SOME RESULTS OF APPLICATIONS OF STATISTICAL METHOD TO CLIMATE CHANGES AND SHORT-TERM CLIMATE PREDICTION IN CHINA

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I. INTRODUCTION

In recent years, much attention has been paid to climate changes and short-term climate prediction, because the large area climate anomaly has constantly occurred in many areas of China and of other places in the world since the 1960's. From 1974 to 1981, ten national meetings on climatology in China were held. More than 100 papers were presented at each of these meetings. Two collections of papers presented at these meetings have been printed. At present, in addition to research at meteorological institutes and universities, the research of climate changes and short-term climate prediction is also being carried out in the weather bureaus of the 30 provinces and autonomous regions (including Taiwan). The gaps in the research in this field in China have been filled[1].

In the study of climate changes and short-term climate prediction, statistical analysis is now an indispensable method. In recent years, widespread applications of statistical methods to the climatological data and short-term climatic prediction in China have made a great progress. There are many long-range climatic data available to the research work. When these statistical methods are applied to these long-range data, many interesting results arise. This paper gives a summary of the results in this field using the following approaches, some of which have been refined by Chinese scientists: correlation analysis, periodicity analysis, time series predictions, regression models, stage analysis, variance analysis of series of pseudo-variables, empirical orthogonal functions, Chebyshev polynomial analysis, and stochastic dynamic models.

II. CORRELATION ANALYSIS

The method of using correlation analysis to expose the laws of climatic data evolution has been widely developed.

In the analysis of droughts and floods for the last 500 years in China[2], the correlation coefficients among drought indices in the country and those in the latitude belts and among

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those in each pair of latitude belts were calculated. The results showed that the drought index changes in North China are representative of those in the country as a whole, while droughts in China as a whole and droughts in South China are not closely allied; the droughts in North China are often connected with the droughts in the Huaihe River Basin or those in NE and NW China. Furthermore, the correlation analysis between the drought indices of each latitude belt and the sea level pressure field of the world for July in the same year showed that the subtropical high intensity in winter in the Southern Hemisphere is connected with the rainfall in the summer months (May to September) in southern areas of China. The results of the analysis are shown in Figs. 1—3.

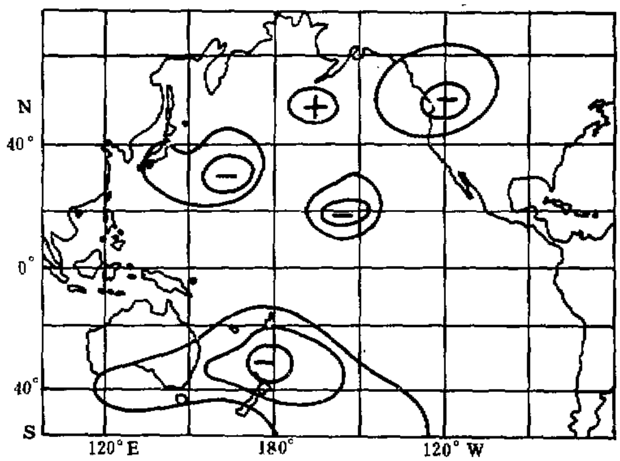

Fig. 1. The distribution diagram of the correlation region between the drought indices of the first latitude belt and the sea level pressure field in July. From the exterior to the interior, the levels of significance of the equiscalar lines are 0.05, 0.01, and 0.001, respectively.

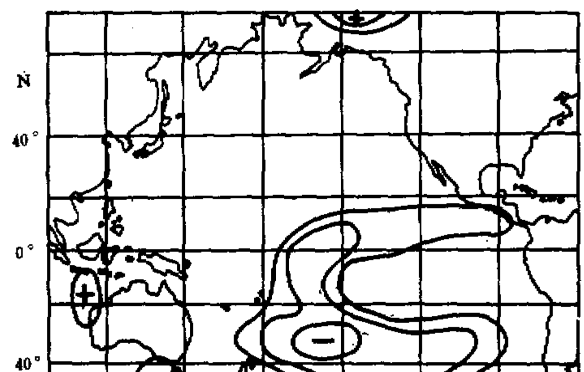

Fig. 2. The distribution diagram of the correlation region between the drought indices of the second latitude belt and the sea level pressure field in July.

