Key points on temperature change of the past 2000 years in China*

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Abstract Temperature change of the past 2000 years in China is discussed based on the winter half-year temperature series of the past 2000 years in eastern China reconstructed recently, and other related studies. The main conclusions are as follows: (1) The Little Ice Age (LIA) in China began in the early of the 14th century (1320s) and ended in the beginning of the 20th century (1910s), which was composed of four evident cold stages and three short warming stages. The cold period in the Wei, Jin and South-North dynasties (210s~560s) was the only one comparable with LIA for the past 2000 years. (2) The Medieval Warm Period (MWP) in China began in the 930s and ended in the 1310s, which was composed of two warm stages over 100 years and a cold stage less than 100 years. (3) The climate in the Sui and Tang dynasties should be divided into two stages: the climate in the 570s~770s was as warm as that in the 20th century; while the temperature in the 780s~920s was lower than that in the 1950s~1970s. (4) In eastern China as a whole, winter half-year temperature variation with over 1 ℃ occurred between the cold and warm stages on centennial scale, while the changing rate exceeded 1.0 ℃ per century. (5) There exists an about 1350-year periodicity in the historical temperature change. Inferred from the periodicity, the most likely historical analogue for the warming in the 20th century is the warm stage of the Sui and Tang dynasties (570s~770s), instead of the Medieval Warm Period. (6) Although it was critically warm, the temperature of the 20th century in eastern China is still within the threshold of the variability of the last 2000 years.

Keywords: eastern China, past 2000 years, temperature change.

It is important to study the temperature change during the past 2000 years for understanding the issues such as the greenhouse effect and global warming induced by human activities. China has advantages in reconstructing historical climate change for its aburrdant documented historical records and other natural evidence obtained from tree rings, lake sediments, ice cores, and stalagmite. Since Dr. Chu laid a foundartion on the study of temperature change in China for the past 5000 years[1], significant progress in the study of temperature change of the past 2000 years has been made through the great efforts of generations. These achievements not only help us to understand the characteristics of temperature change in the past 2000 years, but also to assess some key scientific points. In this paper, temperature change of the past 2000 years in China will be discussed based on the winter half-year temperature series of the past 2000 years in eastern China[2,3], as well as other related studies.

1 Improvement in reconstructing methods

Reconstruction on temperature change derived from the historical documents is one of the most important issues in historical climate study in China. The historical documents related to temperature change can be divided into two categories according to their characteristics. The first category is "natural evidence" which provides information about temperature directly. It includes phenology of plants (including some crops), the date of the first and last frost or snow, and the duration of frost or snow; the duration and dates of freeze-up and thaw of rivers, lakes and seas; the distribution and its northern boundary of subtropical crops and economic crops (e.g. citrus, tea, bamboo); the spatial-temporal distribution of farming and farming systems (e.g. sowing date, harvest date, the distribution of double harvest rice). The second category is "impact evidence", specifically the effect on "man and society" associated with the cold/warm events (e.g. the feeling of "rather cold" and "warm winter"). The evidence can be used to extract information about changes in temperature through comparison with other evidence at different times[2]. Because of the differences of the evidence, before reconstructing the temperature changes quanti-

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tatively, it is necessary to strictly distinguish the category of each record and to answer the following three key questions: (1) How to quantify the documented records to temperature value? Because the sources of historical records and record formats are different from one another, it is very difficult to calibrate and verify these records together and make them compatible with instrumental temperature data. (2) How to keep the temporal continuity? For the uneven temporal and spatial distribution of these records, it is difficult to obtain continual data even in the area with most abundant records. (3) How to assess the spatial validity of the record? Because China is a large country with various kinds of environment, how to assess the spatial validity of the record from the individual region, and how to compare and combine the individual series from different locations or subregions is the important issue for temperature reconstruction.

