Vol 17 No 6, June 2008
1674-1056/2008/17(06)/2311-06

Chinese Physics B

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Detection and attribution of abrupt climate changes in the last one hundred years*

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(Received 15 October 2007; revised manuscript received 29 December 2007)

Based on physical backgrounds, the four time series of the Guliya (Tibetan plateau) ice core (GIC) δ^{18}O, and three natural factors, i.e. the rotation rate of earth, sunspots, and El Nino–Southern Oscillation (ENSO) signals, are decomposed into two hierarchies, i.e. more and less than 10-year hierarchies respectively, and then the running t-test is used to reanalyse the data before and after filtering with the purpose of investigating the contribution of natural factors to the abrupt climate changes in the last one hundred years. The results show that the GIC δ^{18}O evolved with a quasi-period of 7–9 years, and the abrupt climate changes in the early 1960s and in the period from the end of the 1970s to the beginning of the 1980s resulted from the joint effect of the two hierarchies, in other words, the two interdecadal abrupt changes of climate in the last one hundred years were global. The interannual variations of ENSO and sunspots were the important triggering factors for the abrupt climate changes in the last one hundred years. At the same time, the method of Information Transfer (IT) is employed to estimate the contributions of ENSO signals and sunspots activities to the abrupt climate changes, and it is found that the contribution of the interannual variation of ENSO signals is relatively large.

Keywords: abrupt climate change, time series analysis, running t-Test
PACC: 9260X

1. Introduction

The applying of concept and theory of abrupt change is a young research direction of modern climatology, especially in studies of climate change.[1−8] The so-called 'abrupt climate change' refers to the phenomenon in which the climate jumps from a stable state to another one. There exist instability and abrupt changes in climatic variations on various timescales, for the complex interactions of climate system lead to the transition of different climate states. The spatial distribution of climate is a specific climatic characteristic of the climate system rather than an arbitrary combination of various station-based data, and it depicts the evolution of climate system at a certain climate level, which according to the point of view of modern dynamic system, might evolve into a certain attractor (equilibrium point, limit cycle, and chaos), or tend to infinity. The latter circumstance is meaningless for a specific physical system, because for climate and temperature their approaching to infinity acts against the principle of energy conservation. Therefore, the state or scenario of climate system must approach to a certain attractor. Projection of the scenario space of the attractor is the 'attractor' of climate scenarios. The so-called 'abrupt change of the system state' in fact refers to the state of system that no longer approaches to the original attractor, but to a new one. This could happen under two circumstances: one is the internal mechanism or relation of system changes, causing the original attractor to disappear (or become an unstable attractor) and bifurcate into a new attractor, and the other is the disturbances of system state which are so large that the state is forced

*Project supported by the National Natural Sciences Foundation of China (Grant No 40675044) and the State Key Development Program for Basic Research (Grant No 2006CB400503).
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to leave the basin of original attractor and arrive at the basin of a new one, but the structure of the system is still stable. In a word, the abrupt change corresponds to the change in the attractor to which the state of system approaches. Obviously, if climate does not change, the scenario of climate should oscillate in the vicinity of a certain scenario attractor.

Evidently, for national economy it is of significance to find the mechanism for the transition and abrupt changes of climate state, and to predict the turning and abrupt changes of climate. Observational facts suggest that abrupt climate change possesses a complex spatiotemporal distribution on multiple scales. The jump of climate state exists in a wide range of time domain on seasonal, interannual, decadal, centurial, or even geological timescales; therefore it is a general phenomenon in climate changes on various timescales. However, the turning and abrupt changes of climate arise from the complexity of nonlinear climate system, and up to now, the abrupt change theory has remained to be further developed and improved, thereby the study on the detection and the attribution of the climate change based on physical backgrounds especially in the last one hundred years is of importance for disaster prevention and mitigation as well as for food security.

The climate system is a typical non-stationary, nonlinear, forced, and dissipative open system, and its multiple hierarchical structures have been recognized and understood in the last 10 years. In fact, the multiple hierarchical structure of climate system is the cause for its non-stationary behaviours, while the non-stationary characteristic of the system is indicative of the hierarchical structure. Based on the hierarchy theory, the four time series of the Guliya ice core (GIC) δ^{18}O[9,10] and natural factors, i.e. the rotation rate of earth, sunspots,[11] and ENSO signals[12] in this paper are decomposed into two hierarchies, i.e. more and less than 10-year hierarchies in the context of physical meaning, and then the running t-test is used to analyse the original time series and the two hierarchical time series and compare the former with the latter, to explore the mechanisms of climate change, and especially to investigate the contribution of natural factors to the abrupt climate change in the last one hundred years.