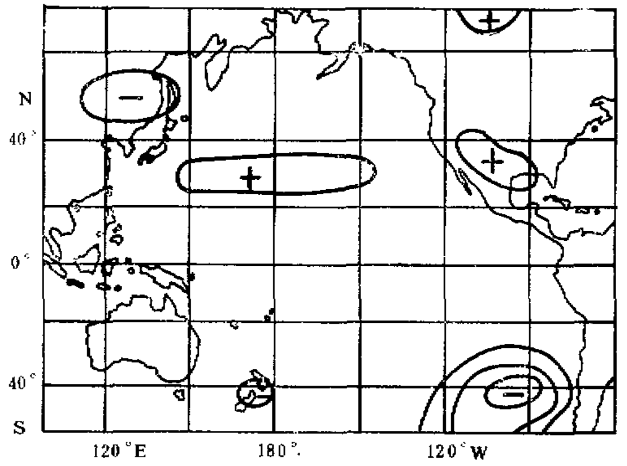

Fig. 3. The distribution diagram of the correlation region between the drought indices of the third latitude belt and the sea level pressure field in July.

Wang and Zhao[3] calculated the correlation coefficients between the droughts–floods and atmospheric action centers and between the colds–warms and atmospheric action centers for initial series, long-range changes, and two- to three-year changes, respectively. The results showed that the relationship between the climate changes and general circulation varies with the length of the periodicities. Therefore, the mechanisms of the form of the variant periods may be different, but the periods of each kind have stationary areas. This fact shows that the climate changes and the circulation mechanisms may have the character of stationary waves.

The establishment of the long-range sequence of climate history is important for researching climate changes over historical periods. In the analysis of the temperature variation in winter in southern China for the last 100 years[4], the correlation coefficients among the temperatures of each station for each climatic region in China were calculated. The results showed that it is reasonable to use a temperature index series to express the temperature of a climatic region. Then we can get long-range series of temperature and apply them to the study of cold-warm laws over historical periods.

In the western areas of China, the research of dendroclimatology has been developed, because the references and data are lacking in this area. The correlation analysis between the breadth data of neighboring meteorological stations is made. The climate data in this area have been effectively extended[5–11].

Many correlation analyses showed that East Asia circulation indices,the South Oscillation indices, and the positions and intensities of the subtropical high and Indian low are all important circulation predictors for the droughts and floods in China[12–16]. The correlations between the SST of the Pacific Kuroshio and the droughts–floods in eastern areas of China are very strong too[17–20]. Zhang et al.[21] and Xu[22] pointed out that the beginning of plum rains,the amount of rainfall, and the duration of plum rains are related not only to the SST of Kuroshio but also to the coastal SST of Peru in winter. Xu and Wang[2] pointed out that the sunspot number is connected with the yearly frequency of various circulation types, and the values of cross-correlation coefficients between the data, with a lag of several years, reached their maximum. This may provide a definite basis for the short-term climate prediction of the circulation. In addition, the relationship between the number of sunspots and the droughts-floods in lower latitude areas of China is linear while the linear correlation is less obvious in other areas. This latter result indicates that the relationship between the number of sunspots and the droughts-floods in China as a whole can be nonlinear. Lin[23] pointed out that the oscillation of climatic periodicity determines the instability of the correlation coefficients.

III. PERIODICITY ANALYSIS

Periodicity analysis is widely used in the analysis of climate data. Variance analysis, energy spectrum analysis, and harmonic analysis are the most frequently used methods.

In research on climate changes over historical periods in the Qinghai-Xizang Plateau, energy spectrum analysis and variance analysis for the sequence of growth-ring breadth were made[5]. The results obtained were that the main periods of two to three years are consistent with the famous "two-year pulsation" in meteorology. This explains why the changes of the growth-ring breadths and meteorological elements are affected by the same general circulation.

Energy analysis and variance analysis for the series of the mean flow of Hankou between June and September were performed[24]. The results showed that the flow changes of the Changjiang River form a mixed wave. It consists of waves of different periods, i. e., short waves of two to four years, medium waves of six to seven years and fourteen years, long waves of forty-one years, and ultralong waves of about one century.

In research on the periodicity of cold-warm and drought-flood, energy spectrum analysis and cross spectrum analysis of the temperature types in January and rainfall types in July were used[25]. The results showed that the temperature in January mainly has periods of more than twenty years and quasiperiods of two years and the rainfall in July mainly has periods of around four years and quasiperiods of two years and secondarily has periods of seven and thirty-five years. The data used in the energy spectrum analysis were ten-year moving averages. It can be seen that the period of around twenty years is very prominent for the temperature in January, while the period of around thirty-five years is very prominent for the rainfall types in July. The cross-spectrum analysis confirmed that the major relationship between the high in the South Pacific and the rainfall in China is the period of around thirty-five years in the low-frequency part; the relationship of twenty-year periods between the high intensities in Siberia and the temperatures in China is very strong. This result shows that the general circulation plays a very important role in climate changes.