Four kinds of approaches have been adopted to reconstruct temperature change by Chinese scholars. (1) Phenology model: inferring temperature changes from the differences of phenology and boundaries of crop distribution for different periods. It is able to reconstruct past temperature quantitatively by comparing the same kind of phenology and crop distribution between the past and the present[1]. (2) Grade model: giving grades or indices based on the description of the cold/warm events in historical records, then converting the grades and indices into temperature departure by comparing them with the modern records[4,5]. (3) Ratio model: describing the temperature change by the occurring frequencies of the cold/warm events, then reconstructing the temperature series by the ratio of them[6~9]. (4) Linear regression model: establishing the conversion equation between the temperature and some given weather/climatic phenomenon (such as snowing days in winter), then using this function to convert the historical records of the phenomena into temperature values[10~12].

The phenology model was used by Chu to reconstruct his quantificational temperature series in unfixed temporal resolution[1], by supposing the temperature changes are consistent in whole China, and sampling data in different temporal resolutions (Fig. 1). After Chu's study, the grade model and the ratio model were used to reconstruct temperature changes for a certain region with a temporal resolution. But the reconstructed series by the above two models could not exceed 1000 years for the limitation of the original records[4~9]. The quantification was also limited by the inherence shortage of the "impact evidence". Quantificational results at a high resolution may be gotten from the linear regression model, but the model was limited by strict demands to the source data, so the length of reconstruction series could not exceed 300 years[10~12]. Recently, temperature series with a certain temporal resolution (50 years) for the whole China, eastern China and western China were reconstructed respectively by integration of the published temperature series. The length of these series was only 1200 years, limited by the available series and evidence (Fig. 1)[13].

In order to reconstruct the continuous temperature change series with a fixed spatial and temporal resolution, it is necessary to use a proper model to calibrate and convert reconstructed results from different regions, different seasons and different kinds of historical records, and to make comparisons between them. A four-step approach is used as follows: (1) First, to classify the records into "natural evidence" and "impact evidence", and to work out the conversion functions of the temperature for different types of records. (2) According to the functions, to convert the cold/warm event records into temperature value for a region (site). (3) To analyze the relationship between the temperature change in individual station and in the domain, then to calculate the contribution ratio of the temperature changes in different seasons and from different stations to the domain temperature change. (4) Based on the contribution ratio to reconstruct the domain mean temperature anomaly derived from the temperature anomaly for the individual region[2].

While reconstructing the winter half-year temperature series of the past 2000 years in eastern China, we established the equation of the variation of plant phenological date with the location (latitude) and the function between the variation of temperature and pheno-date, under different cold/warm conditions based on the large amounts of the pheno-date data and instrumental temperature data[14]. These equations and the approaches discussed above were used as the basis for reconstructing the temperature anomaly derived from historical phenological records for individual region. They made the reconstructed results from different regions, different seasons and different sources be comparable[2,3], and provide us a possibility to quantitatively analyze the temperature change in the past 2000 years.

