Latest Advances in Climate Change Detection Techniques*

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ABSTRACT

In recent years, the global warming and its influences on people and social economy have received increasing attention from international communities. Determining the current trend of global temperature variation has become one of the critical issues in climate change research. Obviously, it is rather important to develop new climate change detection technology in order to identify new characteristics of the global warming. This review introduces the latest advances and past achievements on the climate change detection technology in China with emphases on new detection methods in the following five aspects: (1) abrupt climate change detection, (2) signal separation and extraction from observed data, (3) intrinsic complexity of the climate system, (4) recognition of the dynamical characteristics of the climate system, and (5) definitions and detection of extreme events. At last, some cruxes and key problems in the current climate change detection technology research are briefly discussed.

Key words: abrupt climate change, extreme climate events, detection method, dynamical structure characteristic

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1. Introduction

In the latest ten or more years, a series of progress and achievements have been made on climate change research in China, among which a significant contribution is the recovery, reconstruction, and compilation of historical climate data and the homogeneity processing of various observed data (State Meteorological Science and Department of Geophysics of Peking University, 1975; Chinese Academy of Meteorological Sciences, 1981). Wang et al. (1998a) constructed 1600–2000 annual mean temperature data for 10 regions in North China, Central China, and Central-South China. Yao and Thompson (1992), Wang et al. (1998b), and Shi et al. (1999) constructed various temperature and precipitation time series in China using the proxy data of multiple types of tree rings, ice cores, and stalagmites. In regard to observed data, Information Center of China Meteorological Administration, etc., successively released daily, monthly, and yearly surface climate data sets and the satellite remote sensing vegetation index data set (Liu and Li, 2003; Li and Li, 2007). The increase in observed data is, on one hand, beneficial to the detection and analysis of characteristics of climate change on wider and longer spatial and temporal scales; on the other hand, it also brings challenges to climate change detection methods and techniques due to the diversity and differences in resolution of data and the nonlinear and non-stationary characters of data itself.

The fourth assessment report of IPCC pointed out that the average linear warming rate over the recent 50 years (0.13°C/10 yr) is almost twice that over the past 100 years. The linear increment of temperature over 1906–2005 is 0.74°, and the 11 years out of the recent 12 years (1995–2006) belong to the 12 warmest years since 1850. According to the projection of IPCC, the global warming trend might further intensify due

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to human activities. Under the background of the global warming, the climate change caused by various factors may be divided into two parts: (1) the natural change, which is resulted from the external forcing, such as solar activities and volcanic eruptions, and which lead to changes in the dynamic structure of the climate system, i.e., natural change rate; and (2) the anthropogenic change, which is caused by anthropogenic factors, such as greenhouse gases (GHG) emission and changes in aerosol concentration and in land-use, etc., i.e., anthropogenic change rate. Therefore, (1) how to separate the impact and contribution of natural and anthropogenic change rates and to further analyze the characters of local and global climate changes, and (2) how to analyze the observational data based on the intrinsic dynamic structure of the climate system, so as to further detect abrupt changes and turning of climate and find possible causes for changes in the intensity and frequency of extreme climate events, have become new scientific problems. That is to say, the traditional detection technology has been facing new challenges.

In the latest ten or more years, advances in studies on basic sciences of climate change and adaptation to climate change have been made in China under the state government's financial support to a series of scientific and technological programs, thus making special contributions to the development of global climate change and global change sciences and to the formulation of China's adaptation and mitigation plan. Achievements have been obtained on the detection techniques of the global climate change (Ye and Huang, 1990; Fu and Yan, 1996; Ding et al., 2007; Wang, 2001). The referred publications pointed out the possible research direction of climate change, and reported necessary theories and technical methods (Wang and Zhu, 1999; Ye et al., 2003; Ding et al., 2007; Qin et al., 2007). On the above basis, Wei (2007) proposed statistical diagnosis and prediction techniques in modern climate studies, and Feng et al. (2006) summarized new nonlinear theories and methods in mathematics and physics in the latest five years and combined those new methods with climate change detection studies through numerical experiments. Climate change detection techniques are used in the following five aspects: (1) abrupt climate change and turning detection, (2) signal separation and extraction from observed data, (3) intrinsic complexity of the climate system, (4) recognition of the dynamical characteristics of the climate system, and (5) definitions and detection of extreme events. This paper briefly summarizes new progress and some of the research achievements of our research group on climate change detection techniques in the recent five years with emphases on the introduction of new detection technology and methods.

2. Abrupt climate change and its detection techniques

The gradually developed abrupt change theory pioneered by Thom (1972) has currently been widely applied in various research fields, such as climatology, seismology, etc. (Dansgaard, 1982). Abrupt climate change, i.e., climate jump or discontinuity of climate change, is an important phenomenon that generally exists in the climate system. Since Lorenz (1963, 1976) theoretically showed the possibility of the abrupt change of climate, studies on abrupt climate change have developed rapidly (Feng et al., 2005). Generally, due to the evolution of the intrinsic dynamic structure of the climate system or large external disturbances, the state of the system in the phase space tends to be a new attractor instead of the original one, i.e., occurrence of abrupt change, which is a nonlinear behavior of the climate system (Weaver and Hillaire, 2004; Dai et al., 2005). Abrupt climate change mainly manifests in time scales and statistical attributes of climate variables. It occurs on different time scales including inter-century, inter-millennium or longer scales, such as alteration of glacial and interglacial, transition of the little ice age and the medieval warm period, etc., as well as on interdecadal scale, but there are still controversies on the last scale. Abrupt climate change also occurs in amplitudes of statistic characteristic quantities of climate variables, such as in mean value, variance, frequency, trend, etc. There are different detection methods for the above two different categories of abrupt climate change.