Energy analysis has been applied to the temperature and rainfall series in Qinghai-Tibetan area after low-pass filtering[26]. The results showed that many series have remarkable periods of general significance. These periods include the quasipulsation of two years, the period of around eleven years, and the Bruckna period of more than thirty years.

The SP_{01} index expresses the major trend of the climate changes over the last 100 years in China. In Zhang et al.[9], energy spectrum analysis and harmonic analysis for the

SP_{01} index series of ten-year moving averages were conducted. The results explained that the periods of the climate changes in China have been 600—700, 300—400, 180—220, 110—150, 80—90, 26, 13, and 2—3 years. These periods of the climate changes may be connected with the periods of sunspot movements.

In addition, the relationship between the increment of the breadth of the growth-rings and intensity of the sunspot movement was analyzed. It was found that the increment of the breadth of the growth-rings is connected with the century period of the sunspot movement, and the increment of the breadth of the growth-rings is somewhat related with a twenty-two year period of the sunspot movement.

The results of energy analysis and variance analysis for the drought index of the whole country showed that the periods above the 95% significance level are 2—3, 8—10, 22—26, 30—50, 140—170, and 320—350 years[17]. In the low- latitude areas, one must consider not only the changes of short periods, but also those of long periods. Therefore, it is more difficult to analyze the arid-moist changes south of the Changjiang River than north of the Changjiang River.

In Wang and Zhao[3] the energy analysis of cold-warm and drought-flood for stations throughout the country was made. The results of the analysis are shown in Fig. 4.

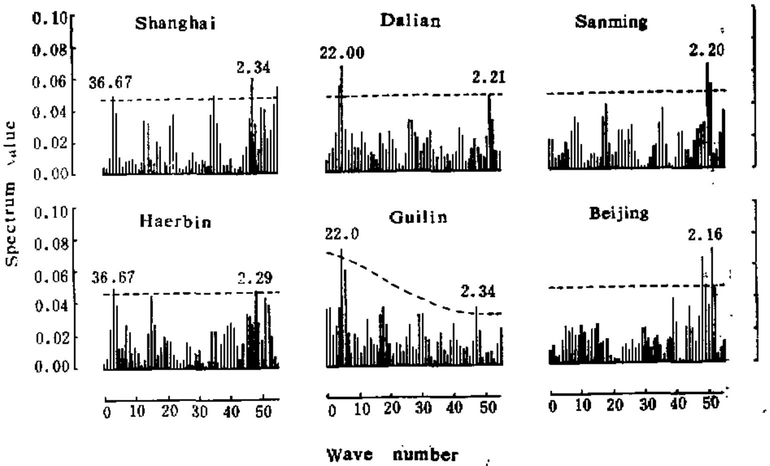

Fig. 4. The energy spectrum of drought-flood (top) and cold-warm (bottom). The dashed lines are the dividing lines at the 0.05 level of significance; values are the numbers of years of the major periods.

It may be seen that the important periods are 36, 22, and 2—3 years. While for different areas predominant periods are not the same, the distribution areas of each period of the drought-flood are consistent with those of the cold-warm. The same analysis for the global general circulation has also been made. The results are shown in Fig. 5.