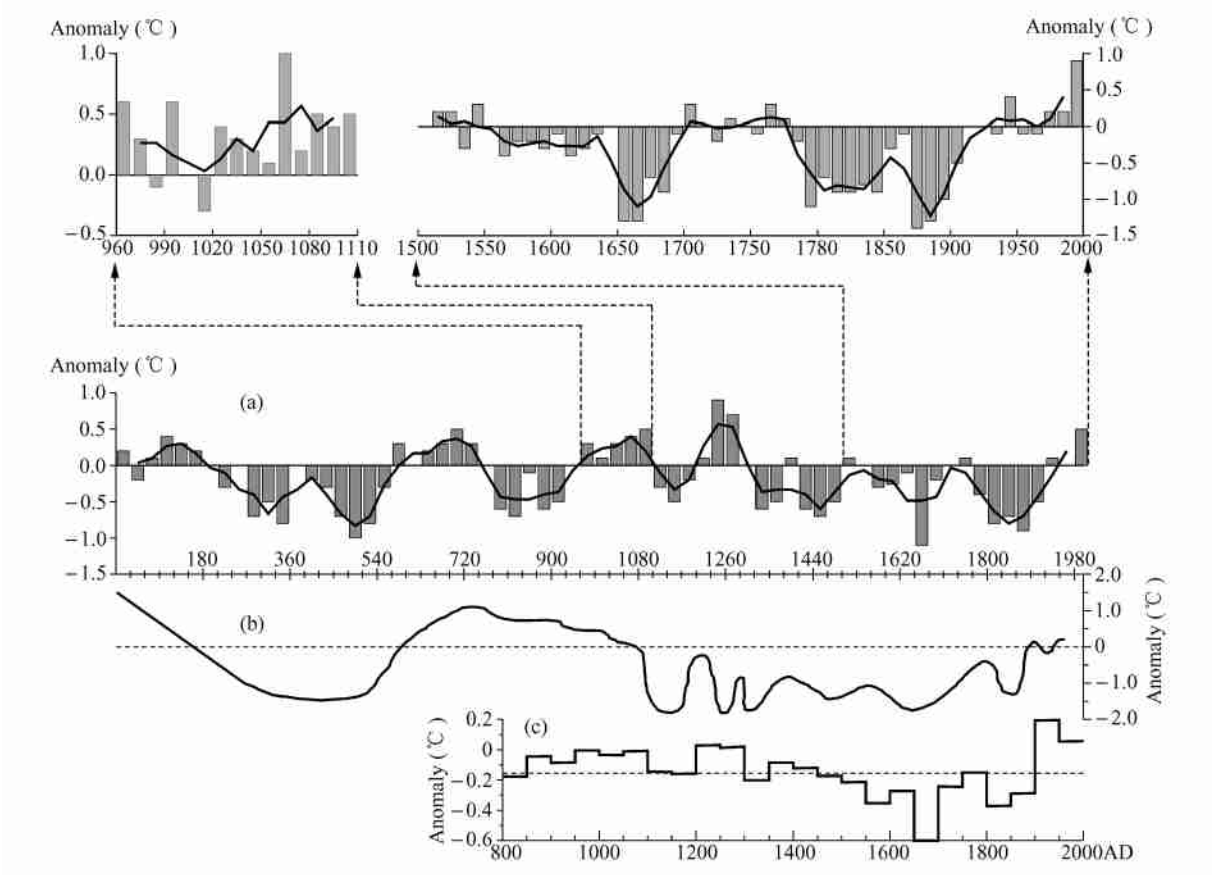

Fig. 1. Temperature change series of the eastern China for the past 2000 years. (a) Winter half-year temperature series of the past 2000 years[2], (b) temperature change of the past 2000 years in China reconstructed by Chu (1972)[1], (c) temperature change from AD 800 in eastern China reconstructed by Wang (2000)[13].

2 Duration of the cold period and cold climate in the Little Ice Age and the Wei, Jin and South-North dynasties

The Little Ice Age usually refers to the cold period with a mountainous glacier advance in Europe and surrounding areas from the 16th century to the middle of the 19th century. If defined as a large-scale event, the Little Ice Age must instead be considered a time of modest cooling of the Northern Hemisphere, with temperature decreased by about 0.6 ℃ during the 15~19th centuries[15]. In China, there are many studies focused on the climate in the Little Ice Age. For instance, Chu figured that there were three major cold periods in the past 2000 years in China, which existed in the Wei, Jin and South-North dynasties, the Southern-Song dynasty and the Ming and Qing dynasties. The cold period in Ming and Qing dynasties corresponds to the Little Ice Age in Europe, of which the coldest stage occurred from the middle to late 17th century when the winter temperature in Beijing was 2 ℃ lower than that of the 1950s~1960s[1]. Most of the later studies agreed that there were cold periods in the 16~19th centuries with several cold stages[4~9,16~18], while mountainous glacier advanced in western China responding to the cold climate[19]. But not all viewpoints on the beginning and ending time and the degree of the cold stages are identical due to the differences in the researching areas, adopted parameters of temperature (such as annual average temperature, winter average temperature, cold seasons average temperature), and the length of series and the referring period. According to Fig. 1, the Little Ice Age in China began in the early 14th century (1320s) and ended in the beginning of the 20th century (1910s). It was composed of four evident cold stages (Table 1) and three shorter warm stages. In the Little Ice Age, the average winter half-year temperature in eastern China was 0.4 ℃ lower than that of the 20th century. The coldest 30 years occurred in the 1650s~1670s, when the winter half-year temperature in eastern China was 1.1 ℃ lower than that of 1951~1980.

