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Nonlinear evolution characteristics of the climate system on the interdecadal-centennial timescale*

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To better understand the physical mechanism of the climate change on interdecadal-centennial timescale, this paper focuses on analysing and modelling the evolution characteristics of the climate change. The method of wavelet transform is used to pick out the interdecadal timescale oscillations from long-term instrumental observations, natural proxy records, and modelling series. The modelling series derived from the most simplified nonlinear climatic model are used to identify whether modifications are concerned with some forcings such as the solar radiation on the climate system. The results show that two major oscillations exist in various observations and model series, namely the 20–30a and the 60–70a timescale respectively, and these quasi-periodicities are modulated with time. Further, modelling results suggest that the originations of these oscillations are not directly linked with the periodic variation of solar radiations such as the 1-year cycle, the 11-year cycle, and others, but possibly induced by the internal nonlinear effects of the climate system. It seems that the future study on the genesis of the climate change with interdecadal-centennial timescale should focus on the internal nonlinear dynamics in the climate system.

Keywords: nonlinear, climate change, interdecadal-centennial timescale, modelling
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1. Introduction

The influences induced by the climate change on the development of economies and societies have become an important topic concerned by many scientists in the world. Among them, the climate change on interdecadal-centennial timescale has even greatly impacted the normal lives of human beings. The African drought lasting for many years made a lot of nations suffer from the most serious crisis of grain in the twentieth century and consequently several million people are in the state of famine.[1,2] The durative drought in North China since 1970s and the drought in USA during 1930s influenced widely and lasted for many years.[3] All of them are the well-known examples that climate changes on interdecadal timescale influence largely the human society. How to understand and forecast the climate change on interdecadal timescale for the future has become an urgent scientific topic.

Since 1990s, the investigations on climate change and its predictability at interdecadal-centennial timescale have been documented.[4] By analysing the documental records, natural proxy and observed data, the study on climate change has been expanded.[5–12]

A series of research indicates that the indices of North Atlantic Oscillation (NAO), Pacific-North America pattern (PNA), and North Pacific Oscillation (NPO), all show obvious interdecadal change characteristics.[13–16] Zhu and Yang[17] applied wavelet analysis to the Pacific Decadal Oscillation index (PDOI) and North Pacific index (NPI), and identified two dominant interdecadal components, the bidecadal (15–25a) and pentadecadal (50–70a) modes. And the two modes have different propagating patterns, which suggest that the two interdecadal modes may arise from different physical mechanisms.

The temperature features on interdecadal time-

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scale in the globe and hemispheres have also been described.[18–22]

So far, the mechanism for the climate change on interdecadal-centennial timescale has been ambiguous, and all kinds of thoughts are available. Kushnir[18] thought the basin-scale interaction between the large-scale ocean circulation and atmosphere to be the most important factor. Thresher[23] indicated that the marked quasi-decadal variation for circum-Antarctic zonal west winds broadly correlates with the sunspot cycle. Zhu and Wang[10] suggested that the movement of the position of rain belt over the east part of China might be related closely to the solar activity. It was possible that the variation of solar radiation affects distribution and balances of energy in the climate system, the atmospheric circulation and the intensity, also the movement of rain belt. Bertrand and van Ypersele[24] pointed out that neither the individual responses nor the combined natural or anthropogenic forcings allow one to reproduce all of the recorded major temperature fluctuations since the latter half of the nineteenth century. They show that these temperature variations are the result of both naturally driven climate fluctuations and the effects of industrialization.

In summary, the climate change on interdecadal-centennial timescale has been recognized. However, two issues are still remained. One is on what periodicities or oscillations are dominated on interdecadal-centennial timescale for the climate change and another is on what causes are concerned with these oscillations. To address the first question, the main oscillations embedded in the data are detected in this paper. For the second one, the most simplified nonlinear climatic model (MSNCM) with the forcing and dissipative processes is applied to produce the model series and to compare with those proxy and observed data.

2. Data, method and model

2.1. Data and method

Four data sources including the climate observation and natural proxy series used in this paper are listed in Table 1. Selecting these types of climate series, we attempt to testify some possible periodicities or oscillations in the climate change on interdecadal-centennial timescale with the spatial scope from regions to the globe.

Table 1. Climate observation and natural proxy series.

