Quasi-periodicity of temperature changes on the millennial scale*

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Abstract Quasi-periodicity of temperature changes on the millennial scale is found according to the proxy data both from historical documents and natural evidence in China. The auto-correlation of the temperature changes series for the last 2000 years is most significant on the 1350 a time lag. The period of 1350 a includes 4 warm/cold stages: 200～250 a warm stage, 150～200 a cold stage, 300～350 a warm stage, and 550～600 a cold stage. In contrast to the 550～600 a cold stage, the other three stages can be united in one warm dominant stage. Inferred from the 1350 a period, the 20th century warm stage belongs to the 200～250 a warm stage, which is similar to the warm stage occurring during the 570's～770's. The process of temperature change in the 20th century warm stage is similar to that of the 570's～770's. But the warming rate in the 20th century is more rapid. The temperature anomaly in the 1980's～1990's shows a greater departure from the regression equation of that between 1500's～1900's and 150's～650's. Whether it can be regarded as the forcing of human activities is worth studying further.

Keywords: quasi-periodicity, temperature change, millennial scale, the period of 1350a.

Climatic changes on the decade to century scales are highlighted by the global change research[1]. Climatic changes are the overlap of periodic changes on different time scales. So the changes on the millennial scale are essential to the understanding of the climatic changes on the decade to century scales. Till now, the climatic periodicity on the millennial scale has been less studied as compared with the periodicity on other time scales because the length of the series with a high resolution is too short to cover a thousand years, and the resolution of longer series is too low. Recently, the existence of the 1450～1500 a period has been reported according to the evidence of ice core records and deep-sea sediments mainly from the GISP2 and GRIP ice cores in Greenland, ice core at the Orient Station in Antarctica, sediments in the North Atlantic Ocean and sediments in the Arabian Sea. The period is explained as the response of the millennial period forced by the harmonic period of precession period, the thermohaline circulation of ocean, activities of the sun, and so on[2～7]. However, such a period is less reported from the evidence on lands.

Recently, the quantitative series of the winter-half-year temperature in eastern China over the past 2000 years in 10～30 years resolution was reconstructed, mainly based on the phenological records and the other proxy data with cold/warm description extracted from Chinese historical documents[8,9]. The warm/cold stages on century scale during the past 3000 years were also reconstructed based on the natural proxy data that are able to clearly indicate cold/warm changes, fairly dating, and less affected by human activities[10]. Based on the above work, quasi-periodicity of temperature changes on the millennial scale is discussed in this paper.

1 Quasi-periodicity on the millennial scale indicated by the century scale warm/cold stages

According to the 30-year resolution temperature anomaly series of winter-half-year in eastern China, the temperature changes during the last 2000 years could be divided into seven warm-cold stages that lasted more than 100 years. Among the seven stages, there are four warm stages whose temperatures are higher than the average value from 1951 to 1980: 0's～200's, 570's～770's, 930's～1310's and since the 1920's; there are three cold stages whose temperatures are lower than the average value from 1951 to

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1980: 210's ~ 560's, 780's ~ 920's, 1320's ~ 1910's. Moreover, each warm/cold stage also includes obvious warm or cold phases, especially in the warm stage during 930's ~ 1310's, a cold valley in 1110's ~ 1190's whose duration is over 90 years. Restricted by lack of detailed historical records, it is difficult to divide the warm/cold stages during the first millennium before Christ in such detail as for the past 2000 years. But two cold stages have been identified. One is around 1000BC, which was first identified by Chu[11]. Another is around 350BC[12].

According to the natural proxy data on temperature change collected from the published papers in the recent 20 years, the warm/cold stages on century scale during the past 3000 years were divided qualitatively. The result is as follows: cold stage in 3100 ~ 2700 a BP (1150 ~ 750BC), warm stage in 2700 ~ 2500 a BP (750 ~ 550BC), cold stage in 2500 ~ 2300 a BP (550 ~ 350BC), warm stage in 2300 ~ 1950 a BP (350 ~ 1BC), cold stage in 1950 ~ 1400 a BP (1 ~ 550AD), warm stage in 1400 ~ 1150 a BP (550 ~ 800AD), cold stage in 1150 ~ 950 a BP (800 ~ 1000AD), warm stage in 950 ~ 650 a BP (1000 ~ 1300AD), cold stage in 650 ~ 50 a BP (1300 ~ 1900AD), and warm stage since the 20th century (Fig. 1). Relative warm or cold phases could be identified in detail in each cold or warm stage[10].