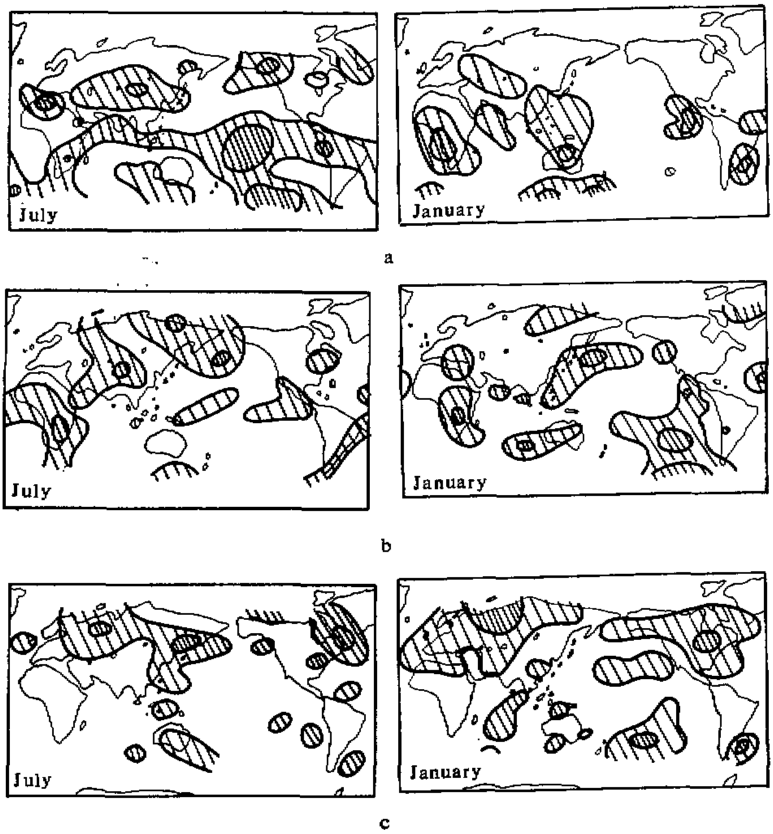

Fig. 5. The periods of (a) 36, (b) 22, and (c) 2—3 years for the general circulation in July (top) and in January (bottom). The regions with sparse and dense oblique lines represent two different levels of significance, 0.05 and 0.01.

It can be seen that the periods of 36, 22, and 2—3 years are also significant in the global atmosphere. The periods of 36 and 22 years are most obvious in the Southern Pacific, Australia, and the zone of the Western Pacific to Asia, and these two periods are also reflected in East Asia general circulation. The periods of 2—3 years are concentrated in Eurasia, Eastern North America through the North Atlantic to Western Europe, and the Australia-New Zealand area.

In a word, a great deal of work in this field has been done, and many results of significance have been obtained[28—31].

Besides, for predictions of the climatic trends of typhoon movements, rainfall, temperature, SP_{ci} index, and so forth, the method of analysis of variance was used widely[9,32—35], and good results were obtained.

IV. TIME SERIES PREDICTIONS

This method is mainly used for short-term climate predictions. In most of the cases the following additive model is assumed

$$X(t)=f(t)+S(t)+\eta(t)+\xi(t), \tag{1}$$

where $X(t)$ is a realization of a stochastic process, which is composed of a trend term, $f(t)$, a period term, $S(t)$, a stationary stochastic term, $\eta(t)$, and a white noise term $\xi(t)$. This model was used in the rainfall predictions of twenty-three stations of the Haihe and Luanhe drainage[34]. Based on the data of yearly frequency number of the circulation types, W, C, and E, in the Northern Hemisphere since 1891, Zhang[36,37] studied the law of secular changes of the general circulation and its relationship with the climatic oscillation in China. Using the additive model of nonstationary time series, Zhang also made short-term predictions of yearly frequency numbers of the circulation types and yearly rainfall in Eastern China.

According to the curves of historical evolution of rainfall and sunspots, the predictions of rainfall or rainfall and sunspots were made by using two-dimensional stochastic processes. In the predictions of the Haihe and Luanhe drainage this method was used most successfully[34].

Yao[38] first applied Markov chain theory by using pseudo-variables in the study of historical climate changes. Using this method, we can estimate the cycle time of drought-flood or that of cold-warm, the amount of time that drought-flood or cold-warm is sustained, the yearly change ratio of the sustained state, and so on.

V. REGRESSION MODELS

Regression models were widely applied to predictions of temperature, rainfall, the breadth of growth-rings, and so on. Furthermore, in addition to linear regression models, nonlinear regression models were also used[5,39]. Good results have been obtained by using the models mentioned above.

The methods for fitting the autoregressive model were also applied to climatic prediction. Yao[40] pointed out that the last parameter of the autoregressive model used for climatic prediction is just the partial autocorrelation coefficient, and therefore the order of the model can be chosen by means of the t-test or F-test. The fitting of the autoregressive model can thus be performed by a simple procedure if the autoregressive parameters are estimated by the recurrence formula. In the forecast of the monthly rainfall this method was used most successfully.

VI. STAGE ANALYSIS

Stage analysis is a major method used in climatic prediction in China[41,42]. It involves the use of the mean and variance of a meteorological element to identify the different stages of time evolution of a long-range time series and applications to climatic prediction[43]. In this method, the number of stages can be adjusted by Mahalanobis distance D^2, so that the identification of the different stages may be suited to the scale of prediction. Then, with the F-test, suitable stage numbers can be obtained.