Indices	Tree-ring index	Dry-wet intensity	Temperature sequences	Monthly precipitation
Resolution	year	year	10 years	month
Unit			°C	mm
Coverage or location	Northern Hemisphere	Lower Yangtze River valley	Ten regions in China	Seoul, south Korea
Length (A.D.)	1001–1995	1470–1999	1600–1999	1777–1999

The tree-ring series is useful for studying the climate change in the historical period. The width and density of tree-rings reflect the corresponding conditions of climate and environment. Individual tree-ring series only represents climate and environment variations locally so that the synthetical analysis from multitudinous tree-ring series scattered in a larger area can supply a reliable climate variation. A series of synthetical tree-ring index used in this paper was combined from numerous tree-ring series in the Northern Hemisphere.[25] Since the 1970s, Chinese climatologists have combined effort to extract climatic information from the historical documentary records for the last 530 years. An outcome of this effort was the *Yearly Charts of Dryness/Wetness in China for the Last 500-Year Period*.[26] In this dataset, the summer season climate (May–September) was categorized into dry and wet intensity (DWI) of 1 to 5, from very wet (flood, 1), wet (2), normal (3), dry (4), and very dry (drought, 5). An averaged DWI series at the lower Yangtze River valley including 5 sites of Shanghai, Nanjing, Suzhou, Hangzhou and Yangzhou is selected for our research. On the basis of having constructed annual temperature series of 1880–1996 for each of ten regions in China, more utilizing the historical document, ice core and tree-ring series, Wang *et al*[27,28] reconstructed the 10a-average temperature series for ten regions in China. These ten regions include Northeast China, North China, East China, South China, as well as Taiwan, Central China, Southwest China, Northwest China, Xinjiang and Tibet regions. The long-term monthly precipitation series for the last 220

years were based on the Korean traditional rain gauge and modern observation in Seoul.[8]

The method of wavelet transform is applied to detect the interdecadal oscillations from the above-mentioned data. Wavelet transform could provide localized time and frequency information without requiring the time series to be stationary.[29–32] If a close pair of minimum and maximum centres for wavelet coefficients appear at a certain timescale, we may consider that there is a quasi periodicity at the timescale. And the wavelet variance reflects the characteristics of wavelet spectrum, and opens out the energy distribution of the signal.

2.2. Model

When the dynamic equations are used, the further simplification may provide clearer understanding for the climate change.[33] For the MSNCM with the coupling of the atmosphere and the boundary layer, the essential factors representing the climate are retained, namely the forcing, dissipative, and nonlinear processes, which are the basic characteristics of the climate system. The solar radiation is the unique external forcing. From the viewpoint of the climate dynamics, the motion equations in the atmosphere can be replaced by the linear balance equation and the hydrostatic balance equation, while considering only the sensible heat in energy equation. Thus, a set of equations in spherical coordinates are written as

$$\frac{2\Omega}{a_0^2}\frac{\partial \Psi}{\partial \lambda} = \left(-2\Omega\cos\theta\nabla^2 + \frac{2\Omega\sin\theta}{a_0^2}\frac{\partial}{\partial\theta}\right)\chi, \quad (1)$$

$$\left(2\Omega\cos\theta\nabla^2 - \frac{2\Omega\sin\theta}{a_0^2}\frac{\partial}{\partial\theta}\right)\Psi = \nabla^2\Phi, \quad (2)$$

$$\nabla^2\chi + \frac{\partial\omega}{\partial p} = 0, \quad (3)$$

$$\frac{R}{p}T = -\frac{\partial\Phi}{\partial p}, \quad (4)$$

$$\begin{aligned}&\frac{\partial T}{\partial t} + \frac{1}{a_0^2\sin\theta}\left(\frac{\partial\Psi}{\partial\theta}\frac{\partial T}{\partial\lambda} - \frac{\partial\Psi}{\partial\lambda}\frac{\partial T}{\partial\theta}\right)\\ &- \frac{(\gamma_{\rm d}-\bar{\gamma})R\bar{T}}{gp}\omega\\ =&\frac{\partial}{\partial p}\left[\nu\left(\frac{gp}{R\bar{T}}\right)^2\frac{\partial T}{\partial p}\right] + \mu\nabla^2 T,\end{aligned} \quad (5)$$

where the variables are the usual atmospheric ones.

The boundary conditions are

$$T = 0, \quad \text{when} \quad p = 0, \quad \omega = 0; \quad (6)$$

$$T = T_{\rm s}(\lambda,\theta,t) - \hat{T},$$
$$\text{when} \quad p = P, \quad \omega = -K_{\rm D}\nabla^2\Phi, \quad (7)$$

where $K_{\rm D}$ is frictional coefficient near the surface, $\hat{T}$ is the environment temperature, and μ, ν shows the horizontal and vertical dissipation coefficient respectively.