Traditional detection methods for abrupt change include the running t test method, Cramer method, Le Paga method, Yamamoto method, Mann-Kendall method, and Pettitt method. The first four methods are mainly used to detect the abrupt change of the mean value of a time series. The Le Paga method is the relatively most effective one, but at present is seldom applied in the meteorological field. The latter two methods are utilized to detect abrupt change trends of time series. These methods do not require us to know the distribution of samples, and are seldom affected by a few anomalous values; therefore belong to the non-parameter statistical test method. By using traditional abrupt change detection methods, Fu and Flecher (1982) and Fu and Wang (1991) revealed the strong signal of climate change in the monsoon areas and the consistency between the abrupt change of the South Asian monsoon and the East Asian monsoon and the global warming; Yan et al. (1990) discovered the planetary scale banded structure of abrupt changes; Wang et al. (2004) discussed the possibility of the abrupt climate change resulted from climate warming, and suggested to further enhance the research on abrupt climate change. Using the running t test, Xiao and Li (2007a, b) quantitatively detected and analyzed the interdecadal abrupt change points of global sea surface temperature fields, the spatial distributive characters of interdecadal abrupt change, the earliest response time and areas vertical distributive characters, etc. Ma and Fu (2006) detected and analyzed the drying characters of northern China in the recent 45 years using the Mann-Kendall method, and systematically revealed the interdecadal space-time pattern of drying. Mu and Wang (2007) demonstrated the possibility of the abrupt change between non-equilibrium states of ecosystem by using a theoretical grassland ecosystem model forced by certain external forcing.

It is required to specify a window in traditional abrupt change detection methods. Therefore, there might be different extents if the abrupt change shifts. Aiming at the non-stationary character of observed data, Bernaola-Galvan et al. (2001) presented a heuristic segmentation algorithm for abrupt change detection (B-G algorithm). Gong et al. (2006a) examined the effectiveness of the B-G algorithm by numerical experiments, and analyzed the abrupt changes on different time scales in the time series of the Northern Hemisphere tree ring width anomalies and the Beijng Shihua cave stalagmite lamina thickness anomalies, yielding the centurial scale abrupt changes of climate in about AD 380, 900, 1120, 1350, and 1600 from the low-frequency components of the time series of the tree ring and stalagmite. On the decadal scale, different proxy data show differences in abrupt change time, but the temporal distributive patterns of abrupt changes are similar. Using a high-order moment analysis method, Zhang et al. (2007) investigated the tree ring and stalagmite data, and attributed the climate warming in the 20th century mainly to the centurial scale contribution. A further investigation (Gong and Feng, 2008) into the 530-yr dryness/wetness index using the B-G algorithm shows that the natural change rate of climate change governs mainly the interannual variations of climate; the natural and anthropogenic change rates jointly control the interdecadal variations; and the anthropogenic change rate possibly dominates the centurial scale variations (this remains

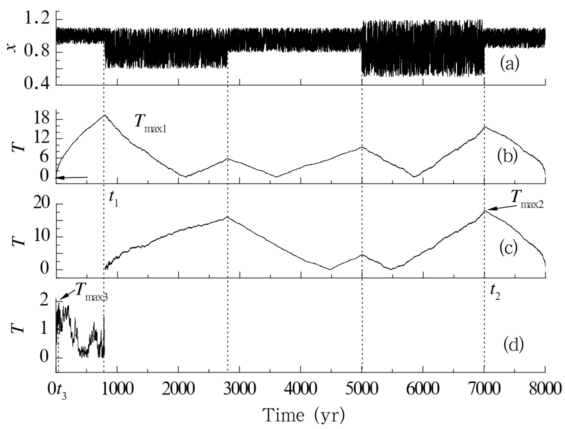

Fig. 1. The test results of the B-G algorithm of an ideal time series. (a) The original series, (b) T series of the original series, and (c) and (d) T series of the sub-series of the original series right and left of the first abrupt change point. $T_{\max1}$ and $T_{\max2}$ are the T values of the first and second abrupt change points, and $T_{\max3}$ is smaller than the T threshold value of abrupt change.

to be further proven; it is difficult to detect the centurial scale abrupt change of climate at present due to the limitation in the length of time series of proxy and observational data).

On one hand, the evolution of the climate system follows the continuity equation, state equation, thermodynamics equation, etc. (Liu and Liu, 1991). On the other hand, the observed series of climatic variables also have statistics such as mean value, variance, etc. Therefore, climate changes may be classified into two categories: one is rapid changes in one or two statistics, such as phase changes of mean value, variance, frequency, etc., while the dynamic structure of the climate system does not change (i.e., no changes in the governing equation); the other is changes in climate state, i.e., the temporal changes in the parameter and variable of the governing equation (i.e., changes in the dynamic structure of the climate system). The climate system itself jumps from a relatively stable state to the other state, which is called the abrupt change of dynamic structure (Li and Chou, 1996; Yang et al., 2003; Yang and Zhou, 2005). In the aspect of the detection of dynamic structure abrupt change, Feng et al. (2006) performed some exploratory works. They combined the latest research achievements in nonlinearity science with the abrupt change detection of the climate system, and proposed several theories and methods for detecting abrupt climate change from the angle of dynamic structure characters, such as dynamic correlation factor index, dynamic exponent segmentation algorithm, detrended fluctuation algorithm, permutation entropy algorithm, approximate entropy algorithm, etc. (Wan and Feng, 2005b; Gong et al., 2006b; Hou et al., 2006), thus opening new possible paths for studying the abrupt change of the dynamic structure of the climate system. Besides, some researchers applied the fingerprint method to detecting abrupt changes in climate, medicine, and chemistry fields, in which abrupt changes are judged by analyzing and comparing the fingerprint characters of gas chromatography, including contour figure, peak range, and some characteristic ratios.

3. Signal recognition and extraction of climate data

The climate system is a complex giant system composed of mutually coupled atmosphere, oceansphere, and cryosphere. Under the background of global warming, its changes are not only controlled by natural change rate but also by the anthropogenic one resulted from the acceleration of human activities, which leads to the multi-hierarchic and multiscale properties of the system. Proxy and observational data, as external manifestations of the intrinsic complexity of the climate system, must have contained signals of the multi-hierarchic and multi-scale properties. Therefore, signal separation and extraction from climate data is of significance in studies of climate changes. Climatic signal extraction is mainly used in the following aspects (Wei, 2007): (1) identifying the natural change rate from hypothetical anthropogenic factors and external effects; (2) inferring physical concept models from detected climatic signals and developing climate models; (3) applying detected climatic signals to comparing basic characteristics of simulated data from a model and corresponding observed data so as to examine the effectiveness of the climate model; and (4) predicting the future trend of climate in terms of climatic signal itself.

