation of precipitation change, especially the character of anomalous change. The concrete procedures are as follows. For example, the observed rainfall in 1951 is 513mm, which lies in the interval (grade) of 420–519. The statistical frequency of the interval is 16, so replaces 513mm with 16/48≈0.3333. After the rainfall in other years is treated similarly, the temporal evolutional curve of the summer precipitation probability of the Yangtze River delta can be obtained.

Figure 2 clearly shows the temporal evolution law of the precipitation probability of the Yangtze River delta from 1951 to 1998. The probability can be at first divided into three hierarchies: normal years, for example, 1951, 1952, and 1953 etc, 31 years; transition years, such as 1958 and 1959 etc, 7 years; and SPE years, such as 1954 and 1956 etc, 10 years. In the 6 years of 1954–59, three SPE years occurred in close succession (1954, 1956, and 1957), and two transition years (1958 and 1959) immediately followed them. Comparison of Fig.2 with Fig.1 shows that the period is a rainy period, while in the 6 years of 1991–96, three SPE years also occur in 1991, 1993, and 1996, and one transition year occurs in 1994. However, in the 30 years since 1960, only 4 SPE years occur, i.e. SPE occurs once about every 7 years, therefore the 30 years are in a relatively stationary period.

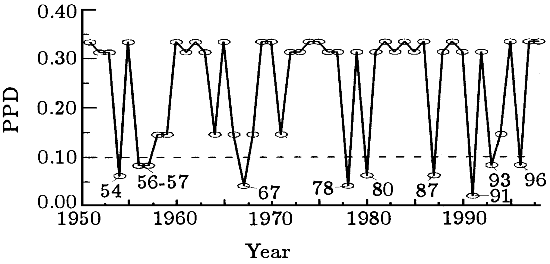

Fig.2. Temporal evolution of the summer precipitation probability of the Yangtze River delta from 1951–98. The abscissa: year; the ordinate: PPD.

With regard to the contributing factors to the summer precipitation in the Yangtze River delta, many researchers in China have studied the topic from two different angles, i.e. external factors, such as solar radiation, the rotation speed and orbital parameters of the earth etc; and the internal factors, i.e. the interaction among sub-systems of the climate system, such as the anomalies of sea temperature and temperature–salinity circulation, changes in the Tibetan plateau snow cover and polar ice sheets, and the increase of atmospheric green house gases etc. They pointed out that El Nino Southern Oscillation (ENSO) has a clear and definite corresponding relation with the precipitation in the tropical area, and the area where the interannual change of climate is most distinctively affected by ENSO is the Changjiang–Huaihe river valley. The variance contribution of ENSO to the summer precipitation of China is about 25%. The influence of ENSO concentrates on the first four modes of empirical orthogonal function, 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 east China is related to ENSO. Furthermore, ENSO mainly affects the middle and lower reaches of the Yangtze River, and southern China, while the relation of ENSO with the summer precipitation in most part of China is complicated, and up to now there is no clear and definite conclusion.[14,15] This paper attempts to uncover the summer precipitation law of the Yangtze River delta from another angle.

3. Analysis of formation mechanism

According to the characters of the summer flood season precipitation in the Yangtze River delta and the theory of hierarchical analysis,[16] the large scale climate provides a background for small scale climate changes. When the quasi-biennial oscillation is strong in some period, it is also controlled by the large scale climatic background.[17] Considering that the total number of samples is only 48, we separate the temporal evolution of the PPD of the Yangtze River delta into the four time series of more than 10y, 7–10y, 3–7y and less than 3y. The filtering method used was put forward by Zhang *et al*, and the separation of high/low frequency bands is realized by a multi-stage filter with a very narrow filtering band. The algorithm of the filter was provided by Wang, and the length of filtered series is the same as that of original series.[18–21]

Figure 3 displays the temporal evolution curve of PPD of the more than 10y-hierarchy, whereon there are two extreme minimum value areas, and between them is the quasi-10y periodic oscillation. Minimum value area A corresponds to 1954–59, and minimum value area B 1991–96. Extreme events likely occur at the minimum value point (infection point) of climatic background, and the SPEs, which occur in the two periods accounts for 60% of the total number of SPEs of the whole time series. However, in the 30y of 1960–90, the climatic background was in a relatively stationary stage. In spite of that, the three SPEs of 1967, 1978, and 1980a still occur at the sub-minimum value point of climatic background. That is to say, the climatic background provides a condition for occurrence of SPEs. The occurrence of SPEs in this period might be associated with the strong signal of ENSO.

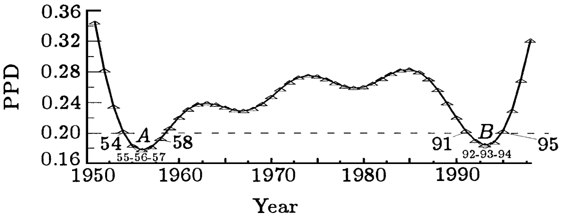

Fig.3. Temporal evolution of PPD of more than 10y-hierarchy. The abscissa: year; the ordinate: separated component of PPD.