As a result of the mathematical transform, the dimensionless forms for the above-mentioned equations are obtained finally.[33–35]

$$\frac{{\rm d}x_1}{{\rm d}t} = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 - \sigma_1(x_2^2 + x_3^3) + b_1, \quad (8)$$

$$\frac{{\rm d}x_2}{{\rm d}t} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \sigma_1 x_1 x_2 - \sigma_2 x_1 x_3 + b_2, \quad (9)$$

$$\frac{{\rm d}x_3}{{\rm d}t} = a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \sigma_2 x_1 x_2 + \sigma_1 x_1 x_3 + b_3, \quad (10)$$

where x_1=$(T_1)_2$, x_2=$(T_2)_2$, x_3=$(T_3)_2$, are three components of atmospheric temperature at the 500h·Pa level.

For the boundary model, the advection effect of the temperature is omitted, and the temperature (anomaly) satisfies the linear heat-transmission equation

$$\frac{\partial T_{\rm s}}{\partial t} - K_{\rm s}^2\frac{\partial^2 T_{\rm s}}{\partial z^2} = 0, \quad (11)$$

where $T_{\rm s}$ is the boundary temperature, $K_{\rm s}$ is the heat-transmission coefficient, and z is the depth coordinate, positive downwards. The continuous condition of the temperature for the interface is

$$(T)_4 = T_{\rm s}|_{z=0} - \hat{T}, \quad (12)$$

where $(T)_4$ is the temperature at 1000h·Pa level. Thus, the boundary model and the atmosphere model make up of a mostly simplified dimensionless coupled climate system.

3. Interdecade-century climate variations

In this section, we will probe into the evolution features of the climate change on interdecadal-centennial scale with various series mentioned above. Firstly, the evolution characteristics of the Northern Hemisphere (NH) tree-ring index are examined. Figure 1(a) indicates that evolution of the tree-ring index possessed obvious interdecadal oscillations. Five pairs of relatively high-value and low-value epochs are mainly involved. The value of the index is relatively high within epochs of 1040–1100, 1380–1450, 1500–1570, 1750–1780, and after 1930. At the same

time, during spells of 1190–1350, 1470–1500, 1580–1640, 1670–1730, and 1790–1860 the value of the index is relatively low. From 1001 to 1995 the long-term trend can hardly be seen, but after 1930 the ascending trend is marked. Wavelet analysis indicates that the 60–70a oscillation is most notable and another oscillation is ranged about 20–30 years (Fig.1(b)).