Traditional signal recognition techniques mainly contain power spectrum, maximum entropy spectrum, multi-site maximum entropy spectrum, cross spectrum, wavelet analysis, etc., among which the power spectrum, cross spectrum, and wavelet analysis methods are based on Fourier transformation, and the maximum entropy spectra on autoregression models. Those methods are mainly used to indentify the periods of climate observations. They have played important roles in previous tests and analyses of climate data, which yielded a chain of important achievements. For example, Huang et al. (2006) analyzed the summer precipitation in China and moisture fluxes over East Asia using the entropy spectrum method, and found that the summer precipitation has a characteristic of quasi-biennial oscillations, which is closely related to the quasi-biennial periodic oscillations of moisture fluxes over East Asia. Zhang and Ding (2001) used the multi-scale analysis to divide changes of climatic variables related to ENSO into three major components: the ENSO cycle scale of 2–7 yr, the interdecadal scale of 8–20 yr, and the change scale of the mean climate state of above 20 yr. Zhu et al. (2003) investigated the interdecadal fluctuations of precipitation in North China and its relation with the East Asian monsoon using correlation analysis, power spectrum and wavelet analysis.

Climate data are high dimensional observational data, which contain two parts: noises and signals, among which the signals represent the principle component of climate change characters. Therefore, denoising and signal extraction from the original observational data are critical for studies of climate changes. Generally speaking, chaotic signal denoising methods take a similar technical route: reconstructing an attractor from the observation series at first, selecting a model to estimate the local dynamic behavior of the original system, fitting the parameter of the model using a statistical technique, and then revising the observational data to make them more consistent with the model (Sugihara and May, 1990; Thomas, 1993). Sauer et al. (1991) proposed the search-average nonlinear denoising (SAD) algorithm. Hou et al. (2007) revised the algorithm and tested the effectiveness of the revised SAD algorithm using Henon mapping numerical experiment, and applied the algorithm to the denoising of the daily temperature observations in 1960–2000. This processing effectively reduces the noise component of the data, thus raising the predictability of the actual temperature. Besides, Morlet (1984) presented the concept of wavelet and applied it to analyzing the seismological data. Wavelet transform, as a signal processing method, can be used as a tool not only for period analysis, but also for separating "noises" from observed data and extracting components on various scales of the major signals of the original series. This method performs the multi-resolution analysis of the observed series through the operations of the dilatation and translation of base functions (Grossmann and Morlet, 1984; Mallat, 1989). However, because the wavelet decomposition in nature is a bandpass filter, various components generally correspond to fixed frequency bands, and the selection of wavelet bases and decomposition scales are very subjective, the accuracy of decomposition remains to be further improved.

Aiming at breaking the limitations of wavelet decomposition, Huang et al. (1998) presented a new time series analysis method–Hilbert-Huang transform (HHT), which contains two parts: empirical mode decomposition (EMD) and Hilbert transform (HT). The EMD is used mainly to stationarize a complex signal series, and then to extract the wave or trend components on various scales or levels from the original series, yielding several intrinsic mode function (IMF) components with different scale characters; and the HT is employed to further perform the transform on obtained IMF components, yielding the transient frequency and amplitude of the IMF (Fig. 2), and at last to produce the three dimensional (amplitude, frequency, and time) spectra (Fig. 3).

The HHT method overcomes some limitations of the wavelet transform, therefore has a higher decomposition precision relative to the wavelet decomposition. It has received wide attention, and been applied to meteorological field, etc. Gong et al. (2005) analyzed the similarity and difference of the EMD and the wavelet transform methods, and discussed the identification of false and real signals in the decomposed components by use of the two methods. Yang and Zhou (2005) decomposed the Nino3 sea surface temperature using the EMD method, and discussed the non-stationary behavior of the climate system in terms of the relations of various IMF components. Wan et al. (2005a) performed the Hilbert transform of the IMF components decomposed from the observed data

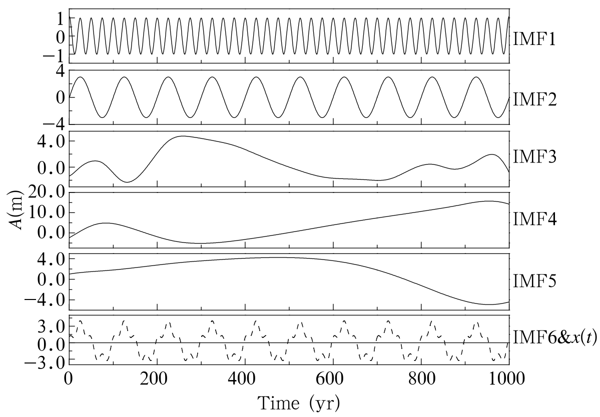

Fig. 2. First six IMF components based on the EMD for the Guliya ice core δ^{18}O time series. IMF1–IMF6 are named in order of the first six components. Solid/dashed lines in the IMF6&S panel are the IMF6 component/the original time series, respectively.

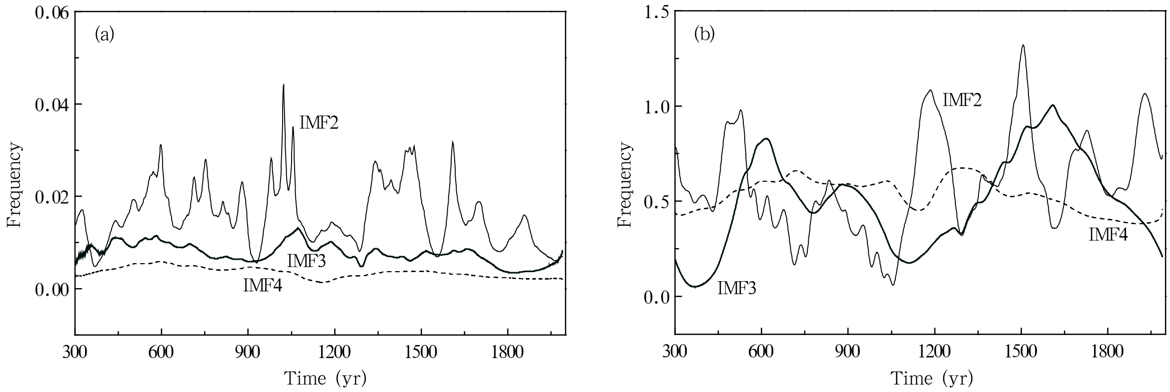

Fig. 3. (a) Time-frequency and (b) time-amplitude spectral structures of IMF2 (thin line), IMF3 (thick line), and IMF4 (dashed line).