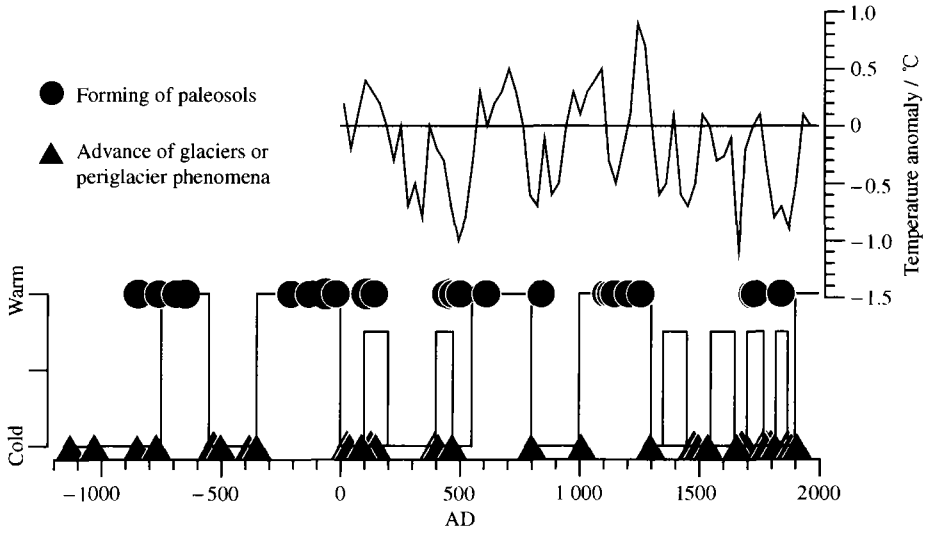

Fig. 1. The temperature series of winter-half-year in eastern China during the past 2000 years reconstructed by historical records (above) and the warm-cold stages on century scale in China during the past 3000 years based on natural proxy data (below).

Comparison of the above two series shows that the only major difference is that, the time interval of 0's ~ 200's which is regarded as a warm stage according to the historical records is regarded as a warm phase in a cold stage according to natural proxy data. If the warm stage of 0's ~ 200's in the series derived from historical records is regarded as a warm phase in a cold stage, the beginning time of the cold stage from 210's to 560's may be extended from 210's to 0's. In this way, the warm/cold stages based on the historical records match well with the warm/cold stages based on natural proxy data, although there are slight differences at the beginning or ending of the stages for the lower resolution of the natural proxy data. In addition, the cold phases in the warm stages or the warm phase in the cold stages are comparable too between the two series.

Dividing the warm/cord stages during the past 3000 years in four groups and summing them up in the way as Table 1, we see that the quasi-periodicity of temperature changes on the millennial scale is remarkable according to the proxy data both from historical records and natural evidence during the past 3000 years in China. The period on the millennial scale is in the length of 1300 ~ 1380 a (Table 1). It is acceptable that there exists a slight difference for the intervals of some warm/cold stages between that inferred from the natural proxy data and that inferred from the historical records due to the lower resolution and uncertainty of dating in the duration of the first 1000 years before Christ.

Table 1. The warm/cold stages during the past 3000 years in China

Warm/cold stage or phase	Time interval/AD						Re-occurring interval between the two stages
	Natural proxy data[10]	Historical records[8,12]	Natural proxy data[10]	Historical records[8,12]	Natural proxy data[10]	Historical records[8,12]	
Cold stage	−1350～−750	−1000's±	1～550	0's～560's	1300～1900	1320's～1910's	1300～1350a
			150±	0's～200's	1450±	1380's～1400's	1300～1380a
warm phases	−1050±				1600±	1500's～1550's	
	−850±		450±	360's～380's	1750±	1710's～1760's	1300a
Warm stage	−750～−550	−600's±	550～800	570's～770's	1900～	1920's～	1300～1350a
cold phases	−650±		650±	600's～620's	1960's	1950's～1970's	1300～1350a
Cold stage	−550～−350	−350's±	800～1000	780's～920's			1350a
warm phases	−420±		950±	840's～860's			1370a
Warm stage	−350～1	−200's～0's	1000～1300	930's～1310's			1300～1350a
	−310±		1070±	990's～1010's			1380a
cold phases	−250±		1130±	1110's～1190's			1380a
	−150±		1200±				1350a

Note: The warm stage during 0's～200's based on historical records is regarded as a warm phase in a cold stage.

2 The quasi-periodicity on the millennial scale revealed by the winter- half-year temperature series in eastern China in the past 2000 years

An outstanding feature of the winter-half-year temperature anomaly series in 30-year resolution in eastern China during the past 2000 years is that the fluctuation during the last 510 years (1500's～1990's) is quite similar to that during 150's～650's (Fig. 2). The reoccurring interval between the two phases is 1350 a.