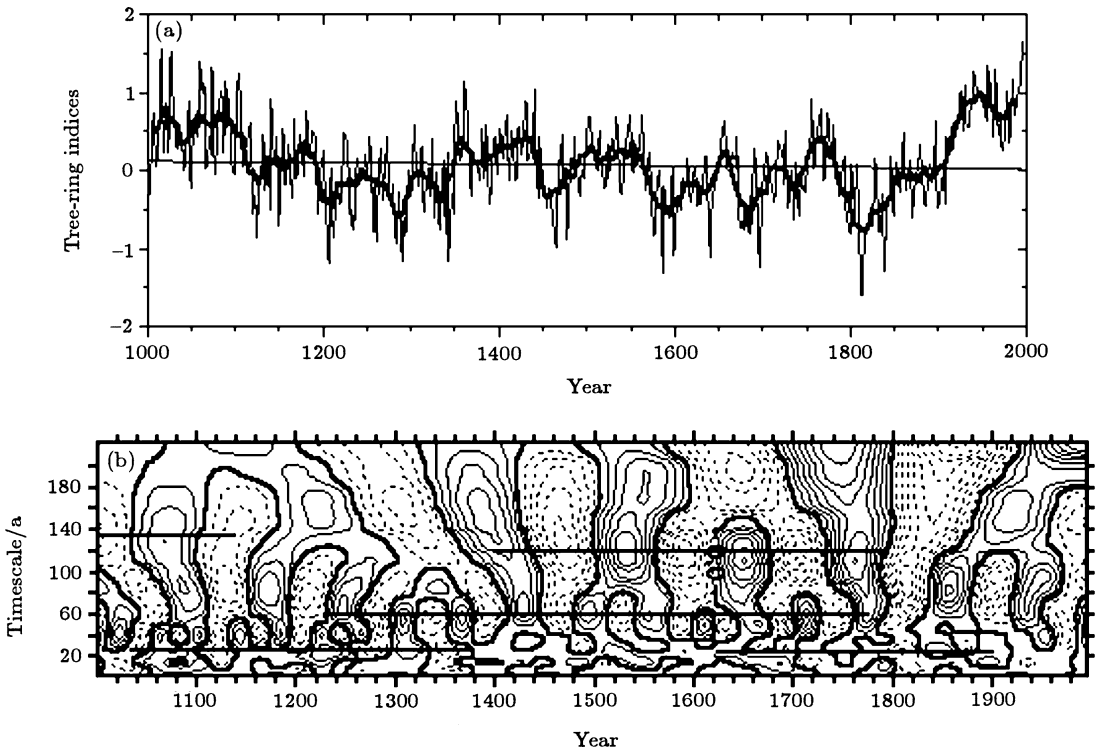


Fig.1. The time series of the NH tree-ring index (a) and its real-part coefficients of wavelet transform (b). The beeline denotes linear trend and the thick curve the 21-point smoothing in (a).

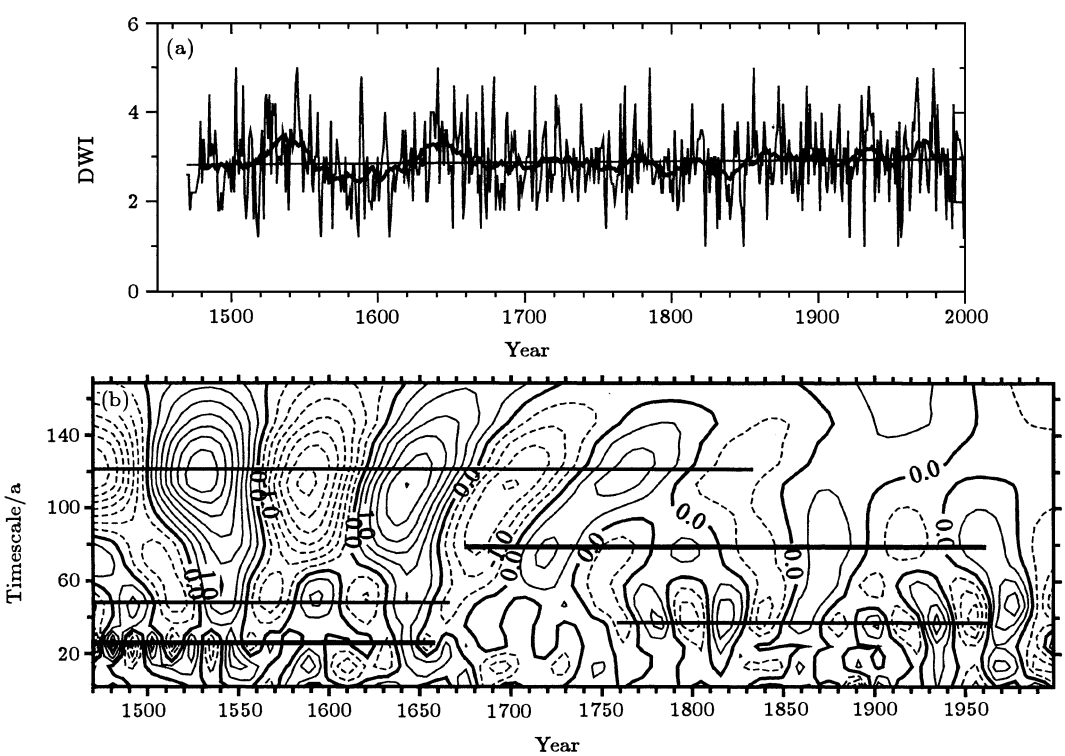


Fig.2. Same as Fig.1 except for the DWI at the lower Yangtze River valley.

For the DWI in the lower Yangtze River valley (Fig.2(a)), the interdecadal oscillations are exhibited in Fig.2(b). The value for the wavelet coefficients with the positive sign corresponds to the dry climate, while a wet climate is indicated with the opposite one. It is clear that four oscillations with the 20–30a, 40a, 60–70a and 110–120a timescales are concluded in Fig.2(b) as listed in Table 2.

Table 2. Multi-timescale oscillations within various climate data.

Data	Interdecadal timescale unit/a		Timescale beyond century unit/a
The NH tree-ring index	20–30	60–70	110–120
DWI in the low Yangtze River	20–30	40 60–70	110–120
North China	20–30	60–70	/
Seoul summer precipitation	20–30	60–70	/

Wavelet analysis of summer precipitation at Seoul makes it clear that there exist 20–30a and 60–70a oscillations. At the same time, the dominant oscillations for precipitation in spring, autumn, winter and the annual mean in Seoul are coincident with that in summer (figures omitted).