using the EMD method, and obtained the transient frequency and amplitude of the IMFs (Fig. 2), and the three dimensional (amplitude, frequency, and time) spectra (Fig. 3). Then they used the mean generation function model to make the first prediction of various components and combined the optimal subset regression model to construct a new prediction model. Obviously, the contribution to the variance of the original series from each IMF component decomposed by the EMD method is different, and the intensity of the interaction between different climatic variables is also different. How to assess such differences using statistical methods is one of the problems that are eagerly concerned by researchers. Schreiber (2000) developed the transfer entropy algorithm, which is able to effectively assess the impact of two or multiple components on another component; under the present background of global warming, the algorithm is inspirable for discrimination between natural and anthropogenic change rates of climate change. Zhi et al. (2007) used the transfer entropy algorithm to analyze the possible impact of different scale systems in climate change on precipitation of China.

4. Complexity of the climate system

The climate system is undoubtedly a complex system, because it completely satisfies the six basic characteristics of complex systems (Lorenz, 1963, 1976): (1) the climate system consists of multiple subsystems, and the complex nonlinear and non-equilibrium interactions among the subsystems result in its nonlinear characteristics; (2) it is such a complex system where ordered, stochastic, and chaotic states coexist, showing diverse attributes; (3) it contains various time-space patterns showing obviously the hierarchic property; (4) it is highly sensitive to small disturbances in initial conditions, parameters, and the environment; (5) its overall behavior is not just simply related to its subsystems, which requires us to grasp its development trend on the whole; and (6) its basic dynamics reflects the statistical mean of properties of a large quantity of its subsystems and the various physical quantities representing its complexity, such as various meteorological variables, entropies, topological dimension, etc., also possess statistical property.

At present, there are many methods dealing with non-linearity and complexity, and previous studies on the non-linearity and complexity of the climate system can be classified into three types: (1) studies of the non-linear differential equations describing climate changes, (2) studies of continuous observational data, and (3) studies of discrete historical climatic category data. From the physical point of view, two most commonly used quantities for quantitatively describing the complexity of non-linear dynamic systems are fractal and Lyapunov exponent, which measure the regularity or complexity of the geometric structure of the phase space of non-linear dynamic systems, respectively. The entropy theory and methods (Excess entropy and Shannon entropy) are also used to investigate the statistical complexity and Kolmogorov complexity (David and Crutchfield, 1998; Zebrowski and Poplawska, 2000). However, the reliability of computed results are based on the assumption that the observed data are sufficiently long. Hao (1999) built the relation between motion orbit and formal language through symbolic dynamics, and depicted the complexity of non-linear dynamic systems in terms of grammatical complexity theory whose core content is coarse granulation. The coarse granulation of different extent neglects the details on smaller scale and highlights the intrinsic characteristic on the scale of interest. Sebastein and Zoltan (1999) pointed out that one should judge what function can be used as the symbolic complexity function of the series first, and then make sure of the relation between the complexity of the series and the associated dynamic system; if one gives a topological dynamic system or a dynamical system of measure theory (not necessary to be a symbolic system), a corresponding symbolic system can be established, and then under the adequate condition the complexity function of the system can be discussed.

Concerning the complexity of climate and environment evolution, Chen (1991) reviewed the complexity and systematicness of geoscience. Chou (1997) reviewed atmospheric non-linearity and complexity from combined phenomena and observation studies of many freedom systems on specific spacial and emporal scales, and revealed that the predictable period for the atmospheric motion on synoptic scale is less than 2–3 weeks; and except the chaotic component on the synoptic scale, there is also a stable component on the planetary scale, and the atmospheric complexity manifests in the non-linear interaction between the chaotic and stable components. In recent years, Kaspar and Schuster (1987) proposed the Lemper-Ziv complexity algorithm, which can measure the complexity of symbolic series of arbitrary finite length. By using the above algorithm, Hou et al. (2005) assessed the complexity of the proxy data series of the Guliya ice core and the stalagmite lamina thickness from the Shihua cave of Beijing and the time series generated by using the Lorenz model and logistic mapping, and further analyzed the complexity of the climate system using the numerical experiment of an ideal chaotic model and the proxy data.

The scale-free property of the climate system is achieved from complexity studies, which have just begun vigorously. Kiraly and Janosi (2002) analyzed the detrend daily temperature data at 16 stations in Hungary during 1951–1989 using the analysis of detrend fluctuation (DFA), and found that there is a better scaling law in the daily temperature from the statistical analysis of physical quantities evaluating temperature fluctuations. Peters (2002) defined rain rates and statistically computed the occurrence probabilities of various rains based on rainfall rates, and also found the scaling law characteristics in precipitation. Zheng et al. (2007) analyzed temperature and precipitation series using the DFA method, and discovered that the annual mean temperature and rainfall of Beijing can be both divided into multiple scaling invariant domains, and they showed the long range correlation in the specific scaling domain. Zhi et al. (2006) revealed the scale-free property of precipitation (Fig. 4) based on the daily rainfall data at 740 stations in China during 1960–2000, and discussed the spatial-temporal evolution characters of the scale-free property of rainfall and the possible impacts of different scale systems on the characters in terms of power-law tail exponent. Those studies to some extent indicated that the climate system is also characteristic of scale-free, a common attribute of non-linear complex systems, thus providing the theoretical basis for interannual and interdecadal climate forecasts.

Besides, the natural change rate and the increasing anthropogenic change rate greatly aggravate the complexity of the climate system itself, which gives rise to new requirement to the attribute study on the climate change and its external forcing signals. Allen and Tett (1999) proposed a new possible path for climate change research with multi-variant regression and optimal fingerprinting. Considering the fact that commonly used atmospheric circulation models are not able to simulate the impact of the small scale external forcing on climate changes, they estimated the possible impact of local external forecing on the general atmospheric circulation by employing the residual consistency test.