2. Data and method

2.1. Data

The ice core δ^{18}O is a reliable indicator of precipitation.[9,10,13] This paper is devoted to the detection and the attribution of climate changes in the last one hundred years, and on other hand, the natural factor data are limited, therefore the four time series of GIC δ^{18}O, the rotation rate of earth, sunspots, and ENSO signals in the years from 1900 to 1990 within an annual resolution are used to investigate their respective contributions to the abrupt climate changes.

2.2. Running *t*-test

Running t-test is a statistical method to detect abrupt change through examining whether the difference in mean value between two groups of samples is significant. If the difference in mean value between the two sub-series of one time series is significant at more than a certain confidence level, then it is considered that the mean value has had an abrupt change. For a time series with the volume of n $\{X_i,\ i{=}1, 2, \cdots, n\}$, we select a certain time as a cutting point before and after which x_1 and x_2 sub-series are obtained, and define statistic t as follows:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{s.\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}}, \tag{1}$$

where $s = \sqrt{\dfrac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}$, n_1, n_2 are sample numbers, $\bar{x}_1$, $\bar{x}_2$ mean values, and s_1^2, s_2^2 variances for the sub-series before and after the cutting point, respectively. Statistic t is subjected to the t-distribution with the freedom degree of $\gamma = n_1 + n_2 - 2$. The limitation to the method is lacking of a definitive criterion in selecting the lengths of sub-series. In general, the length of two sub-series is equal to each other, i.e. $n_{1=}n_2$.

3. Information transfer (IT)

Consider interacting sub-systems of a system X, Y, and Z, visiting states x_i, y_i, and z_i with probabilities $p(x_i)$, $p(y_i)$, and $p(z_i)$, respectively. Recently,

Verdes[14] presented the concept of information transfer (IT) to assess the relative influences of Y and Z on X. The information transfer from Y to X is defined as

$$\mathrm{IT}_{Y\to X} = \frac{1}{N}\sum_i p(x_i,y_i,z_i)\log\frac{p(x_i|y_i,z_i)}{p(x_i|z_i)}. \qquad (2)$$

Unlike mutual information or conditional entropy, it is essentially asymmetric in X and Y, non-static, and detecting the directional transport of information. The sign $p(\cdot|\cdot)$ in expression (2) denotes the transition probabilities, $p(x_i|y_i,z_i) = p(x_i,y_i,z_i)/p(y_i,z_i)$ and the latter can be approximated by the visitation frequency i.e. $p(\varepsilon_x,\varepsilon_y,\varepsilon_z)/p(\varepsilon_y,\varepsilon_z)$, and N is the length of the available database. In the computation of the influence of Y on X, ε_x among three scale control parameters ε_x, ε_y, ε_z is fixed, i.e. $\varepsilon_x = \varepsilon$, and $p(x_i|y_i)$ is thought of as a function of ε_y only, then a possible option is given by

$$\varepsilon_y = \arg\max p(x_i|y_i).$$

And along the same lines, ε_z can be determined also by $\varepsilon_z = \arg\max p(x_i|y_z)$. The relative influence of subsystems Y and Z on subsystem X could be measured with the integration areas of $\varepsilon_x \cdot \mathrm{IT}_{Y\to X}$ and $\varepsilon_x \cdot \mathrm{IT}_{Z\to X}$ respectively.

The results in Ref.[14] shows that $\mathrm{IT}_{*\to X}$ is unaffected by noises, and has a strong ability to prevent interferences. It is suitable for analysing observed sequences without the limitation to the sequence length, and it is also able to analyse relatively short sequences, even much shorter than what is needed for calculating the sum of incidence. Its advantage is that it is essentially asymmetric, and able to detect the transferring direction of interaction between subsystems.

4. Results and discussion

4.1. Detecting results of the GIC δ^{18}O

The filtering method used here was put forward by Zheng and Dong,[15] in which the separation of high frequency from low frequency is realized by a multistage filter with a very narrow filtering band. Rasmusson *et al*,[16] Wang and Ropelewski,[17] and Shi *et al* [18] used the method to obtain the mean value of sea surface temperature of the slow-varying process that took more than 30 years. Its most appealing feature is that the length of filtered series is the same as of the original series.

This paper employs Zheng and Dong's filtering method to divide the GIC δ^{18}O into two hierarchies, i.e. more and less than 10 year hierarchies, and for convenient narration the original series of GIC δ^{18}O, and the two hierarchies are hereafter denoted with O series, and H and L hierarchies, respectively. Figure 1 displays their temporal evolution. According to running t-test, $n_1 = n_2$=5 are adopted for O series and L hierarchy, and $n_1 = n_2$=10 for H hierarchy, and α=0.01 for the significance level. Figure 2 exhibits the results from the running t-test.