Using this method to analyze rainfall in Beijing we were able to obtain results which are in accord with the spectrum analysis. The method can be used to estimate the trend of future changes.

In identifying the different stages of the drought index series, the method of optimal identification was used[44]. The results showed that drought also has stages and periods of different lengths. In the stage of a century length, a vibration of the second-order scale was obtained. In doing the above, one should make the variances between the drought indices at different times larger, but within a single period of time as small as possible.

In short, stage analysis has been widely used in the short-term climate prediction in China[3,32].

VII. VARIANCE ANALYSIS OF SERIES OF PSEUDO-VARIABLES

In singular period analysis, Yao[45] pointed out that it is better to use variance analysis of series of pseudo-variables to test the significance of periods. Other methods such as spectrum analysis, periodogram analysis and so on, can obtain only those periods of frequentoccu rrence. Applying variance analysis to series of pseudo-variables usually gives an undistorted analysis of ultralong periods.

In practical applications, variance analysis of series has proved superior to the method of the periodogram in testing the significance of periods.

VIII. EMPIRICAL ORTHOGONAL FUNCTIONS

In order to investigate the climatic variation of the last 140 years in China, researchers used the method of empirical orthogonal functions to analyze the types of temperature in January and the types of rainfall in July[25].The January temperature at 90 stations throughout the country from 1951 to 1975 was analyzed. Five types were obtained, i. e. Type I, warm (1952); Type II, partially warm (1973); Type III, normal (1953); Type IV, partially cold (1955); and Type V, cold (1969). The years in parentheses are typical years corresponding to the various types.

The same method was used to analyze rainfall in July at 100 stations throughout the country from 1951 to 1975. Again five types were obtained, i. e., Type I, abundance of rainfall throughout the country (1954); Type II, rainy south of the Changjiang River, shortage of rain north of the Changjiang River (1974); Type III, two rainbands (1969); Type IV, rainy north of the Changjiang River, lack of rain south of the Changjiang River (1962);and Type V, not much rain throughout the country (1972).

Furthermore, the method of empirical orthogonal functions was used to analyze the drought-flood orders at 100 stations and the cold-warm orders at 30 stations between 1871 and 1970, as well as the rainfall between June and August and the temperature in January during the years 1951 to 1974[3]. The results showed that the above-mentioned drought-flood and cold-warm series can be used to study climate changes in China.

The method of factor analysis was applied to SST fields of the North Pacific by Li and Huang[46]. The results showed that SST in the tropical areas (180°—90°W, 10°N—10°S) is more representative, and it is most representative in winter and spring. SST in tropical areas has the best persistence. The two-year period of SST changes is dominant in low-latitude tropical areas and in high-latitude areas, while in middle latitude sea areas the semi-annual periods predominate.These characteristics of the climate changes of SST fields are very important to the study of the relationship between the pressure fields and SST.

and between the rainfall fields and SST.

IX. CHEBYSHEV POLYNOMIAL ANALYSIS

Previous investigations of applications of Chebyshev polynomials in meteorology dealt with only the expansion in equidistant grids. By introducing a nonlinear transformation, Chebyshev polynomials were generalized into irregular grids by Zhou[47]. This transformation is accomplished by replacing the independent variables with their ordinal numbers.

Two-dimensional ordinal numbers (ξ_1, ξ_2) are assigned to each station. The distributions of meteorological elements are expanded by using the expression

$$\tilde{Z}_{ij}=\sum_{K=0}^{K_0}\sum_{S=0}^{S_0} A_{KS}\phi_K(i)\psi_S(j), \tag{2}$$

where $\tilde{Z}_{ij}$ denotes the meteorological elements at station (i, j), (i, j) is the two-dimensional ordinal number of the station, $\phi_K(i)$ and $\psi_S(j)$ are normalized Chebyshev polynomials, k and s are the orders of the polynomials, $A_{KS}(z)$ is the expansion coefficient, and K_0 and S_0 are the truncation orders of the expression.

Various distributions, including those of SST, precipitation over the middle and lower reaches of the Changjiang River, and temperatures of areas in NE China, were expanded in terms of Chebyshev polynomials to extract their main characteristics[48,49]. Moreover, by using expansion coefficients of SST as predictors of precipitation (or temperature), a series of prediction equations for coefficients $A_{KS}(R)$ or A_{KS} (T) were established. The forecast of $\tilde{R}_{ij}$ or $\tilde{T}_{ij}$ for large areas can then be evaluated to form (2). In practical applications, this method was used most successfully.