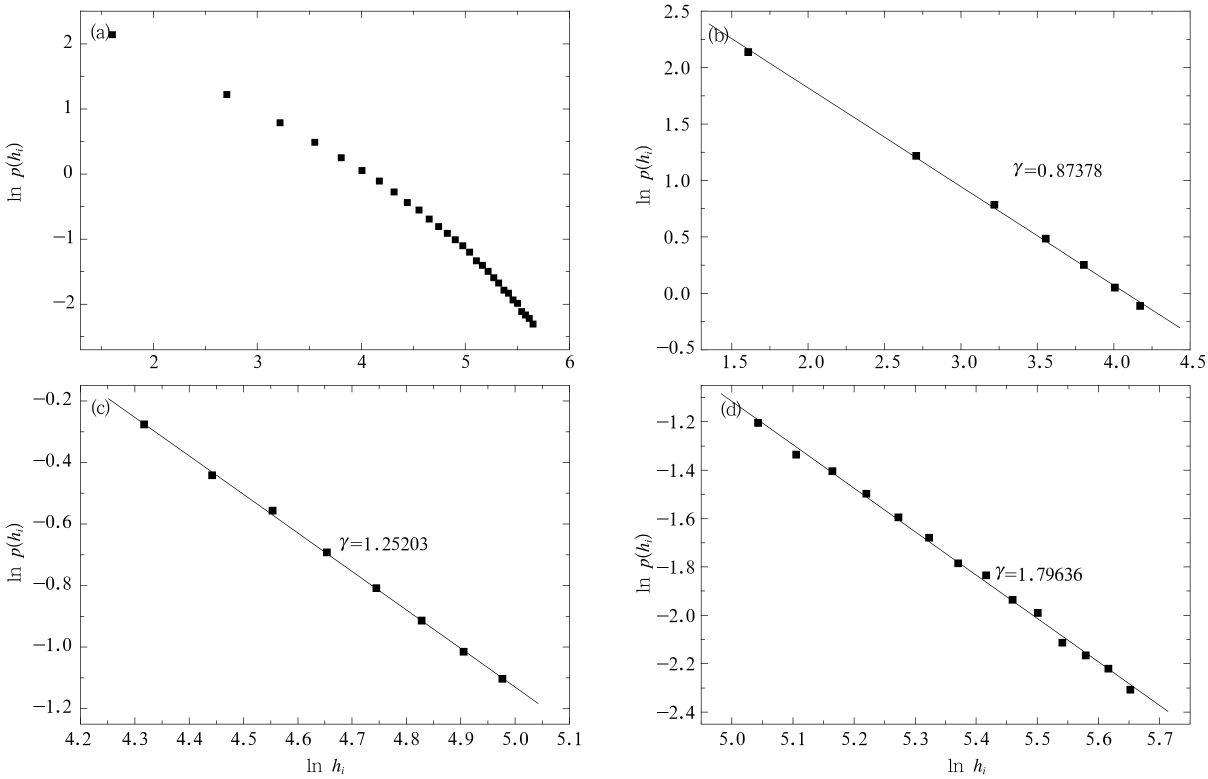

Fig. 4. Scale-free property of precipitation series at 435 stations in China during 1960–1969. (a) 0–29 mm, (b) 0–7 mm, (c) 7.1–15 mm, and (d) 15.1–29 mm.

Although complexity studies are still in a primary stage, the theories and methods of complexity science will provide new ideas and paths for global climate change research, and such a study is also of theoretical significance. To understand the nature of the complexity of the climate system from the angle of nonlinear dynamics is a frontier topic rapidly developing in the modern climate science field, and it has important scientific value and practical application perspectives.

5. Dynamic structure characteristics of the climate system

After the 1970s, Taken (1981) pointed out that the evolution of an arbitrary component of a system is determined by the other components that interact with it, therefore the signals of those related components are embedded in its development process. Packard et al. (1980) presented the idea of time lag to reconstruct the phase space of dynamic systems, which provides a possibility of studying the dynamic behavior of systems for researchers who cannot directly measure variables in depth of the system, but only know a set of time series of a single variable. For example, if the observational data of surface pressure are known, then part of the upper level information can be retrieved through the reconstruction of phase space using the surface pressure data, to remedy the deficit in upper level observational data. The basic idea of the reconstruction of phase space is that the information of related components of a system is embedded in the evolution process of the arbitrary component, and to reconstruct an equivalent state space, it is necessary to investigate only one component of the system. If one chooses the value of a certain variable along with time-delayed values (for example, one second before, two seconds before, and so on) of the same variable at some fixed time-lag points as phase-space coordinates, then those coordinates determine a point in a multi-dimension state space; repeating this process and measuring different time delayed values yield many such points, and then some other methods are used to test whether those points exist in an attractor or not. After the phase space reconstruction, some invariant quantities, such as fractal, Lyapunov exponent, etc., still remain. Through the phase space reconstruction of a time series with chaotic characteristics, one can obtain a low-dimensional nonlinear system, which is the first step in the analysis of a nonlinear time series, and the reconstruction quality directly impacts the subsequent modeling and prediction. The two important parameters in phase space reconstruction are time-delay τ and embedding dimension m; the adequate value of τ can be determined using many methods, such as the self-correlation function method, the mutual information function, the periodic orbit method, etc.

Li and Chou (1997) explored the theory for determining attractor dimension using the phase space reconstruction of a one dimensional time series. They found the essential problem in the construction, and demonstrated the existence of attractor in the atmosphere from the angle of the phase space theory. Climate dynamic studies suggest that climate behavior on a longer time scale can be described with a few of freedoms; however, on the other hand, the Navier-Stokes equation describing the atmospheric motion is difficult to be simplified, even only for long range climate evolution, due to the existence of interactions between different scale systems. Therefore, pure dynamic equations and traditional statistical methods are not enough for analyzing the climate dynamics on long time scale. In recent years, regarding the dynamic structure analysis of time series, Bezruchko et al. (2001) proposed a method that allows one to estimate the parameters of model scalar time-delay differential equations from time series based on a statistical analysis of time intervals between extrema in the time series. Sun and Liu (1999) divided a tropical cyclone into two parts: an inner region and an outer region, and by using the scale analysis and the perturbation method they obtained different governing equations for motions in the two regions: a cyclostrophic balance relation, an evolutional equation for the inner region, and a gradient wind relation and another evolutional equation for the outer region, respectively. To effectively diagnose the dynamic structure of chaotic

