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CLIMATE CHANGE: LONG-TERM TRENDS AND SHORT-TERM OSCILLATIONS

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ABSTRACT: Identifying the Northern Hemisphere (NH) temperature reconstruction and instrumental data for the past 1000 years shows that climate change in the last millennium includes long-term trends and various oscillations. Two long-term trends and the quasi-70-year oscillation were detected in the global temperature series for the last 140 years and the NH millennium series. One important feature was emphasized that temperature decreases slowly but it increases rapidly based on the analysis of different series. Benefits can be obtained of climate change from understanding various long-term trends and oscillations. Millennial temperature proxies from the natural climate system and time series of nonlinear model system are used in understanding the natural climate change and recognizing potential benefits by using the method of wavelet transform analysis. The results from numerical modeling show that major oscillations contained in numerical solutions on the interdecadal timescale are consistent with that of natural proxies. It seems that these oscillations in the climate change are not directly linked with the solar radiation as an external forcing. This investigation may conclude that the climate variability at the interdecadal timescale strongly depends on the internal nonlinear effects in the climate system.

Key words: climate change; trend and oscillation; natural climate system; nonlinear model system

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1 INTRODUCTION

Climate change or the global warming becomes a research focus of many scientists in the recent two decades. A report by Working Group I of the Intergovernmental Panel on Climate Change[1] indicated that the rate and duration of warming in the 20th century has been much greater than in any of the previous nine centuries. The report also indicated that the 1990's have been the warmest decade and 1998 the warmest year of the millennium. Evidence also showed that over both the last 140 years and 100 years, the best estimate is that the global average surface temperature has increased by 0.6±0.2°C. The report concluded that the warming of the latter half of the 20th century was due primarily to human activities. According to the present warming speed as well as future emission scenarios of greenhouse gases and aerosols the globally averaged surface temperature is projected to increase by 1.4°C to 5.8°C over the period from 1990 to 2100. Based on this projection a large number of works are focused on how to adapt, mitigate and assess damage and impacts on both global and regional levels[2-6].

For this projection, uncertainty was emphasized in the report. Analyzing the historical features that happened in the past on various temporal-spatial scales will be useful for us to apply and understand this projection. In the report, the projection was resulted from the bases of the past climate analyzing and modeling based on several emission scenarios. It is well known that the natural climate system is a chaotic dynamic system so that all observational series of the system are, whether it be daily or yearly, irregular. The natural climate system has only one, which is the Earth climate system, but a large number of model systems with various complexes have been developed in the

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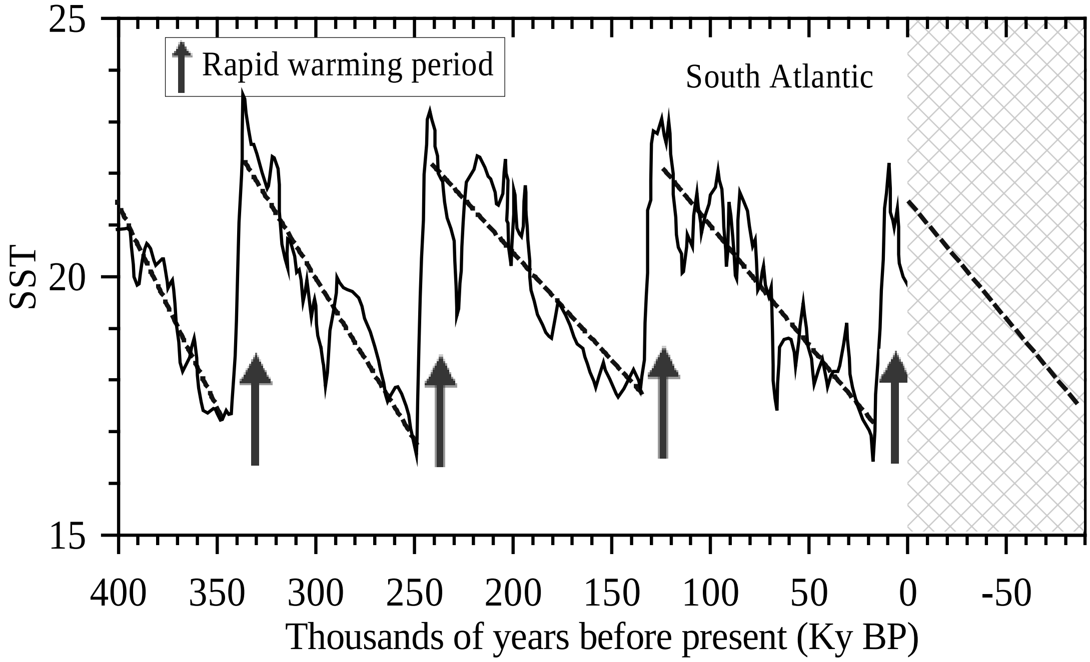

Fig.1 Time-series illustrating temperature variability over the last 400 Ky in the South Atlantic [8]. Long-term trends of temperature decreasing are indicated by the heavy-dashed lines while their rapid increases are denoted by the arrowheads. The present trend of temperature decreasing is projected by the last heavy-dashed line within the diagonal cross gray-shaded area.

Tab.1 Linear trends and ratios of warming and cooling episodes based on the time-series illustrating sea surface temperature (SST) variability over the last 400 Ky in the South Atlantic [8]

Linear trend (°C/Ky)		Ratio of warming to cooling episodes within per-cycle	
Period (Ky BP)	Linear trend	Warming ~ cooling Period (Ky BP)	Ratio
400~348	-0.078		
338~249	-0.06	(348-338)~(338-249)	~1:9
240~135	-0.04	(249-240)~(240-135)	~1:10
123~ 18	-0.046	(135-123)~(123- 18)	~1:9

past decades. There are unknown initial conditions in the natural climate system but model systems strongly depend upon the initial conditions and model complexity.