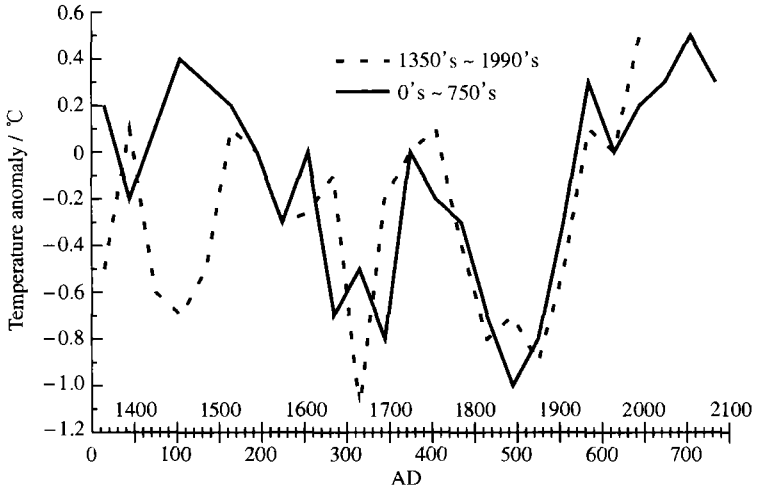

Fig. 2. Comparison of the temperature changes between 1350's to 1990's and 0's to 640's in eastern China.

Such a similarity of the temperature series may be described by the lagged auto-correlation coefficients of the series. The method is, to take the data from now to the past in the length of 20 points (1410's～1990's, 600 a), 17 points (1500's～1990's, 510 a), and 13 points (1620's～1990's, 390 a), as subsequences respectively; then to calculate the lagged auto-correlation coefficients backward to the past point by point (e.g. 30-year as an interval). All of the above three groups of lagged auto-correlation coefficients indicate that the time lag for the auto-correlation coefficient reaching the maximum is 1350 a, in which, the correlation coefficients lagged at 1350 a of the two subsequences of 1500's～1990's and 1620's～1990's are 0.72 and 0.71 respectively, which have passed the 0.01% correlation significance level. The correlation coefficients lagged at 1350 a and 1380 a of the subsequence of 1410's～1990's are

0.45 and 0.47 respectively, which passed 0.05% correlation significance level (Fig. 3). The high correlation of the lagged auto-correlation coefficients around 1350 a implies that there should exist a period of 1350 a in the process of temperature changes, although it is difficult to figure out by the general methods such as power spectrum for the limitation of the series length (2000 years only). Moreover, the lagged auto-correlation coefficients of the series reach the sub-peak values around the times that lag 210～240 a, 450～480 a, 690～720 a, and 960～990 a, respectively. Although the lagged auto-correlation coefficients at the above time does not reach 0.05% significance level, it also shows that, on the century scale climatic fluctuations, the fluctuations on the scale of double centuries are most outstanding.

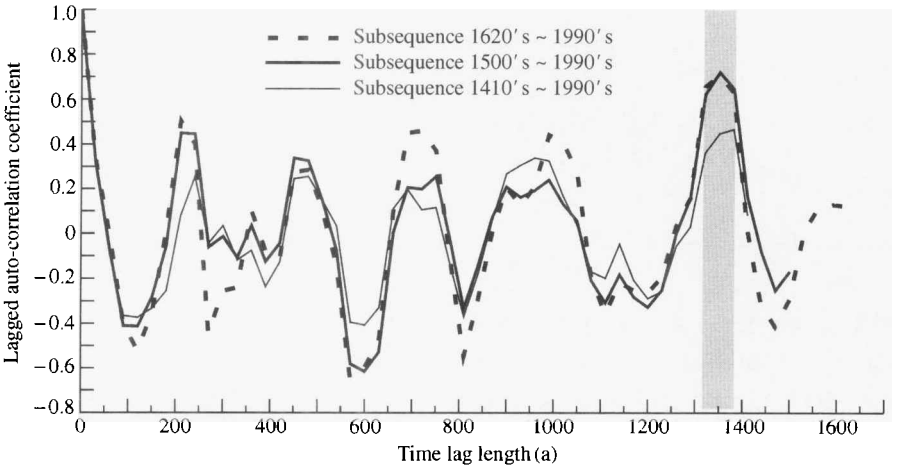

Fig. 3. The series of lagged auto-correlation coefficients of temperature change in eastern China during the past 2000 years.