Temperature evolution of North China in the recent 400 years experienced three relatively cold spells and four relatively warm spells. The linear trend suggests that warming is obvious in North China in the past 400 years, especially after the 1980s. Wavelet analysis indicates that the 60–70a oscillation is most notable and the 20–30a oscillation takes second place (figures omitted). Since the 1680s, climate change on 60–70a timescale is the most distinguished, and the amplitude becomes larger in the twentieth century. At the same time, cold–warm abrupt points existed in the 1910s and the 1980s while the warm–cold jump appeared in the 1950s.

The dominant oscillations for temperature at other nine regions in China are consistent with that at North China (figures omitted). Using the precipitation series of 35 stations and the temperature series of 10 regions in China for the last 120 years, Qian and Zhu[9] also found that the quasi-20a and quasi-70a oscillations existed in these dataset and the vibration of temperature possesses synchronous property in the whole nation.

4. Model climate variations

A set of parameters in the MSNCM is taken from Ref.[33]. The integral time interval is 0.25 hour. One model year is 360 days with 30 days per month. Winter solstice sets at the 1st January. After performing the model integration, the yearly average values of X_1, X_2, and X_3 for 1000 years are obtained. The major parameters are solar radiation S_0 and draggling coefficient $C_{\rm d}$, because solar radiation is the unique external forcing for the MSNCM, and draggling coefficient controls the feedback intensity, which is the important tache of evolution mechanism. Totally, seven experiments are made (see Table 3), such as for experiment 1, solar radiation varies with 1a cycle, the initial values (X_1, X_2, X_3, T_1, T_2, T_3)=(–1.68078, –0.80321, 0.23754, 0.48165, 0.03022, –0.51504), $C_{\rm d}$=2.8×10^{-2}, and values of other parameters are same as the Ref.[33]; The arrangement of the experiments is to identify which factor(s) could be the reason for the climate change on interdecadal timescale.

Table 3. The main parameters in experiment 1 – experiment 7.

Experiment	Parameters
Exp.1	(X_1, X_2, X_3, T_1, T_2, T_3)=(–1.68078, –0.80321, 0.23754, 0.48165, 0.03022, –0.51504), $C_{\rm d}$=2.8×10^{-2}, Solar radiation varies with 1a cycle, and the values of other parameters are the same as the Reference [33].
Exp.2	Same as exp.1 except solar radiation with 11a cycle
Exp.3	Same as exp.2 except $C_{\rm d}$=8.0×10^{-2} (stronger feedback intensity)
Exp.4	Same as exp.2 except $C_{\rm d}$=2.8×10^{-3} (weaker feedback intensity)
Exp.5	Same as exp.1 but assuming that the fixed state of solar radiation is at winter solstice (the distributions of solar radiation still varies with latitudes)
Exp.6	Same as exp.5 except at summer solstice
Exp.7	Same as exp.5 except at spring or autumn equinox

The evolutions of X_1, X_2, and X_3 in Exp.1 are illustrated in Fig.3. The 21-point running-mean series experienced obvious interdecadal oscillations while no linear trend can be found. The time-frequency distributions and wavelet variances of X_1, X_2 and X_3 in Exp.1 indicate that the interannual variation takes the first place, and at the same time, the interdecadal oscillations are also notable. Major oscillations concentrate on the 20–30a, 40a, and 60–70a timescales. These oscillations appear clearly in one epoch and disappear in other epochs (Fig.4), namely modulate with time, which reflects the essence of the nonlinear system. Wavelet variances of X_1, X_2, and X_3 under Exp.1 are shown in Fig.5. Based on the wavelet variances distribution, it is clear that the larger energies focus on the 20–30a, 40a, and 60–70a timescales.