Evidence showed that a system, not only for the natural climate system but also for model systems, has a long-term behavior or property including certain regularity, i.e., alternating from a periodicity to another non-periodicity, such as what is with the system of Lorenz[7]. This regularity that exists in natural and model systems does not depend upon its initial conditions.

What regularity can be gained from the climatic system and model systems and how to understand it? To answer these questions this paper undertakes three tasks. The first is to identify some long-term trends in the natural climate system and to see how they alternate. The second is to extract useful and regular information from climatic proxy series by using the method of wavelet transform analysis. The third is to compare the regularity from a simplified nonlinear model series with the natural proxy series. Finally, the conclusions and discussions are given.

2 LONG-TERM TRENDS AND SHORT-TERM OSCILLATIONS

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period, typically for decades or longer. Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. In terms of a set of

Tab.2 The main parameters in Experiment 1 to Experiment 4

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), $C_d=2.8\times10^{-3}$, solar radiation varies with 11-year cycle
Exp.2	Same as exp.1 except $C_d=2.8\times10^{-2}$
Exp.3	Same as exp.1 except $C_d=8.0\times10^{-2}$
Exp.4	Same as exp.2 except solar radiation with the 1-year cycle

timescales, climate change includes long-term trends, various mean states and lots of extreme events, namely long-term trends and short-term oscillations.

2.1 Trends and oscillations in the last 400 Ky series

Several features can be characterized from the time series of sea surface temperature (SST) in the South Atlantic[8] (Fig. 1). Climate variability had four cycles in the South Atlantic, which was consistent with that of variations of temperature, methane, and atmospheric carbon dioxide concentrations derived from the air trapped within ice cores from Antarctic[9] and the time series of temperature in the North Atlantic[10]. Roughly speaking, the four climate cycles consist of a regular oscillation with its period about 100 Ky. This regular cycle should be a behavior of natural climate system in the last 400 Ky and the range of SST variation was from about 16°C to 23°C. To see these cycles in detail, four long-term trends of temperature decreasing can be separated with various periods. A feature is found that the trend of temperature decrease was slow but the trend of temperature increase was so fast. A spell ratio between decreasing trend and increasing trend is about at least 9:1 (see Tab.1). Linear declining trends for four periods were from -0.04 to -0.078 °C/Ky. Following a long-term trend, some small oscillations with short time scales can also be observed. The present climate state has just passed a peak point and an uncertainty is if the present trend of temperature decreasing will continue in the coming years following this natural oscillation.

2.2 Trends and oscillations in the last 1000yr series

It is well known that the global climate in the past 1000 years has experienced remarkable variations. Two episodes, so-called the Medieval Warm Epoch (MWE) and the Little Ice Age (LIA), were often mentioned in literatures[11-13]. Usually, the MWE was referred to the time around the late 10th to the 13th or 14th century, while the LIA the period that occurred in many parts of the world during the 15th to 19th century. In the last millennial series, a long-term linear trend of temperature decrease from 1000 A.D. to the late 19th century and a short-term linear trend of temperature increase in the last century can be clearly observed in Fig.2a. This series was based on the millennial Northern Hemisphere (NH) temperature reconstruction and instrumental data from 1000 A.D. to1998[14] and thereafter will be referred as the NH series. The long-term linear trend of temperature decrease was an evolution process from the MWE to the LIA. The two trends were formulated with $y = -0.0002x + 0.17$ and $y = 0.0068x -13.28$, respectively. Many cycles folding upon the two trends can also be noted from the yearly series. A transition point of the two trends occurred in the early of the 20th century, after which the increasing trend is discernable. In the last 1000 years there were about 13 cycles in the temperature series. Two cycles of about 70-year oscillation have not ended in the present since the early 20th century but two warm states were obviously observed in the 1930's-1940's and the 1990's, and a cold state was in 1960's-1970's (Fig.2a). These events with decadal warm and cold states were also observed in China and the Arctic regions[15, 16]. It is interesting to note that the linear trends and the 70-year oscillation are major signals within the millennial climate variability. According to these signals a short cold state of the oscillation besides the trend should be expected early this century. A temperature feature with slow decrease and fast increase is obviously observed in the last 1000-year series.

2.3 Trends and oscillations in the last 140yr series

Fig.3a shows the series of annual averages of CRU (Climatic Research Unit) lead by Jones et al.[17], together with an approximately decadal smoothed curve, to highlight interdecadal oscillation and a long-term trend. This series is globally adjusted for sampling density in grid box land and ocean surface temperature.