3 The structure of the 1350a quasi-period

Both the winter-half-year temperature series during the past 2000 years in eastern China derived from the historical records and the warm/cold stages during the past 3000 years in China derived from the natural proxy data show that the period of 1350 a includes four warm or cold stages whose length is more than 100 years. They are 200～250 a warm stage, 150～200 a cold stage, 350～400 a warm stage and 550～600 a cold stage. Each cold or warm stage includes some relatively cold or warm phases on decadal scale. The winter-half-year temperature series in eastern China during the past 2000 years may cover one and half of the periods. The duration from 570's to 1910's makes up of one full 1350 a period. In the period, 570's～770's is a warm stage in 210 a length; 780's～920's is a cold stage in 150 a length; 930's～1310's is a warm stage in 390 a length; 1320's～1910's is a cold stage in 600 a length. The basic climatic feature in each cold or warm stage is in Table 2.

In contrast to the cold dominant stage from 1320's to 1910's, the two warm stages during 570's～780's and 920's～1310's plus the cold stage during 780's～920's between them may be united in one warm dominant period from 570's～1310's. The temperature in the duration from 570's to 1310's, including 4 major warm peaks and 3 major cold valleys, tended to rise at the rate of 0.25 ℃/1000 a. The temperature in the duration from 1320's to 1910's, including 3 major warm peaks and 4 major cold valleys, tended to drop down at the rate of 0.37 ℃/1000 a. The temperature alternated quickly between the warm dominant period and the cold dominant period. In the alternation from cold to warm, the temperature rose 1.3 ℃ within 90 years from 480's～500's to 570's～590's which equals the rate of 1.44 ℃/100 a; and rose 1.0 ℃ within 60 years from 1860's～1880's to 1920's～1940's which equals the rate of 1.67 ℃/100 a. In the alternation from warm to cold, the temperature dropped by 1.4 ℃ within 90 years from 1230's～1250's to 1320's～1340' which equals the rate of 1.56 ℃/100 a.

Table 2. The structure and basic feature of the 1350 a period of temperature changes

Warm or cold stage	Time	Temperature anomaly	Basic climatic feature
Warm stage	570's~770's (210 a)	+0.23	Warm. The amplitude of warm/cold fluctuation is small. The temperature difference is 0.5 ℃ between the coldest 30 years and the warmest 30 years. The slight cold phase during 600's to 620's divides the warm stage into two warm phases, in which the latter is warmer and longer than the former.
Cold stage	780's~920's (150 a)	−0.50	Cold. It includes two cold valleys in 760's~830's and 870's~920's. The temperature returned warm shortly around 850's. The amplitude of warm/cold fluctuation is small. The temperature difference is 0.6 ℃ between the coldest 30 years and the warmest 30 years.
Warm stage	930's~1310's (390 a)	+0.18	Warm. The amplitude of warm/cold fluctuation is large. The temperature difference is 1.4 ℃ between the coldest 30 years and the warmest 30 years. There is an obvious cold valley from 1110's to 1190's. The temperature anomaly during the warm stage except for the cold valley (1110's~1190's) is 0.33 ℃. The temperature anomaly is 0.4 ℃ and 0.57 ℃ in the two warm phases from 1020's to 1110's and from 1200's to 1280's, respectively. The 30 years from 1230's to 1250's is the warmest 30 years in the past 2000 years. Besides, there is a weak cold valley from 990's to 1010's.
Cold stage	1320's~1910's (600 a)	−0.39	Cold. It includes four cold phases from 1320's to 1370's, from 1410's to 1490's, from 1560's to 1700's, and from 1770's to 1910's. There are three relatively warm phases from 1380's to 1400's, from 1500's to 1550's and from 1710's to 1760's. The temperature tends to decrease during the stage. The amplitude of warm/cold fluctuation is large. The temperature difference is 1.2 ℃ between the coldest 30 years and the warmest 30 years.

4 Viewing the on-going warming from the quasi-periodicity of temperature changes on the millennial scale

One important purpose of research on the past global changes is to understand the status and cause of the on-going global warming from the view of global changes in long time scale. The periodicity of 1350 a cycle of temperature changes provides an effective way for understanding the on-going warming process.

The warm stages experienced in the past are often regarded as the historical analogues for predicting the global warming in the future. The Medieval Warm Period during 9~13th centuries is highlighted as the most possible historical analogue for the on-going global warming in the previous researches. But from the result of the periodicity of 1350 a cycle of temperature changes, the on-going global warming started from the early 20th century is even more similar to the warm stage in 570's~770's, whose length is about 200 a.