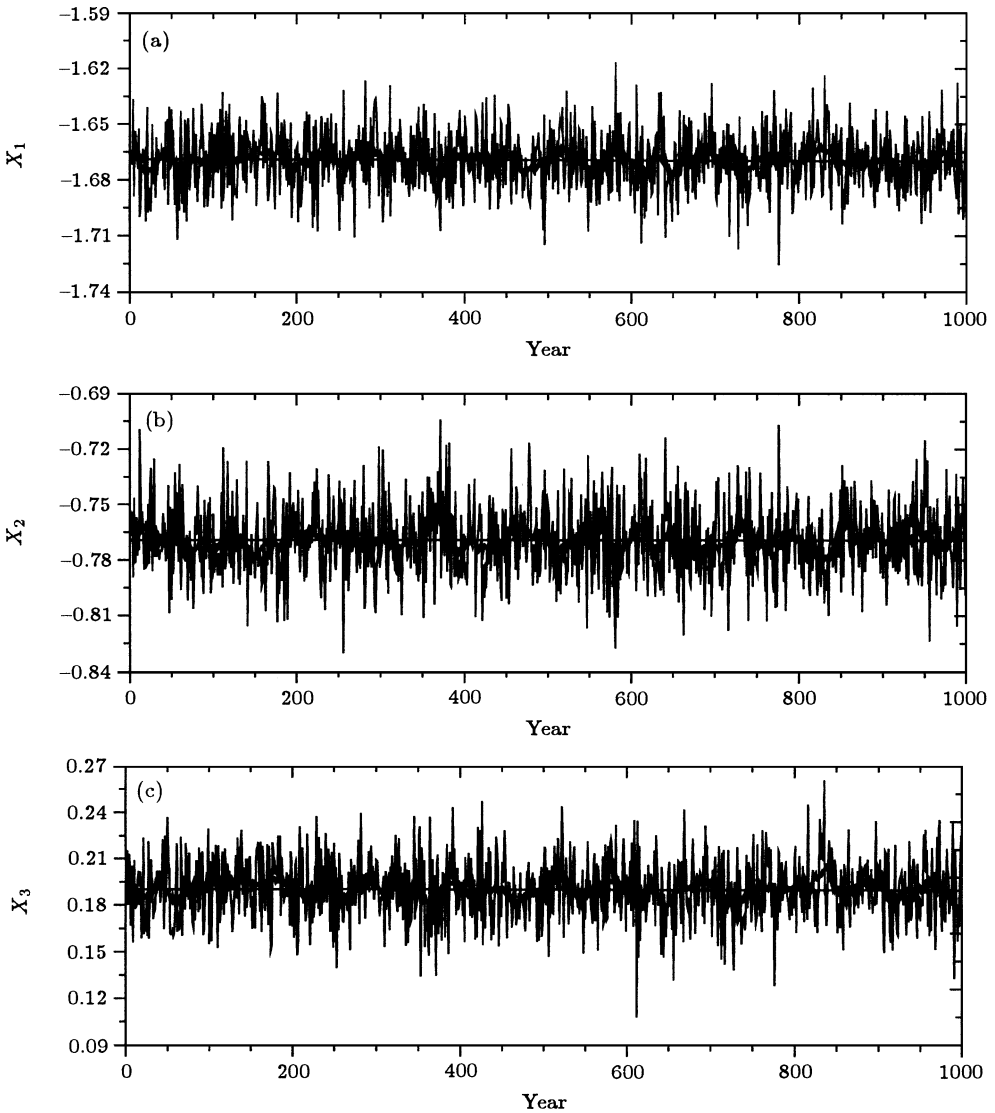


Fig.3. Same as Fig.1(a) except for numerical solutions of the MSNCM under the Exp.1: (a)X_1; (b) X_2; (c)X_3 for 1000 years.