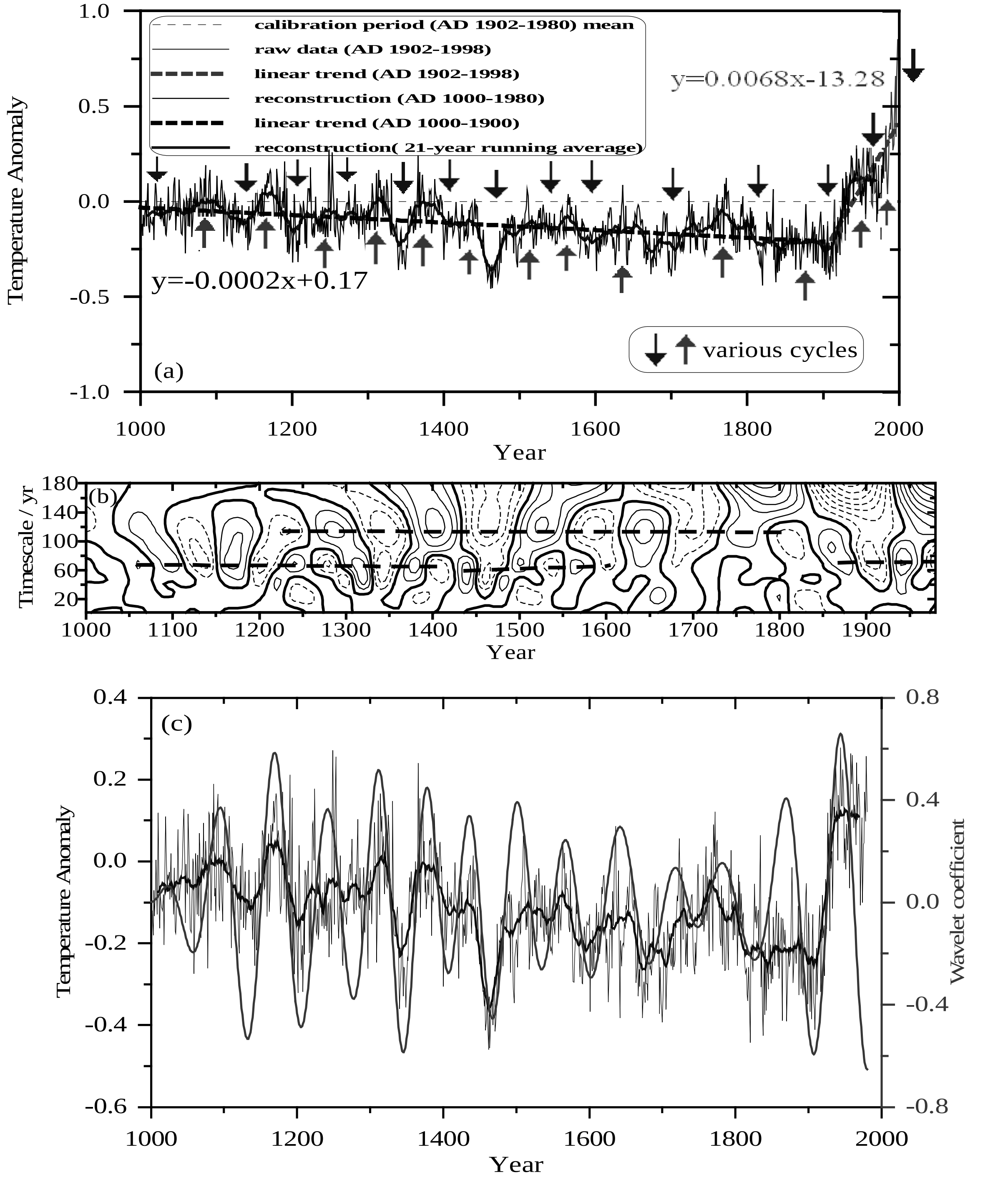

Fig.2 (a) Millennial Northern Hemisphere (NH) temperature reconstruction and instrumental data from AD 1000 to 1998 [14], (b) wavelet coefficients for reconstruction without the linear trend, and (c) quasi-70a oscillation component in (b) as well as reconstruction. Smoother version of NH series (heavy-solid line), long-term linear trend (black-dashed line) of temperature decreasing from AD 1000 to the late 19th century and linear trend (gray-dashed line) of temperature increasing are shown. Short-term cycles of the series are highlighted (upward and downward arrows) in (a). Heavy solid line in (b) denotes the zero coefficients while relatively warm and cold states are indicated by solid areas and dashed areas and centered on the quasi-70-year timescale and the 120-130-year time scale (heavy dashed beelines), respectively.

According to the long-term trend, it is true that the global average surface temperature has increased by 0.5°C-0.6°C in the past 100 years. This trend may be combined by human activity and natural long-term variability. We believe that this trend will extend in future for at least 50 or 100 years. If this projection is true, the global average temperature in the end of the 21st century can reach a value about +0.7° to +0.8°C relative to the time from 1961 to 1990. This projection is different from the one that the global temperature can increase by 1.4°C to 5.8°C in the end of this century. If the long-term trend $y = 0.0045x - 8.84$ is removed, a new series is obtained as what is plotted in Fig.3b. A quasi 70-year oscillation with three warm states in the 1870's, 1940's, and 1990's was clearly shown in the past 100-year series. This 70-year oscillation was also found in dry/wet and clod/warm variations in the East Asian monsoon region[15, 18]. According to the 70-year oscillation, a clod state will be expected in the 2040's. In that time the global average temperature will be in a normal stage relative to 1961 to 1990. At about the 2070's the global average temperature will be possibly at the level of +1.0°C if the trend is combined with the 70-year oscillation at a warm state.

Tab.3 The main oscillations from Experiment 1 to Experiment 4

Experiment	Variable	Interdecadal timescale	
Exp.1	X_1, X_2, X_3	20-30a	60-70a
Exp.2	X_1, X_2, X_3	20-30a	80a
Exp.3	X_1, X_2, X_3	20-30a	60-70a
Exp.4	X_1, X_2, X_3	20-30a	60-70a

2.4 Oscillation in spatial scale

Evidences show that long-term opposite trends and oscillations existed in many natural time series. Fig.4 shows two opposite long-term trends of temperature variations from the global mean annual series and the Darwin annual mean series. The decreasing trend in intensity at the site of Darwin was more obvious than the increasing trend of the global mean annual temperature series. The two trends were formulated by $y = 0.0048x - 9.35$ for the global series and $y = -0.0059x + 39.21$ for the Darwin series, respectively. Long-term trends in many places of the world were consistent with the evolution of the global one but in some other places such as Southwest China opposite temperature trends can be found since the 1940's[15]. In the world many natural phenomena show that there are oscillations such as the well-known Southern Oscillation, which shows annual pressure anomalies in the west and east parts of the Pacific.