The temperature oscillation in the on-going warming stage is similar to that in the warm stage in 570's~770's according to the winter-half-year temperature changes in eastern China in the past 2000 years (Fig. 2). The on-going warming that started from the early 20th century is corresponding to the alternative phase from a cold stage to a warm stage when the temperature rose very fast like the one that happened in the duration from the end of 5th century to the early 6th century. However, the rising rate in the early 20th century is even faster. Both the slight cooling in 1950's~1970's and the quick warming since the 1980's correspond to the oscillation in the warm stage that started from 600's, which should be governed by natural fluctuations. Inferred from the changes during 570's~770's, the winter-half-year temperature in eastern China is going to keep rising in the next 50 years. However, it is noticeable that the temperature during the 1980's~1990's has risen so fast that it has already been comparable with the maximum in the warm stage of 570's~770's. Compare the regression function of temperature anomaly between 1500's~1990's (y) and 150's~650's (x):

$$y = 0.762118x - 0.0426837 \quad (r = 0.72).$$

The temperature anomaly in the 1980's~1990's is much higher than the regression value (Fig. 4). If the regression value is regarded as the basic value of

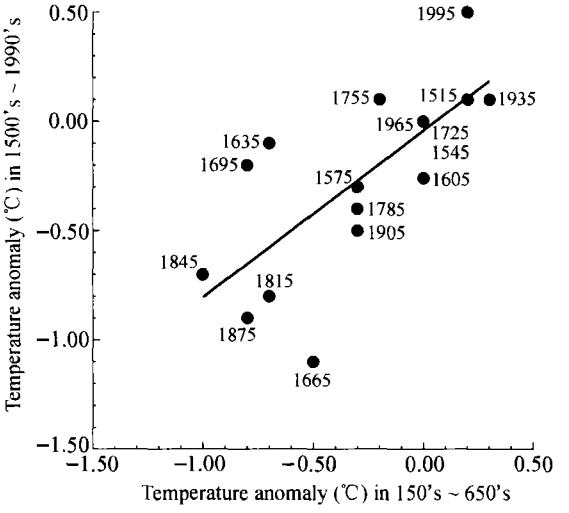

Fig. 4. Correlation between the temperature anomaly during 1500's~1990's and 150's~650's.

temperature changes in nature, the unusual high temperature in the 1980's ~ 1990's could likely be regarded as the forcing of the greenhouse effect induced by human activities on climatic changes. This coincides with the conclusion that the greenhouse effect induced by human activities has been increasing remarkably since the 1950's concluded by the IPCC based on results of modeling[13].

5 Conclusions

(1) The quasi-periodicity on the millennial scale of historical temperature changes in China is identified by both the temperature change series derived from historical documents and the cold/warm change derived from natural proxy data. The lagged auto-correlation coefficients of the temperature change series derived from historical documents are the highest at the lagged time around 1350 a (e.g. 1300 ~ 1380 a), which implies that the periodicity of temperature change on the millennial scale should be 1350 a approximately. This period cycle should correspond with the 1400 ~ 1450 a cycle revealed by some previous studies[2~7]. However, the possible reasons for the cycle length in this study being about 50 ~ 100 a shorter than that in previous studies should be discussed here. One possible reason is that the 1400 ~ 1450 a period is identified from the long series covering 10 ~ 100 thousands years, while the temporal resolution is lower than the temperature series in the past 2000 years used in this study. Another possible reason is that the 1400 ~ 1450 a cycle is a quasi-period cycle, whose length may vary to some extent. For example, in the GISP2 ice core in Greenland, the 1450a period is recorded as 1374 ± 502 a in the Holocene (the past 10000a)[3,6], similar to that inferred in this paper.

(2) The 1350a period includes four warm or cold stages longer than 100 a that occurred successively. They are the warm stage in 200 ~ 250 a, cold stage in 150 ~ 200 a, warm stage in 300 ~ 350 a, cold stage in 550 ~ 600 a. Each cold or warm stage includes some relatively warm or cold phases on the scale of several decades. In contrast to the 550 ~ 600 a cold stage in which the temperature tends to decrease, the other three stages can be united in one warm dominated period in which the temperature tends to rise. The temperature alternated quickly between the warm dominant period and the cold dominant period with the changing rate of 1.44 ~ 1.67 ℃/100 a.

(3) Inferred from the 1350a period, the temperature oscillation in the 20th century warming is similar to that in the warm stage in 570's ~ 770's which belongs to the 200 ~ 250 a warm stage in the 1350 a cycle. However, the warming that started from the early 20th century is a little more quick. The temperature anomaly in 1980's ~ 1990's is far from the regression equation of that between 1500's ~ 1900's and 150's ~ 650's. Whether it can be regarded as the forcing of human activities is worth researching further.

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