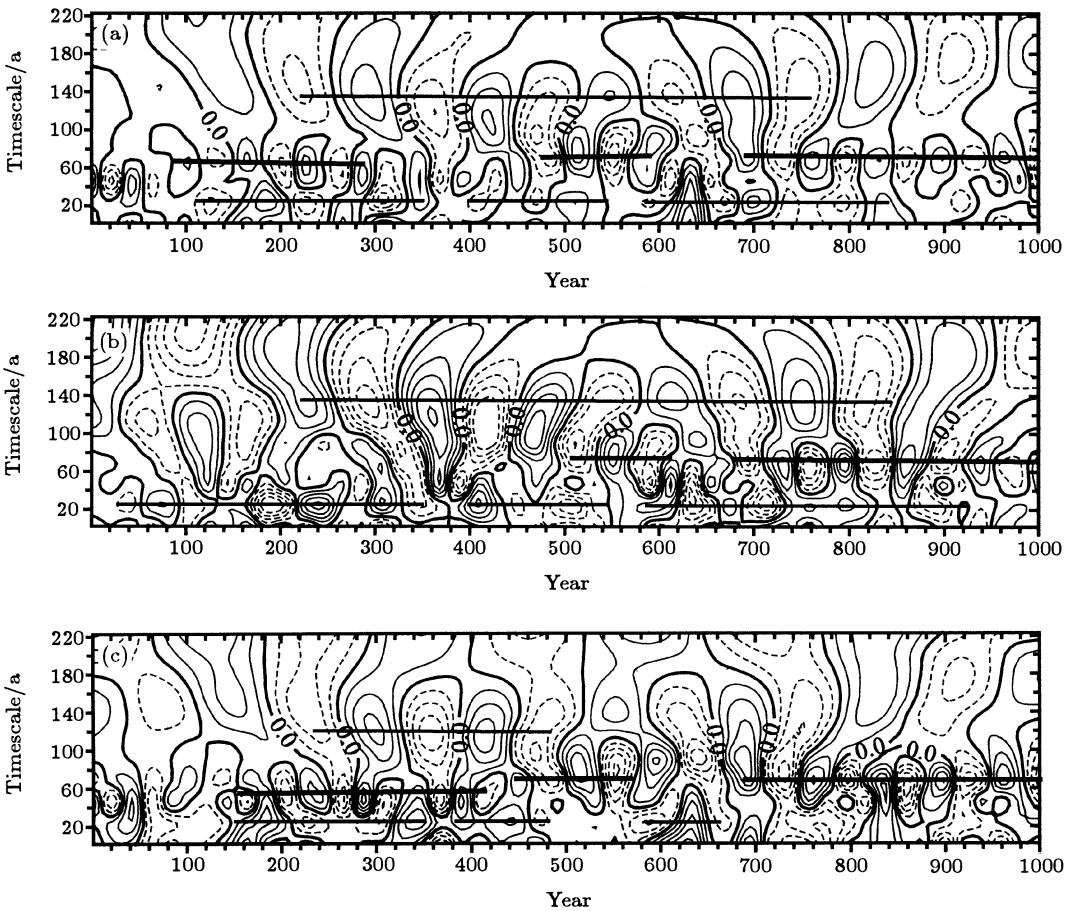


Fig.4. Real-part coefficients of wavelet transform for variable X in the Exp.1: (a)X_1; (b)X_2; (c)X_3.

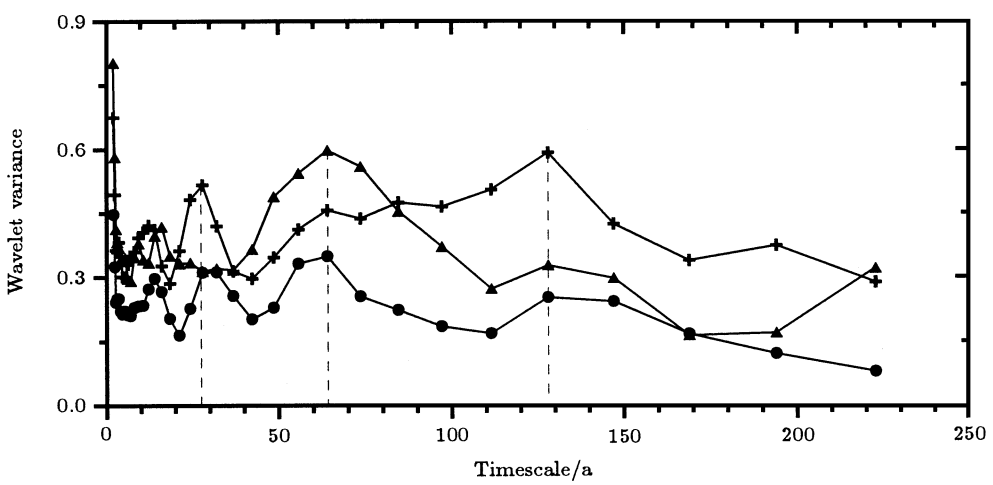


Fig.5. Wavelet variances of X_1 (– ● –), X_2 (–+–), and X_3 (– ▲ –) under Exp.1.

The major interdecadal oscillations in other six experiments are almost consistent with that in Exp.1, which show the distinct multi-decade features similar with that in climate series and natural proxy series (Table 4). With emphasizing the interdecadal components, namely the timescales shorter than 20a being filtered, thus Fig.6 displays the power spectrum of X_2 for Exps.1–7 with the 0.05 significance level, which indicates believably the dominant interdecadal oscillations, coinciding with that in Table 4. This suggests that, although the solar radiation is the unique energy source and the consequent time-dependent evolu-

tion features of interdecadal oscillations is modulated with different parameters in the MSNCM, the origination of the climate change on interdecadal- centennial timescale is not directly linked with the solar radiation with 1a, 11a cycles and others. Because the nonlinearity of the climate system does exist, it seems that the focus for the further research should be on the internal nonlinear dynamics among the sub-systems in climate systems.

Table 4. The main oscillations in Exp.1–Exp.7.