Results of wavelet analysis show that the temporal evolution of precipitation probability in the 48 years exhibits a multi-hierarchic structure, the most distinctive timescale is quasi-11y period, indicating that on the interdecadal hierarchy the precipitation of the Yangtze River delta is closely related to the quasi-11y periodic change of sunspots. In Fig.3, prominent SPEs occur before the 1960s and after the 1990s. The fundamental cause is that in the 1956s and 1990s, not only the quasi-11y period is very distinctive, and its phase is also in the frequent period of SPE; but also there is a distinctive period on a higher hierarchy, and its phase is the same as the quasi-11y period's. The in-phase superposition of the two hierarchies leads to the occurrence of more prominent SPEs (Fig.4). In the period of 1960s to 1990s, although there is a quasi-11y periodic oscillation, there is also a stronger quasi-periodic distribution on a higher time hierarchy, and its phase is in the normal state of precipitation. Generally speaking, the small scale is the disturbance superimposed on a higher hierarchy (larger scale), therefore, precipitation in this period is in a normal state. In short, the interdecadal is an important time scale, it is on one hand a disturbance on long period changes, and on the other hand it is also a background for interannual change.

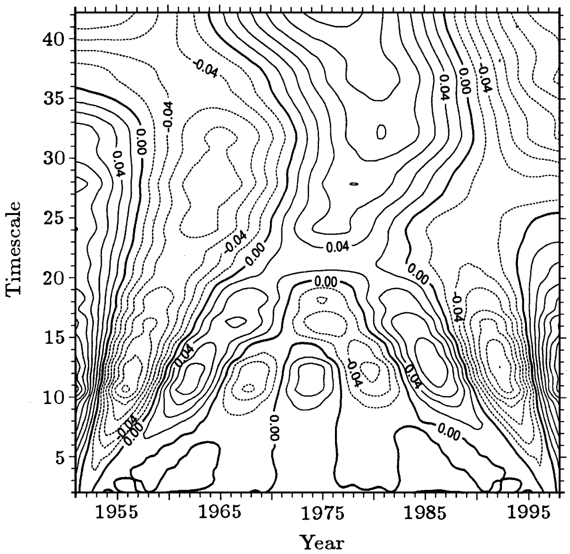

Fig.4. Wavelet analysis of the time series of more than 10y-hierarchy.The abscissa: year; and the ordinate: annual. Contours are wavelet coefficients. The zero value represents the sudden change point; the negative value the SPE of precipitation; and the positive value the normal state of precipitation.

On one hand, the large amplitude of 3–7y time hierarchy indicates its larger contribution to the precipitation of the Yangtze River delta. On the other hand, the SPEs of 1967, 1978, 1980, and 1987 are corresponding to the positive sea surface temperature anomalies (SSTA) from July 1968 to February 1970, March 1972 to March 1973, December 1981 to September 1983, and July 1986 to March 1988, respectively. Therefore, the SPE occurred one year before the onset of the El Nino. In the 1950s, the time series of 3–7y hierarchy did not give any information; while in 1990s, the occurrence of the SPEs was due to the climatic background as well as the ENSO. The events of 1991 and 1996 were corresponding to the SSTAs from December 1990 to July 1992, and January 1997 to May 1998; therefore the SPE occurred also one year ahead of the El Nino (see Fig.5). Table 1 lists the magnitude and date of positive SSTAs.[22]

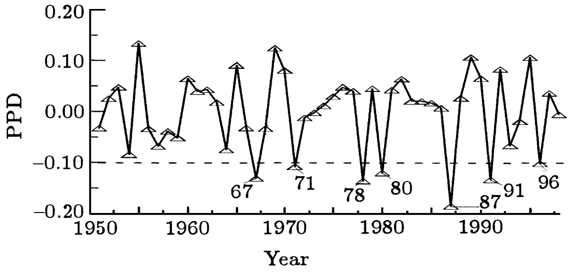

Fig.5. Temporal evolution of 3–7y or higher hierarchies. The abscissa: year; and the ordinate: separated PPD.

Table 1. El Nino events.

Positive SSTA Time/year-month	Duration /month	Time of the Maximum	Maximum value	El Nino	Note
1963–04–1964–01	10	1963-07	0.75	1963 (W)	El.f
1965–04–1966–03	12	1965-12	1.27	1965	El.f
1968–07–1970–02	20	1969-05	1.04	1968/1969 (W)	El.s
1972–03–1973–03	13	1972-11	2.01	1972	El.f
1981–12–1983–09	22	1982-12	3.00	1982/1983	El.f, El.s
1986–07–1988–03	21	1987-09	1.48	1986/1987	El.f, El.s
1990–12–1992–07	20	1992-05	1.49	1994/1992	El.f, El.s
1997–01–1998–05	17	1997-12	3.90	1991/1998	El.f, El.s

W: weak; El.f: the first year of El Nino; El.s: the second year of El Nino.