3 VARIOUS OSCILLATIONS IN NATURAL SERIES

In this and following sections the long-term trends will be filtered out and only the various oscillations or cycles in the natural and model series will be focused on.

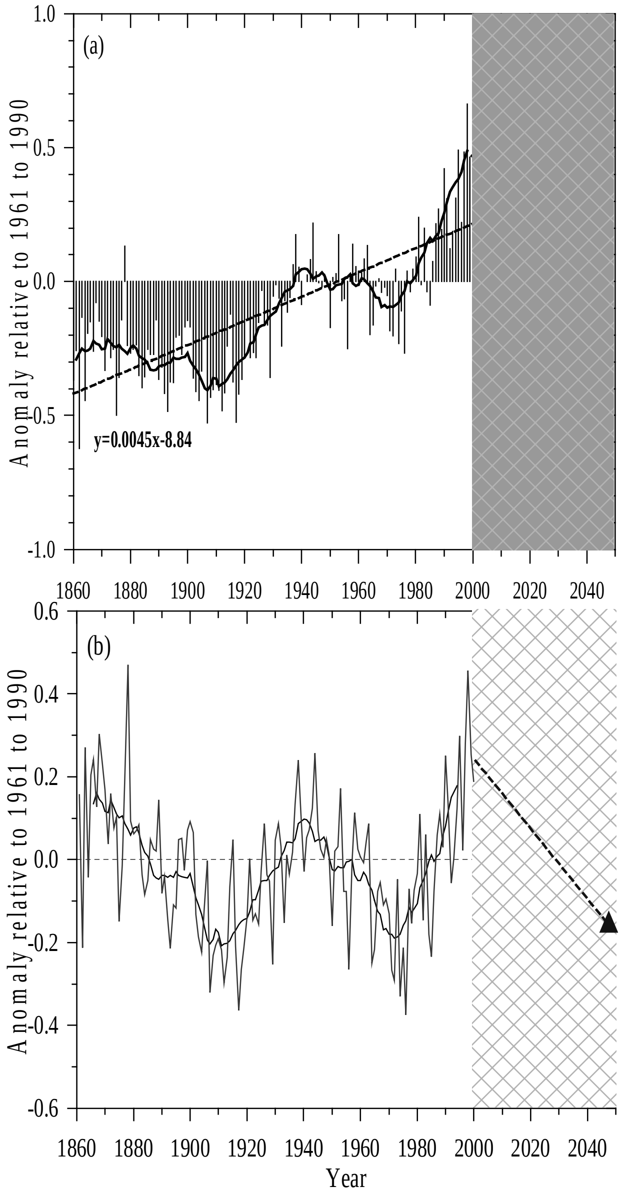

Fig.3 (a) Annual anomalies of global average land-surface air temperature (°C), 1861 to 2000, relative to 1961 to 1990 values [17] and (b) annual anomalies from (a) but the linear trend was filtered out. The smoothed curve in (b) was created using an 11-point running mean. A long-term trend in (a) and a short-term oscillation are projected by ascending dashed line and descendent dashed line within diagonal cross gray-shaded area. The oscillation is also extended from 2000 to 2050.

Among the methods used in the time series analysis, spectral analysis[19] and wavelet analysis[20] are commonly used to reveal components contained in variations in historical datasets. The wavelet transform has been widely applied in the signal detection of climate data series because variations of the Earth's climate are consistent with those exhibited by a

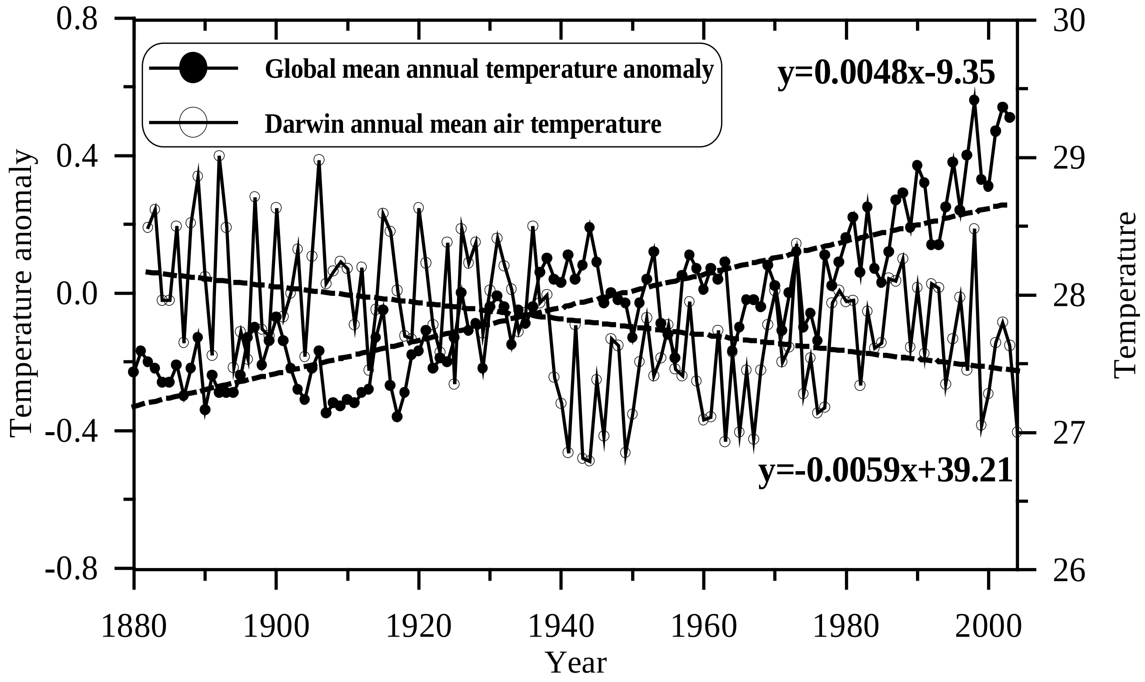

Fig.4 Global mean annual temperature anomaly and Darwin (12.4ºS，130.9ºE) annual mean air temperature (unit: ℃). Two long-term trends are highlighted by dashed lines (series source: http://www.giss.nasa.gov/data /update/gistemp/station_data/)