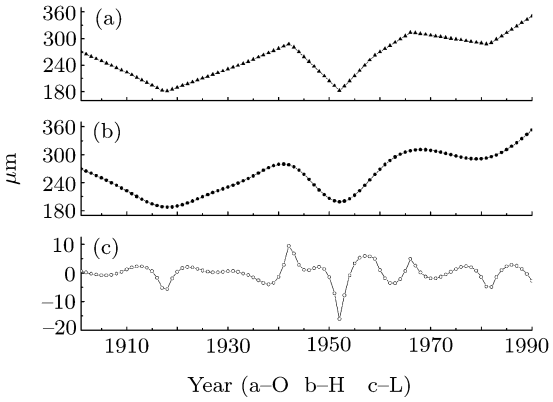


Fig.1. Temporal evolutions of O (a), H (b), and L (c) series.

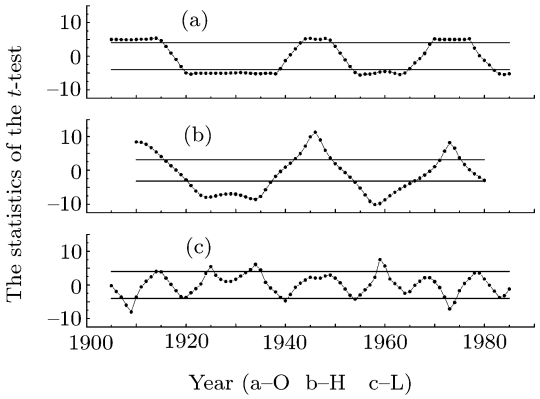


Fig.2. Running t-test of the GIC δ^{18}O series.

It is found from Fig.2(a) that the GIC δ^{18}O series abruptly change in the years of 1905, 1914, 1921, 1938, 1945, 1956, 1963, 1970, 1977, 1984 etc, showing a quasi-period of 7–9 a. H hierarchy displays the abrupt change years of 1910, 1934, 1946, 1958, 1973

(Fig.2(b)), while L hierarchy exhibits different information, i.e. abrupt change years of 1909, 1925, 1934, 1940, 1954, 1959, 1973(Fig.2(c)). It is known from comparing and analysing the detecting results of H and L hierarchies that H and L hierarchies make dominant contributions to the abrupt climate changes of 1914, 1945/ 1905,1921, respectively, while H and L hierarchies jointly contribute to the abrupt change years of 1938, 1956, 1970, and 1977. Meanwhile, we also notice that the abrupt climate changes in the early 1960s and in the period from the end of the 1970s to the beginning of the 1980s might result from the joint effect of the two hierarchies, in other words, the two interdecadal abrupt changes of climate in the last one hundred years were global.

4.2. Attribution of abrupt climate changes

In a way similar to that in Section 4.1, the rotation rate of earth, sunspots, and ENSO signals (lengths of three series are all 91 from 1900 to 1990) are also decomposed into two hierarchies i.e. more and less than 10 year hierarchies, and their abrupt change years obtained by running t test (for the rotation rate of earth, and sunspots) and criterion (the absolute value greater than 1.0) method (for ENSO signals) are listed in Table 1. For convenience, the more and less than 10 year hierarchies of the rotation rate of earth, sunspots, and ENSO signals hereafter are denoted with H_E, L_E , H_S, L_S, H_{EN}, and L_{EN}, respectively.

Table 1. Abrupt change years for the rotation rate of earth, sunspots, and ENSO signals.

rotation rate of earth	H_E	1919	1940	1951	1964	1980								
	L_E	1904	1909	1923	1928	1933	1983	1989						
Sunspots	H_S	1914	1933	1944	1968	1980								
	L_S	1903	1927	1935	1940	1946	1954	1960	1967	1978				
ENSO	H_{EN}	none												
	L_{EN}	1905	1910	1914	1919	1938	1941	1950	1955	1969	1972	1975	1982	1987

For the time interval of about one hundred years, because the ENSO signal is generally a non-periodic oscillation within 2–7 years, none of interdecadal change rates detected is understandable. It is known from a comparison between Fig.2(a) and Table 1 that the abrupt change in 1905's O series might result from the joint effect of L_E, L_S, and L_{EN} factors, that is to say, the 1905's abrupt change is determined jointly by three natural factors on the timescale of less than 10 years. Analysis of other abrupt change years is similar to that for the year 1905, and Table 2 lists their attribution analysis results.