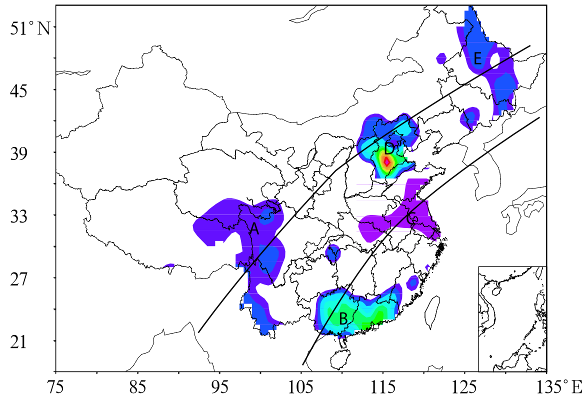

Fig. 5. Five dynamical climate characteristic regions: A for Qinghai-Tibet Plateau pattern, B for South China pattern, C for Jianghuai pattern, D for North China pattern, and E for Northeast China pattern.

time series, Feng et al. (2005) introduced a new analysis method: dynamic self-correlation factor exponent Q (Q exponent), which is able to sensitively identify the nonlinear dynamic structure of stochastic and chaotic time series and is suitable for time series of relatively short length and smaller scale. By using the Q exponent, they analyzed the dynamic mechanism for anomalous summer climate in the late 1970s in China and its relation with the Indian-East Asian teleconnection (IEA) wave-train (Fig. 5). They also analyzed the regional dynamic characteristics of summer monsoon precipitation in China and their responses to external physical factors. Besides, Wan and Feng (2005b) investigated dynamic characteristics of the time series of the proxy data of the Northern Hemispheric tree ring width anomaly and the Shihua cave stalagmite laminar thickness in Beijing (Fig. 6), and found that both of them have similar dynamic evolutional structures, i.e., whether for regional or global climate, there existed two abrupt changes in dynamic structure during A.D. 700–900 and 1300–1700, which might correspond to the medieval warm and the modern little ice age events.

6. Detection of extreme climate events

Under the background of the global warming, how will the frequency and intensity of extreme climate events change becomes an issue widely concerned since

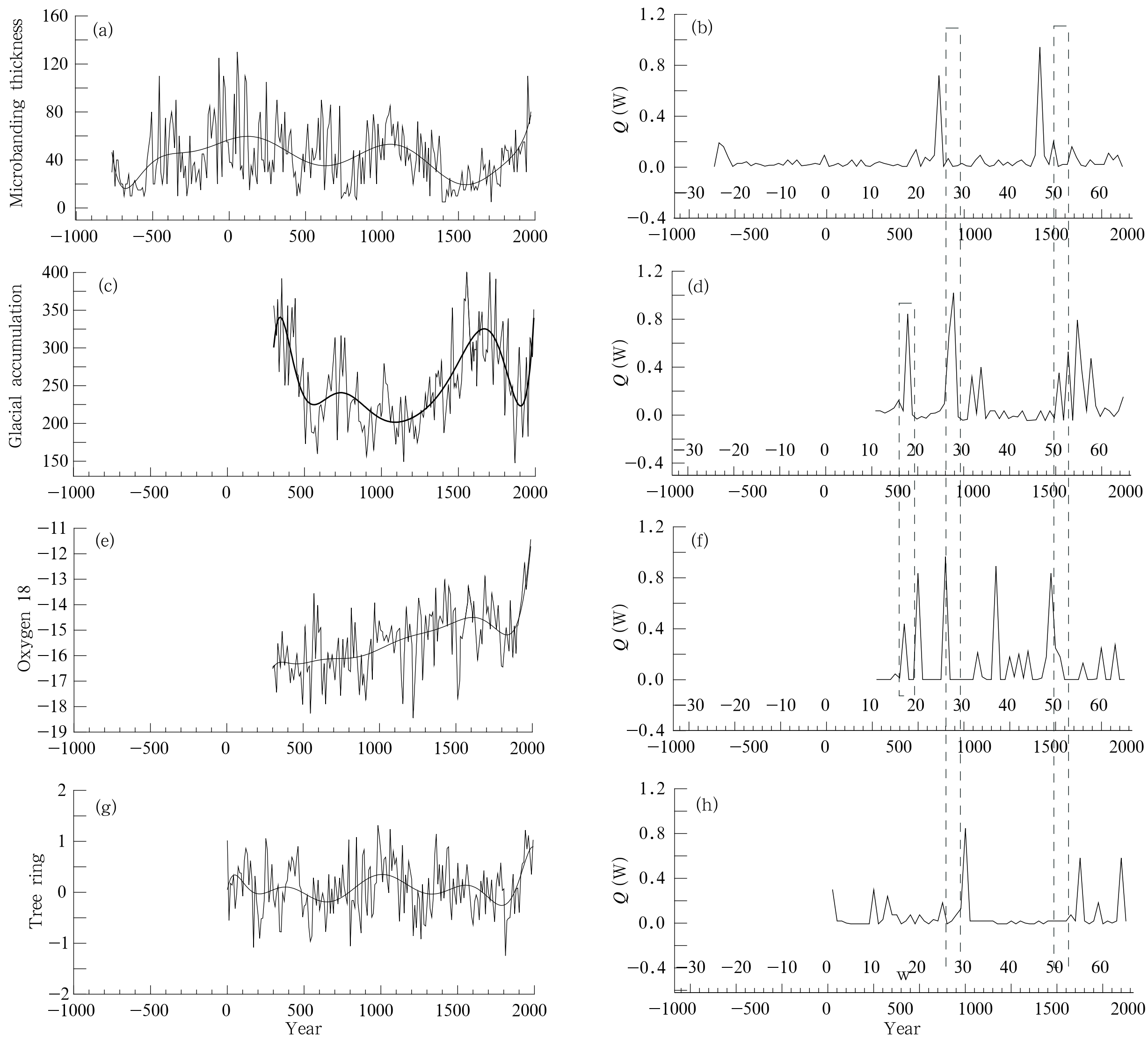

Fig. 6. Q exponent of important climate events in the Medieval Warm Period and Modern Little Ice Age. Time series for (a) Beijing Shihua cave stalagmite laminar thickness (BC 768–1980) and (b) its Q exponent; (c) Guliya glacier core (301–1980) and (d) its Q exponent; (e) Guliya ice core δ^{18}O (301–1980) and (f) its Q exponent; (g) Northern Hemispheric tree ring (1–1995) and (h) its Q exponent.

the Second Assessment Report (SAR) of IPCC. Karz and Brown (1992) considered that extreme climate events are more sensitive to climate change than to climate mean state. Different from changes in climate mean state, any changes in frequency or intensity of extreme climate events may severely impact the nature and the human society.