It is worthwhile to point out that Chebyshev polynomials do not vary with time and they are suitable for predicting horizontal distributions of meteorological elements.

X. STOCHASTIC DYNAMIC MODELS

It is well known that oceans play an important role in the theory of long-range weather procedures and climatogenesis. Li[50] presented a simple stochastic dynamic model to study the climatic anomaly, in which ocean and atmosphere form a coupled system.

Second-order linear differential equations with stochastic terms are

$$\frac{d^2T'_S}{dt^2}+(\lambda_2+\lambda_3)\frac{dT'_S}{dt}+\lambda_2\lambda_4\left(\frac{\lambda_3}{\lambda_4}-\frac{\lambda_1}{\lambda_2}\right)T'_S=\lambda_2 W \tag{3}$$

and

$$\frac{d^2T'}{dt}+(\lambda_2+\lambda_3)\frac{dT'}{dt}+\lambda_2\lambda_4\left(\frac{\lambda_3}{\lambda_4}-\frac{\lambda_1}{\lambda_2}\right)T'=\lambda_1\overline{W}, \tag{4}$$

where

$$W=\frac{1}{\lambda_2}\ \frac{dW_2(t)}{dt}+\frac{\lambda_4}{\lambda_2}W_2(t)+W_1(t)$$

and

$$\overline{W}=W_2(t)+\frac{\lambda_3}{\lambda_1}W_1(t)+\frac{1}{\lambda_1}\ \frac{dW_1(t)}{dt}. \tag{5}$$

If one is considering the forced effect of the stochastic process of the weather disturbance scale on the climate changes of SST, and one assumes that the spectral density of SST, T_S', is $Y(\omega)$, the solution of (3) is given by

$$Y(\omega)=\frac{\lambda_2^2\phi(\omega)}{\left\{\left[\lambda_1\lambda_4\left(\frac{\lambda_3}{\lambda_4}-\frac{\lambda_1}{\lambda_2}\right)-\omega^2\right]^2+(\lambda_2+\lambda_3)^2\omega^2\right\}}, \qquad (6)$$

where $\phi(\omega)$ is the statistical spectrum of the incoming stochastic weather disturbance; when $\lambda_2 \gg \lambda_3$, (6) reduces to a first-order SST Markov model. Its feedback function is

$$\lambda_4\left(\frac{\lambda_3}{\lambda_4}-\frac{\lambda_1}{\lambda_2}\right).$$

If the stochastic input, W, is the white noise, i. e., $\phi(\omega)\sim\phi(0)$, and let

$$\varepsilon(t)=\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} W(t)dt, \qquad (7)$$

then

$$\phi(0)=T\,\overline{\varepsilon^2(t)}\,/\pi=\frac{D}{\pi}(℃)^2/\mathrm{yr}, \qquad (8)$$

where T is taken to be one year.

Taking the data studied by Frankignoul and Hasselmann[51], from (6) we made computations, the results of which are shown in Fig. 6.

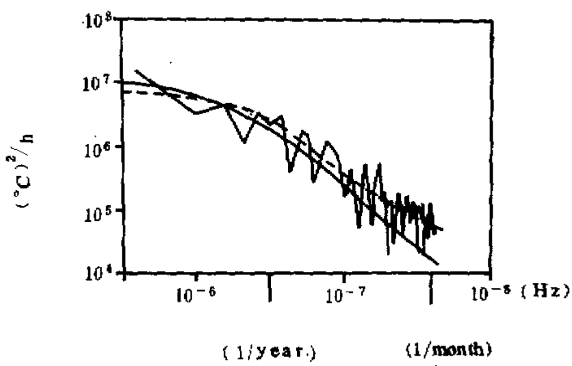

Fig. 6. Spectrum of SST departure. The unsmoothed line is the observed value; the solid line is the theoretical value according to Frankignoul and Hasselmann (1977), and the dashed line is the theoretical value according to Li (1981).

It may be seen that the results of the model of the second vibration conform more to the real situation than those of the first model of Frankignoul and Hasselmann. When $D=2.7$ (°C)²/yr, the statistical variance of SST obtained by Li is 1.0 (°C)²/yr; this result agrees very well with the observations.

Stochastic dynamic models are very important for studying air–sea interaction, climate changes, and short-term climate predictions.

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