nonlinear dynamical system under external forcing[21, 22]. Wavelet transform is a powerful tool to characterize the frequency, intensity, time position, and duration from the climate series. It provides localized time and frequency information without requiring the time series to be stationary as required by the Fourier transform and other spectral methods. Here the discretization form of wavelet transform for the function $f(t)$ is

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

where Δt is the sampling interval, n the sample amount, g the mother wavelet, a the frequency parameter (a smaller a value refers to a shorter scale or a higher frequency), and b the temporal parameter showing the temporal movement. In this paper, the Morlet Wavelet is taken as mother wavelet g, which can provide the amplitude and phase features of various signals respectively. The real-part information of wavelet transform coefficients is utilized and symmetrical prolongation method is adopted in eliminating the boundary effects[23,24]. A close pair of minimum and maximum centers of $W_f(a, b)$ with a large gradient may display an abrupt change from one persistent spell of anomaly to another anomaly with different signs. There is a quasi periodicity at a timescale when a regular oscillation appears.

Wavelet variance reflects characteristics of wavelet spectrum and represents the energy distribution of different signals with scales.

$$Var(a)=\sum_b [W_f(a,b)]^2 \quad (2)$$

Using the introduced wavelet transform method, several possible regular oscillations contained in natural and model series are detected. For the NH series, wavelet coefficients only for reconstruction without the linear trend are displayed in Fig.2b. The quasi-70-year oscillation was obvious during the 12th to 16th century and last two centuries (see Fig.2a and Fig.2c). The 70-year oscillation had an active period from the 12th to 16th century for about 5 centuries with 8 cycles while the second active period was expected to start in just the last two centuries (Fig.2c) and will be continued.

In eastern China, precipitation/temperature series and dry/wet series for the last 120 years and the last 530 years also showed the quasi-20-year and quasi-70-year oscillations[15, 18, 25]. It may be concluded that the 20-30-year and 60-70-year oscillations are commonly exhibited in the climate system.

4 VARIOUS OSCILLATIONS IN MODEL SERIES

In order to study the global climate variability, the result of a simplified climate model system will be applied. This model, which differs from traditional general circulation model (GCM), has been developed by Guo et al.[26] and used by Zhang et al.[27]. A set of