Easterling et al. (2000) classified extreme climate events into two categories: one is simply based on climatological statistics, and those events occur every year, such as very high/low daily temperature, and heavy daily or monthly rainfall; the other category is more complicated and directly determined by whether the events occur or not, such as floods, typhoons, etc., and such events do not always happen at a given site for each year. Beniston et al. (2007) summed up three standards of commonly used extreme event definitions: 1) events with a relatively low frequency; 2) those with relatively large or small intensity value; and 3) those leading to severe losses of social economy. Both the Third and Fourth Assessment Report of IPCC (TAR and AR4) clearly defined extreme weather-climate events as those at a small probability for a given place and time, with its frequency number only accounting for 10% or even less of the weather phenomenon (Houghton et al., 2001; IPCC, 2007). In view of such a definition, characters of extreme weather events are variable with location; and extreme climate event is a mean state of a large number of extreme weather events for a given time period, and it is also extreme relative to the climate state of the category of weather phenomena. Viewed from the angle of climate research, the definition of extreme events by TAR and AR4 only involves the probability of the events, thus avoiding the problem that differences in the absolute intensity of events at different places are important, and it can be hardly used as a uniform standard in comparison of events between different areas.

There are generally two methods, i.e., the direct and indirect analysis methods, for analyzing and studying the change characteristics of extreme events. In the direct method, one analyzes the original observation data and determines the frequency and intensity changes of a weather phenomenon according to the definition of the phenomenon (such as tropical cyclones), and in the indirect method, one define the climatic indices of proxy data which are close associated with extreme events, then analyzes the characters of climate indices to reveal changes in the extreme events. Expert Team on Climate Change Detection and Index (ETCCDMI) defined 27 proxy climatic indices concentratedly for describing extreme climate events, including 16 temperature indices and 11 precipitation indices, and those indices were obtained from daily maximum, minimum, and average temperatures or daily rainfall. Kiktev et al. (2003) sorted those indices into five categories: 1) relative indices based on percentage thresholds; 2) absolute indices representing the maximum/minimum value for some month or some year; 3) threshold value indices of day number for temperature and rainfall greater than or less than some fixed threshold; 4) duration indices for excessive cold, warm, dry, or wet duration or growth periods relative to the length of the growing season; and 5) other indices, including annual total rainfall, daily temperature range, average rainfall rate, differences in extreme temperatures, and yearly ratio of extreme rainfall to the total rainfall.

There are many methods for detecting extreme climate events. The most commonly used methods are the absolute threshold method and the percentile threshold method. In the absolute threshold method, one first sets a threshold value, and a value greater than the threshold is called a extreme value. In the percentile threshold method, some fixed percentile value is taken as the threshold value of extreme values, a value exceeds the threshold is to be considered as a extreme value, and called a extreme event. In determining the percentile value of a climate element, one is generally required to know the probability distribution function of the element or to assume some probability distribution function of the elements, then a formulation easy to operate is given based on statistical and probability theory knowledge. Zhai and Pan (2003) investigated the extreme temperature and rainfall in northern China in 1951–1999 using the above two detecting methods, and found that the frequencies of warm days/nights were increasing, the frequency of cold days, especially cold nights, was obviously reducing; and the frequency of extreme rainfall events was remarkably increasing in western China and the middle and lower reaches of the Yangtze River, but obviously reducing in North China, and further more in those areas the extreme rainfall and mean rainfall showed consistent trends. Gong and Han (2004) discovered that the frequency of extreme high/low temperature distinctively increased/decreased in North China in 1956–2001. Based on the observational data in China in 1961–2001, Wang and Zhou (2005) found that the frequency of extreme rainfall events exhibited an increasing trend in Southwest China, the north of Northwest China, and East China, and a reducing trend in North China and Central China, and the spatial pattern of those trends of extreme rainfall is also consistent with that of mean rainfall. Qian and Lin (2005) calculated various threshold indices of precipitation, such as the percentage, intensity, and duration, from the rainfall data at 494 stations in 1961–2001, and found that the frequency of droughts increased in the Yellow River basin and North China; and the frequency of heavy rain events increased in Xinjiang and Southeast China including the middle and lower reaches of the Yangtze River.

The inclusion of extreme events, i.e., extreme values, in calculating mean-value in the percentile threshold method to some extent conceals the real information of the system background, thus possibly leading to the failure of detecting some extreme events. Therefore, Zhang and Qian (2008) analyzed the daily and monthly temperature data at 194 stations in China in 1957–2001 using the median and mean-value detection methods for extreme events, respectively. Comparing the results from the two methods, they found that in the past 50 years or so, the averaged yearly number of extreme low temperature events generally tended to decrease in most areas of China except part of Southwest China, while the frequency of extreme high temperature events displayed a spatial pattern of decrease in the southeast coastal region and increase in the inland of Northwest China (Fig. 7). Meanwhile, they also discussed the possible association of changes in the frequency and intensity of extreme events with the abrupt change of climate in the middle and late 1970s: the time of the abrupt change in extreme high/low temperature was 3–4 yr later than that of temperature abrupt change, that is to say, the abrupt change process of temperature may be a evolutional process of extreme temperature from a relatively stable state to another stable state (Fig. 8). With regard to studies on the possible relation between natural/anthropogenic change rates (factors) and extreme climate events, at the present time the numerical experiment of