Experiment	Variable	Interdecadal timescale		Timescale beyond century
Exp.1	$X_1X_2X_3$	20–30	60–70	130
Exp.2	$X_1X_2X_3$	20–30	80	120
Exp.3	$X_1X_2X_3$	20–30	60–70	120
Exp.4	$X_1X_2X_3$	20–30	60–70	130
Exp.5	$X_1X_2X_3$	20–30	60–70	110
Exp.6	$X_1X_2X_3$	20–30	60–70	100
Exp.7	$X_1X_2X_3$	20–30	60–70	100

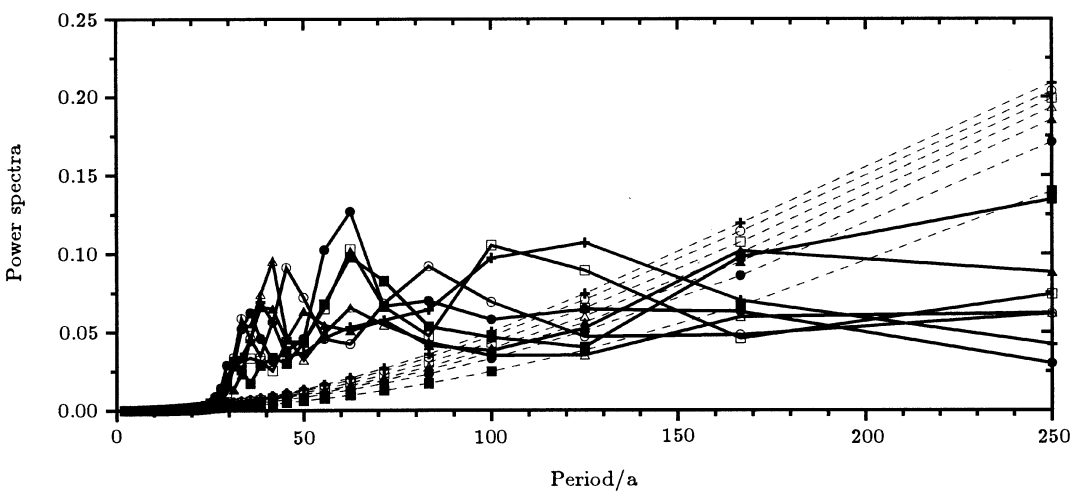


Fig.6. Power spectra of X_2 for Exps.1–7, respectively represented by – ● –, –○–, – ■ –, –□–, – ▲ –, –△–, and –+–. And dashed lines denote corresponding 0.05 significance levels.

5. Conclusions and discussions

By the analysis of climate observation, natural proxy records and modelling series, the major conclusions are highlighted as follows.

1) Climate change has no strict periodicity, and it varies from one timescale to another one even with several major timescales at the same period. That is, climate change takes on the multi-timescale structure and local features in the temporal domain. Utilizing the climate observation and natural proxy series, we have investigated the major interdecadal oscillations and their evolutions. The results indicated that there exist the obvious quasi-periods or oscillations in the climate system, which mainly show 20–30a and 60–70a oscillation and so on. These oscillations are useful information for the climate prediction during a determined period but failure will appear during the moment of modulation.

2) Although the simplification for the MSNCM reaches the utmost, the essential and necessary factors representing climate motion remain, which include nonlinear, external forcing and dissipation effects. Thus the physical mechanism for whether the external forcing can cause the climate change on various timescales is easier to be examined. The results from numerical modelling show that no matter whether for solar radiation with the 1a cycle or the 11a cycle, and in addition invariable solar radiation but varying along the latitudes, the dominant interdecadal oscillations embedded in numerical solutions are consistent with those in climate series and natural proxies, and the time-dependent evolution character-

istics for these interdecadal oscillations are modulated with the parameters. Based on the further investigation, it seems that the originations of these oscillations in the climate change are not directly linked with the solar radiation as an external forcing.

3) This work concludes that the mechanism of climate change on interdecadal timescale has no obvious relation with the periodic variability of the outer forcing such as solar radiation, but possibly induced by the internal nonlinear effects in the climate system. It seems that the future study on the mechanism of climate change on interdecadal timescale should focus on the internal nonlinear dynamics in the climate system.

To better explore climate change on interdecadal timescale, more climate series and natural proxies with longer record and higher resolution should be accumulated. Factors impacting possibly climate change such as chemical components in the air, environment parameters, some geographical or geological course should be secularly monitored in the global scale. More accurate climate model including all kinds of interaction courses should be designed to compare with observations.

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