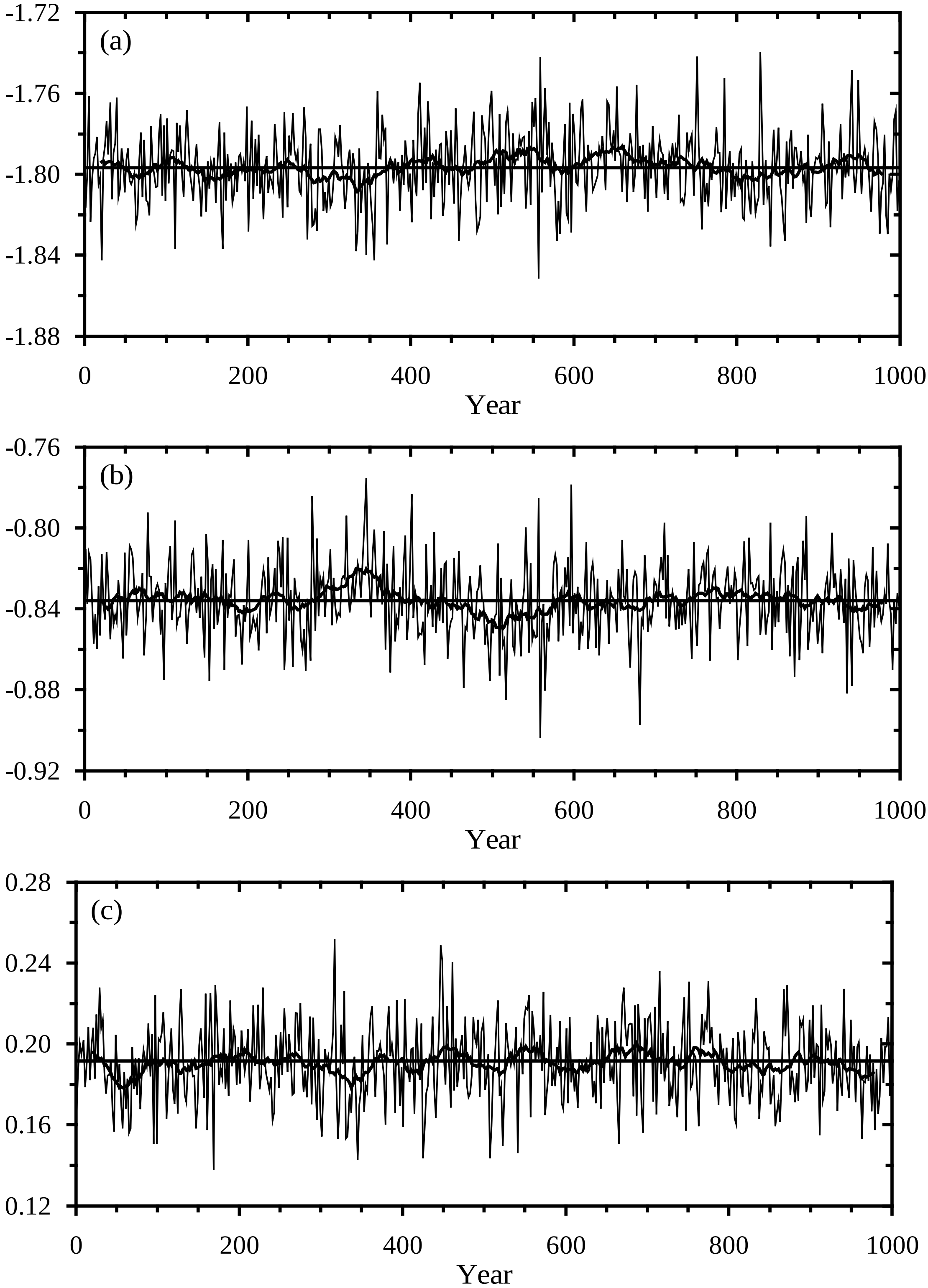

Fig.5 Time series of numerical solutions from the simplified nonlinear model under the Exp.1: (a) X_1; (b) X_2; (c) X_3 for 1000 years. The thick line denotes the mean value while smoothing thick curve indicates the 21-point moving average.

dynamic equations are simplified to yield acceptable ones or to reproduce climate variability. This model is coupled with the atmosphere and its boundary layer. The solar radiation is the unique external forcing for the model. From the viewpoint of climate dynamics, a set of motion equations in the atmosphere can be

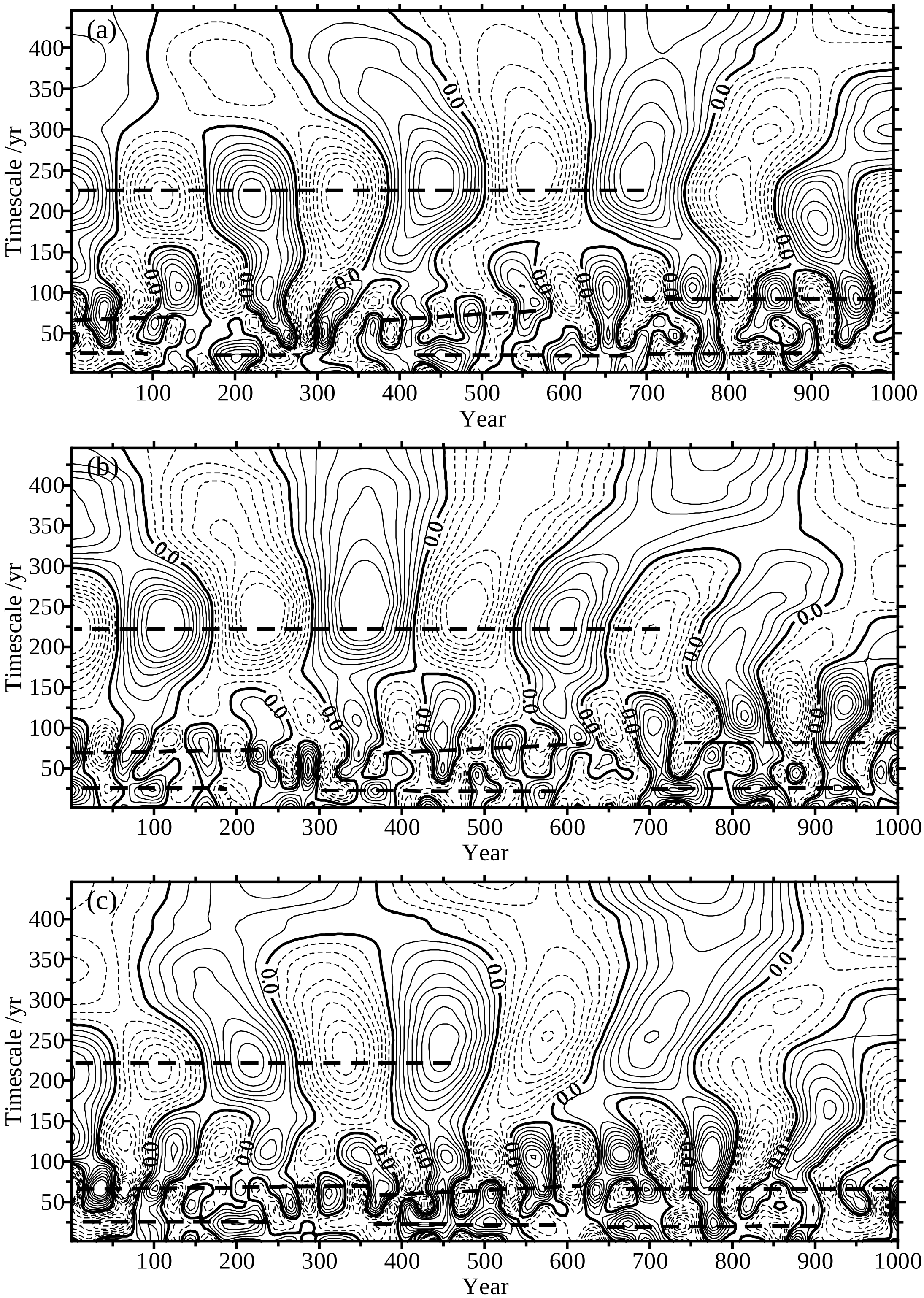

Fig.6 Real-part coefficients of wavelet transform for variable X in the Exp. 1:(a) X_1; (b) X_2; (c) X_3. Regular oscillations are highlighted by thick dashed lines.

reduced as a set of linear balance ones but the energy equation is still nonlinear.