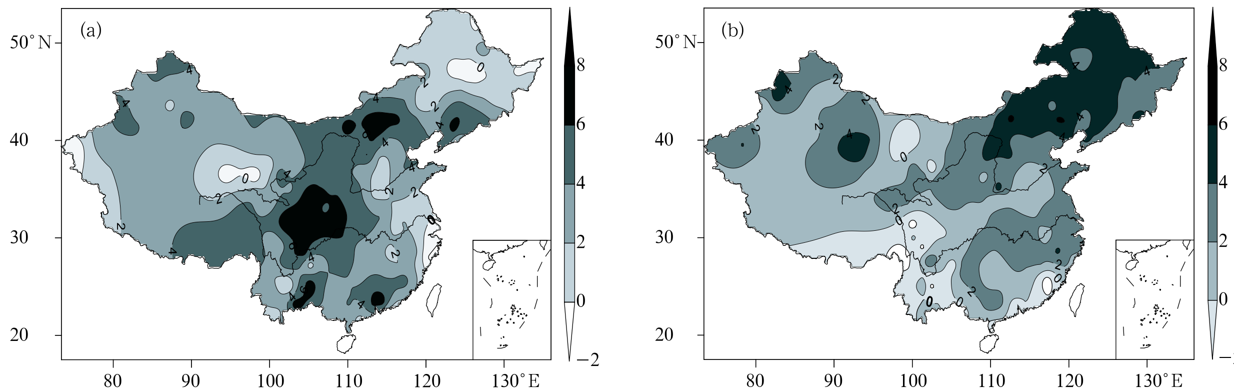

Fig. 7. Differences in annual mean extreme high/low temperature event numbers detected by (a) the median method and (b) the average method from the daily and monthly temperature data at 194 stations in China from 1957 to 2001.

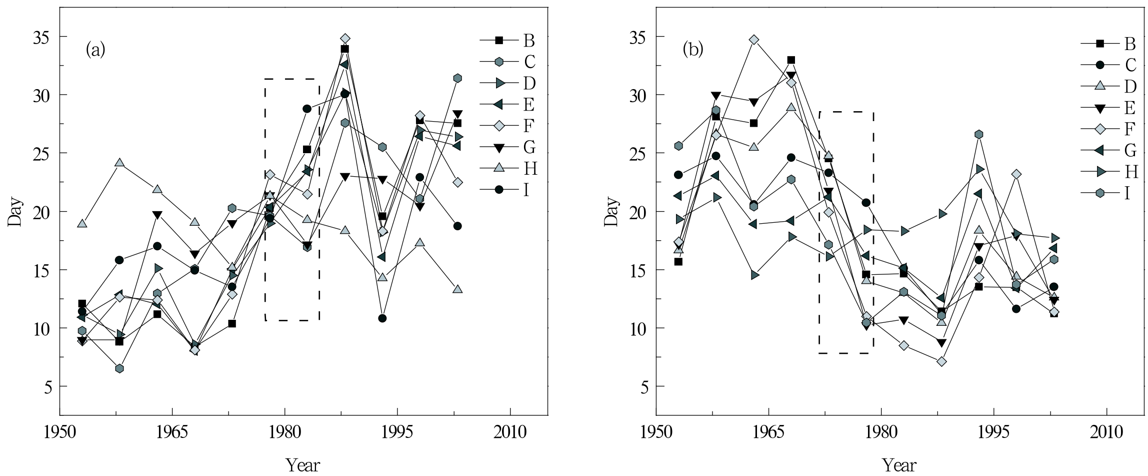

Fig. 8. Frequency changes per five years in extreme high/low temperature of eight climate characteristic regions (B-I) in China. Dashed-line boxes denote the abrupt change periods of annual mean temperature, i.e., the transition periods of the abrupt changes of (a) the extreme high and (b) low temperature, respectively.

models aiming at a special impact factor is mostly used in overseas, for example, Karoly and Wu (2005) comparatively analyzed temperature change trends 30-, 50- and 100-yr scale and their possible responses to the forcing of greenhouse gases and sulfate aerosols using the GFDL R30, HadCM2, and PCM models.

7. Summary and discussion

The climate system is the result of interactions among the internal physical processes in the atmosphere-oceansphere-cryosphere system, Its influential space is wide and its time scale is multiple. Meanwhile, there are positive/negative feedbacks to different extent among its subsystems. Various climate element observation series, as a manifestation of the intrinsic complexity of the climate system, possess nonlinear and nonstationary characters. Therefore, choosing adequate statistical methods, dynamical methods, or statistical-dynamical methods is critical for the detection and analysis of the observed series.

This paper introduces recent advances in the detection technique of climate change and part of the results of our research group in the five aspects: detection and study of abrupt climate change, complexity research of the climate system, dynamic structure characteristics of the climate system, and detection of extreme climate events. Obviously, scientific issues in these aspects are hot topics in the climate change research, and constitute the contents of several important research programs, such as the Major State Basic Research Development Program, the Northern China Desertification and Human Adaptation Project, the National Science and Technology Support Program, Monitoring, Forecast and Adaptation for Major Extreme Weather-Climate Events and Meteorological Disasters, etc. Therefore, the detection methods for these scientific issues are receiving more attention.

Although some achievements have been made in the detection technique of climate change, at present there are still some difficulties and cruxes to be overcome. For example, climate observation series are nonlinear and chaotic, but many presently used detection methods are based on the idea of traditional linear processes. Since the 1970s, some nonlinear detection methods, such as Lyapunov exponent, complexity, entropy, etc., have appeared, but they still have certain limitations. Under the background of the global warming, the climate data displayed some new characters. How to improve and perfect the climate change detection theory and methods is a problem remained to be further studied. Besides, traditional detection techniques are mostly statistical methods, while the various present climate models are based on dynamic processes, therefore, how to combine statistics with dynamics in developing new statistical-dynamic methods is obviously of significance. At last, as to detection and simulation of extreme events, influence and possible external forcing of climate change, identification of natural and anthropogenic change rates of climate change, and judgement of analog fields of climate elements, some new mathematical-physical methods, such as median algorithm, optimal fingerprinting, empirical mode decomposition, complex network theory, etc., have appeared overseas. These methods provide new thinking lines for studies on climate change and its attributes, but they are relatively less used in China. In the subsequent works, we will introduce these methods in detail, discuss their usefulness using numerical experiments, and apply them to the detection of climate change in China.

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