Although the cause of abrupt climate change is very complicated, i.e. some originate from natural factors, and some from human activities, and the climate system has an internal motion law of its own, it is easy to find from the attribution analysis in Table 2 that among nine times of abrupt changes of the O series detected by running t-test (confidence level α=0.01), the eight times except that in 1963 are associated with ENSO signals (L_{EN}); and six times with the sunspot activities of a less than 10-year period, and only the 1914, 1970, and 1977 abrupt changes with sunspot activities of a more than 10-year period although the sunspot, as is well known, has the quasi-periods of 11 and 22 years. Because the rotation of earth is a motion on a large scale, it has made almost no contribution to the abrupt change of O series since the 1960s.

Table 2. Attribution analysis (AA) of abrupt climate changes (ACC).

ACC of O series		1905	1914	1921	1938	1956	1963	1970	1977	1984
AA	Earth	L_E	—	H_E/L_E	H_E	—	H_E	—	—	—
	Sun	L_S	H_S	—	L_S	L_S	L_S	H_S/L_S	H_S/L_S	—
	ENSO	L_{EN}	L_{EN}	L_{EN}	L_{EN}	L_{EN}	—	L_{EN}	L_{EN}	L_{EN}

To sum up, for the abrupt climate change in the last one hundred years, our attention is paid to the contribution of ENSO signals and sunspots, especially the sunspot activities with a timescale of less than 10 years (Table 3), to all the abrupt changes except that in the year of 1909 of the less than 10-year hierarchy of the GIC δ^{18}O series. Therefore for climate changes, especially for time domain of about one hundred years, it is insufficient for us to pay attention only to the 11 and 22 quasi-periodic activities of sunspots, we must pay more attention to and strengthen the study on the influence of the interannual activity of sunspots. Besides, we have also compared and analysed the detecting results of sunspot activity H_S and the H hierarchy of GIC δ^{18}O series, and found that they have a good corresponding relation between before the 1960s and after the 1980s. In order to analyse the relative influence of ENSO signals and sunspot activity on climate change the IT method has been used to judge the dominance and submission of natural factors, i.e. the dominant factor.

Table 3. Corresponding relations between the detected abrupt change years for sunspot L_S series and the L series of the GIC δ^{18}O.

Year	1909	1925	1934	1940	1954	1959	1973
Sun	—	L_S	L_S	L_S	L_S	L_S	L_S

4.3. Dominance and submission of natural factors

Figure 3 displays the information transfer from ENSO signals and sunspots (Fig.3(a)) and their more (Fig.3(b)) and less (Fig.3(c)) than 10-year hierarchies to the GIC δ^{18}O, and the information transfer, whether it comes from the original ENSO series or from its more than 10-year hierarchy to the GIC δ^{18}O, is far greater than the counterpart from sunspots, thus indicating that the ENSO signal exerted a dominant influence on the abrupt climate changes in the last one hundred years. However, the computational results (Fig.3(c)) of the information transfer from the interannual (less than 10-year) variation of sunspots to the GIC δ^{18}O suggest that the influence of the interannual change of sunspots is also not neglectable.

In summary, the GIC δ^{18}O series possessed a quasi-periodic evolution feature of 7–9 years, and abrupt climate changes in the early 1960s and in the period from the end of the 1970s to the beginning of the 1980s resulted from the joint effect of the two hierarchies i.e. more and less than 10-year hierarchies, in other words, the two interdecadal abrupt changes of climate in the last one hundred years were global. The research of detection and attribution of the abrupt climate changes in the last one hundred years suggests that the abrupt change of the GIC δ^{18}O series had a close corresponding relation with one of the interannual timescale of ENSO signals and sunspots. The hierarchical attribution study shows that the contribution of the periodic changes of quasi-11 and 22 years of sunspots to abrupt climate changes in the last one hundred years is not evident. Application of the IT method, which is a latest achievement of nonlinear sciences in time series analyses, to the GIC δ^{18}O, rotation rates of earth, sunspots, and ENSO signals reveals that the interannual variation of ENSO signal and sunspot played an important role in triggering the abrupt change of the GIC δ^{18}O, and the ENSO signal exerted a dominant influence on the abrupt climate changes in the last one hundred years.

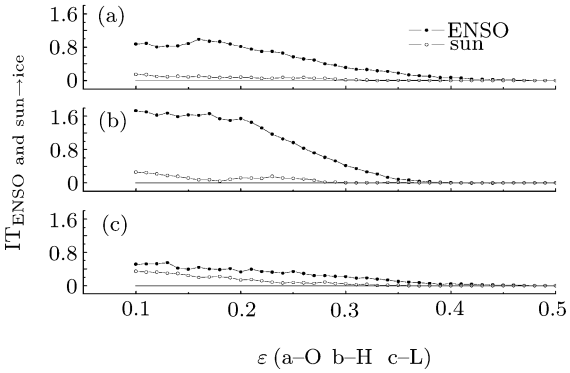


Fig.3. IT from ENSO signals and sunspots to the GIC δ^{18}O.

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