This simplified model is used to identify whether there are various oscillations in the nonlinear system. A set of parameters in the model is taken from the Ref. [26]. The integral time interval is 0.25 hour. One model year is 360 days with 30 days per month. Winter solstice is set at the 1st January. After performing the model integration, the yearly averaged values of X_1, X_2, X_3 for 1000 years are obtained. Series X_1, X_2, X_3 are dimensionless, representing three components of temperature at the 500 hPa level, namely $(T_1)_2, (T_2)_2, (T_3)_2$. The major forcing-dissipative parameters are solar radiation S_0 and draggling coefficient C_d. Totally, four experiments are made (see Table 2), such as for experiment 1, solar radiation varies with a cycle of 11 year, 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), and C_d=2.8×10^{-3}; The arrangement of the experiments is to identify which factor(s) could be the reason for the climate variations at the interdecadal-centennial scale.

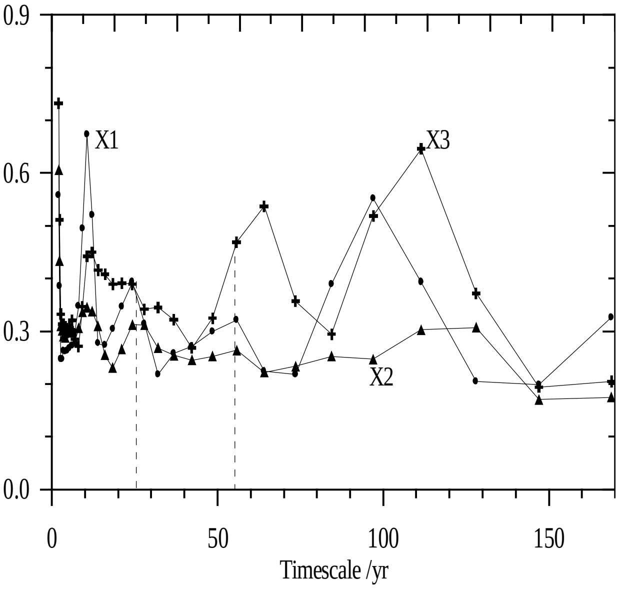

Fig. 7 Wavelet variance for X in Exp.1 with timescales from 2 years to 170 years. Peaks with larger energies are indicated by dashed lines at the timescales of 20-30 years and 60-70 years.

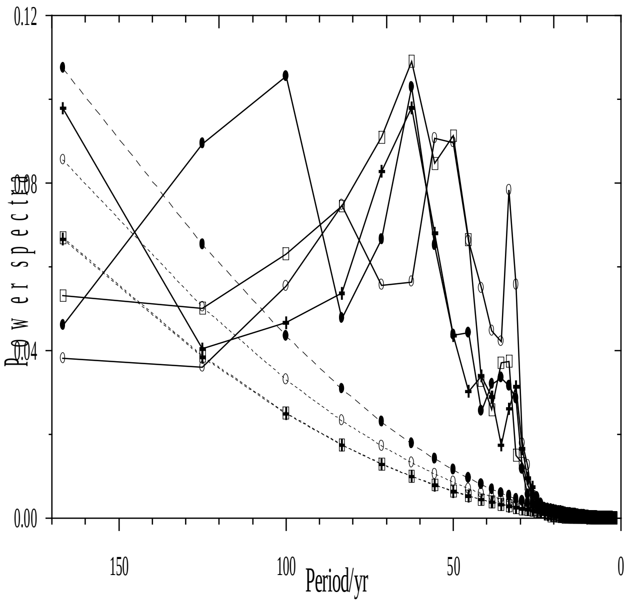

Fig.8 Power spectra of $X_{3\text{-}1}$, $X_{1\text{-}2}$, $X_{2\text{-}3}$ and $X_{3\text{-}4}$ corresponding with Exp.1, Exp.2, Exp.3, and Exp. 4 and by ●, ○, +, and □, respectively. The dashed lines denote 0.05 significance levels.

The results of the model are illustrated in Fig.5, which show the chaotic behaviors of X_1, X_2, and X_3 in Exp.1 for the first 1000 years. The 21-point running-mean series indicate that there are obvious interdecadal oscillations but no linear trend can be found. The time-frequency distributions and wavelet variances of X_1, X_2, X_3 in Exp.1 indicate that the interannual variation and interdecadal oscillations are notable. Major time scales for the interdecadal oscillations concentrate at the timescales of 20-30 years and 60-70 years. These oscillations appear clearly in a time range and disappear in other ranges (Fig.6), indicating that climate change has no strict periodicity, but varies from a timescale to another even with several major timescales existent in the same time range. Wavelet variances of X_1, X_2, and X_3 in Exp.1 are shown in Fig.7. Within the interdecadal timescale, it is clear that larger energies are globally concentrated at the 20-30-year and 60-70-year timescales. With the interdecadal components emphasized, timescales shorter than 20-year are filtered, thus Fig.8 displays the power spectrum of X for Exps.1-4 with the 0.05 significance level, indicating confidently the dominant interdecadal oscillations. Fig.9 plots the projections of the different phase spaces for the numerical solution of the model. Some oscillations from these trajectories could be noted when they are closed from a similar cycle to others. These phase-space projections are rather beautiful as shown by the Lorenz's butterfly pattern. The regularities can be clearly seen from these projections but it is hard to judge when it switches from an attractor to another.