Although the separated amplitudes of 7–10y and quasi-biennial oscillations were both small, their signals did exist in the whole period. Their existence might be an inducing factor for SPEs (Fig.6), especially, the quasi-biennial oscillation embodied in the two extraordinary floods of 1954 and 1991. It is the joint effect of 10y, 3–7y and quasi-biennial oscillations that leads to the occurrence of the 1991 flood. In short, as far as the evolution of whether 10y, or 7–10y and quasi-biennial oscillations should be concerned, their overall evolutional trends do not strengthen or weaken, the important issue is their phase relation. In the 1990s, the interdecadal and 3–7y oscillations are both extraordinarily active, thus covering up the weak signals of quasi-biennial oscillations, and meanwhile it can be expected that they have different motion laws. These are the difficulties in the climatic prediction of precipitation in the decade, and the motion law obtained in the data modelling in the next section will validate this point of view clearly.

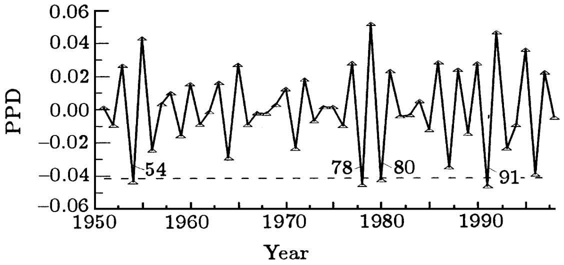

Fig.6. Quasi-biennial oscillations. The abscissa: year; and the ordinate: separated PPD.

4. Numerical prediction

The data of the time series of 10y, 3–7y and quasi-biennial oscillations from 1951 to 1993 are used to construct a model.[23−26] Using x, y, and z to represent 10y, 3–7y and quasi-biennial oscillations, respectively, calculating memorial coefficients in terms of least square method, and screening terms according to the prescribed coefficient criterion, we can obtain the following expression:

$$\begin{aligned}\frac{\mathrm{d}x}{\mathrm{d}t} =& 2.885x_{t-1} - 5.820x_{t-2} + 3.984x_{t-3} \\ & - 1.056x_{t-4} + 0.0136x_{t-2}^2 \\ & - 0.0120x_{t-3}^2 + 0.016x_{t-4}^2, \\ \frac{\mathrm{d}y}{\mathrm{d}t} =& - 1.361y_{t-1} - 0.513y_{t-2} - 0.265y_{t-3} \\ & - 0.360y_{t-4} - 0.038y_{t-2}^2 \\ & + 0.112y_{t-3}^2 - 0.137y_{t-4}^2, \\ \frac{\mathrm{d}z}{\mathrm{d}t} =& - 3.444z_{t-1} - 3.085z_{t-2} - 2.283z_{t-3} \\ & - 0.845z_{t-4} + 0.0131z_{t-1}^2 \\ & - 0.261z_{t-2}^2 + 0.232z_{t-3}^2.\end{aligned}$$

It can be seen from the above equations that the dynamic equations governing the laws for 10y, 3–7y and quasi-biennial oscillations are different. The model obtained in this way is called the inverse-derivation model, and the prediction model, which is established by taking the inversely derived equation as the dynamic kernel and by using the principle of self-memory, is called data-based mechanism self-memory model (DAMSM).

A trial prediction of precipitation probability for 1994–98 and a prediction for 1999–2009 have been performed. Figure 7 gives the comparison between the trial and the prediction of precipitation probability from 1994 to 2009 (dashed line) and the original observed time aeries (solid line). In the period from 1994 to 1998, although the intensity of predicted time series is weaker than that of original series, the time trend of the series is well predicted. Therefore, DAMSM possesses a satisfactory prediction capability.

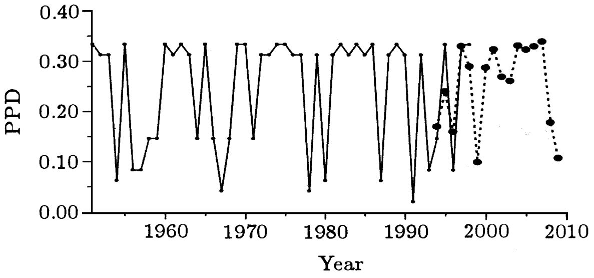

Fig.7. Temporal evolutions of observed precipitation probability from 1951 to1998 (solid line), and predicted one from 1994 to 2009 (dashed line) by the DAMSM model.

Aiming at solving the difficult problems of extraction and prediction of nonlinear time series signals, by using the hierarchical analysis theory, this paper has shown the temporal evolutional laws of the precipitation probability of the Yangtze River delta, and revealed that the interannual variation is controlled by the interdecadal or even larger scale climatic background. In order to accurately predict the change of climate, for different prediction objectives, different motion laws between adjacent hierarchies must be found, and then corresponding prediction model should be established. Meanwhile, this paper has also provided a new train of thoughts for dynamic modelling. Because this method only involves a certain length of data series, it can be used in many fields, such as meteorology, hydrology, seismology, and economy etc, and thus has a bright perspective in practical applications.

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