The results of the other three experiments are almost consistent with that of Exp.1, showing the distinct multi-decadal oscillations (Tab.3) being similar with that in natural proxy series. It can be suggested that climate change on the interdecadal timescale is not directly linked with the solar radiation with 1-year and 11-year cycles, or others.

5 DISCUSSIONS AND CONCLUSIONS

From the analysis of natural proxy records and modeling series, major conclusions include the followings.

(1) Long-term trends and various oscillations existed in all observed natural series not only in temperature reconstruction and instrumental data for the past 1000 years but also in the longer series such as the past 400 Ky proxy. One important feature was

commonly exhibited that these time series with various trends decrease slowly but increase rapidly. In the past 1000 years our planet temperature has experienced a decreasing trend in the LIA and an increasing trend in the Global Warming period. This warming trend will continue and will reach the value about 0.7°C-0.8°C in the end of this century. A quasi-70-year oscillation needs to be considered in this century. Combining the warming trend and 70-year oscillation the global average temperature will reach the previous normal level in the 2040s and will reach a high value about 1.0°C near the 2070s. Communities can obtain benefits of climate change if considering this trend and oscillations.

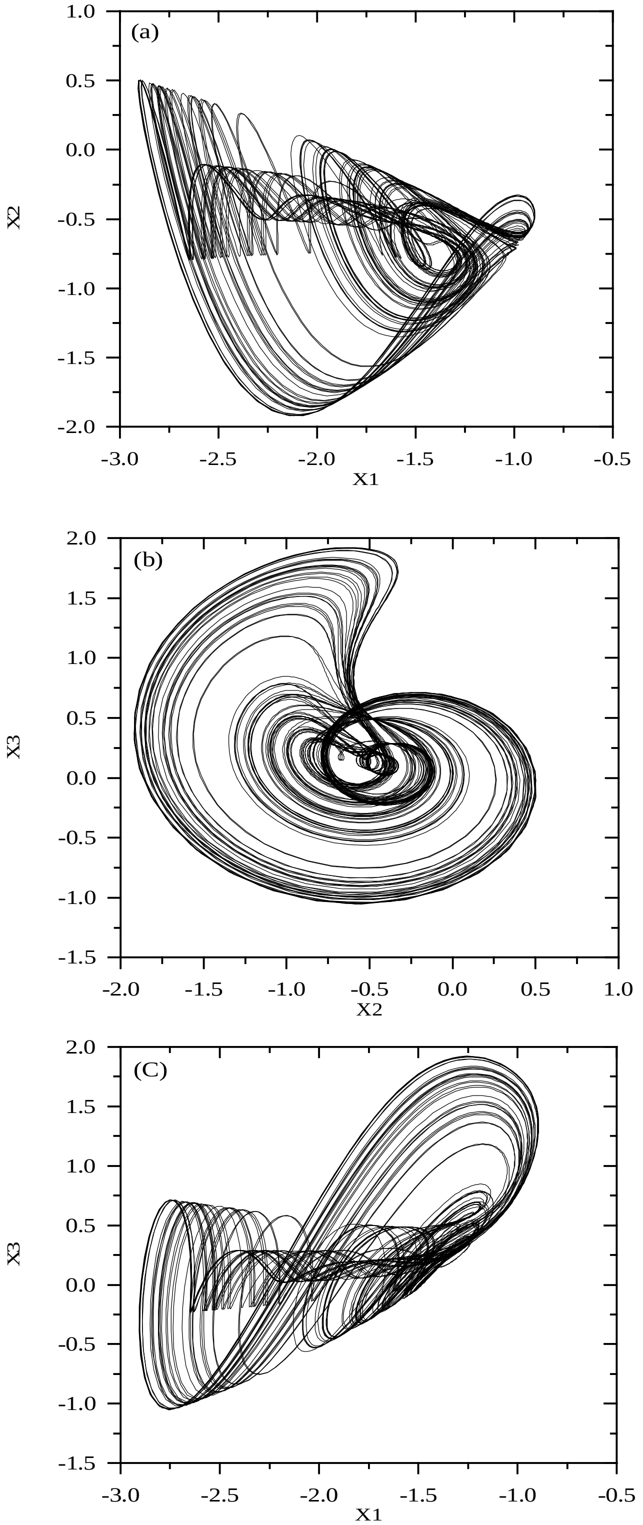

Fig.9 Numerical solution of the simplified nonlinear model. Projections on the different phase spaces: (a) $x_1 - x_2$; (b) $x_2 - x_3$; (c) $x_1 - x_3$.

(2) Utilizing the natural proxy series in the climate system, the evolution characteristics of climate change on the interdecadal timescale can be identified with the wavelet transform analysis. The results indicated that obvious periodicity or oscillations exist in the climate system, mainly showing 20-30-year and 60-70-year oscillations. These oscillations are useful information for climate prediction during a time range. Statistically, a time range with a certain oscillation can persist for many years but failure appears only when oscillations transform so that we can gain the maximum benefits based on a certain oscillation.

(3) The results from the numerical modeling show that no matter what cycles are with solar radiation, 1-year or 11-year or others, the dominant oscillations contained in the numerical solutions on the interdecadal timescale are consistent with that in natural proxies. It seems that these oscillations in the climate change are not directly linked with solar radiation as an external forcing. This investigation may conclude that the climate variability at the interdecadal timescale strongly depends on the internal nonlinear effects in the climate system.

(4) Due to the nonlinear nature of climate change itself within the mutual interactions among the subsystems of climate system, only the information about the long-term trend and various oscillations detected is not sufficient for climate prediction and the adaptation, mitigation, assessment of the damage and impacts due to climate change. In order to reduce the negative impacts or to take advantage of new opportunities presented by changing climate conditions, further work is urgently needed, such as quantitative analysis and assessment.

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