Table 1. Four cold stages of the Little Ice Age in China and their winter half-year temperature anomaly referring to 1951~ 1980

Stage	Cold stage 1	Cold stage 2	Cold stage 3	Cold stage 4
Beginning and ending time	1320s~ 1370s	1410s~ 1490s	1560s~ 1700s	1770s~ 1910s
Duration (year)	60	90	150	150
Temperature anomaly (℃)	- 0.6	- 0.6	- 0.4	- 0.7
The coldest 30-year period and its temperature anomaly (℃)	1320s~ 1340s - 0.6	1440s~ 1460s - 0.7	1650s~ 1670s - 1.1	1860s~ 1880s - 0.9

Although the cold climate in the Wei, Jin and South-North dynasties (from the early 3rd century to the middle of 6th century) had been identified by Chu, some details were absent for the shortage of historical records[1]. Some studies divided the cold period into 3 stages, including two cold and one warm intervals according to the frequency of cold event records, and the magnitude of the two cold stages was also estimated[20, 21]. However, according to Fig. 1, this cold period began in the 210s and ended in the 560s, whose winter half-year temperature mean was 0.5 ℃ lower than that of the 1950s ~ 1970s and the temperature of the coldest 30 years was 1.0 ℃ lower than that of the 1950s~ 1970s. In this period, the two distinct colder intervals happened in the 270s~ 350s (0.7 ℃ lower than that of the 1950s ~ 1970s) and the 450s~ 530s (0.8 ℃ lower than that of the 1950s~ 1970s). The cold period in the Wei, Jin and South-North dynasties is the only one that may be comparable with the Little Ice Age in the past 2000 years. This result can also be validated by the advance of the mountainous glacier in western China[19] and the similarity of cold events recorded by historical documents between this period and the Little Ice Age[20].

3 Duration and warm climate in the Medieval Warm Period and the Sui and Tang dynasties

The Medieval Warm Period refers to a warm period of climatic history during which temperature in Europe and neighboring regions of the North Atlantic are believed to have been comparable to, or to have even exceeded, that of the late 20th century. This period is conventionally believed to have occurred in approximately 900 ~ 1300 AD[22]. Chu concluded that the climate was no longer warmer than today since the North-Song Dynasty, which means the Medieval Warm Period did not exist in China[1]. However, the succeeded studies found that the Medieval Warm Period existed in China when the north boundaries of the subtropical zone and the warm temperate zone were northward at least 1° in latitude than that of the present[23, 24]. Man presented several evidence of the existence of the warm period[23], from the north boundaries of winter wheat, sugarcane, tea plant, citrus and ramee; from the safety date for full heading time of rice in Kaifeng; and from the phenology in Hangzhou. He also reconstructed a winter cold index series and a temperature anomaly series during the 960~ 1109 AD based on cold events recorded in Kaifeng and surrounding area, and analyzed the characteristics of temperature change in the period[23]. Zhang also pointed out that the average annual temperature in the middle of the 13th century was 0.9~ 1.0 ℃ higher than that of today, the average extreme minimum temperature was 3.5 ℃ higher than that of today, and the spring temperature in the South-Song Dynasty (1127 ~ 1279 AD) was at least no lower than today's[24]. According to Fig. 1, the Medieval Warm Period began in the 930s and ended in the 1310s when the winter half-year temperature in eastern China was 0.2 ℃ higher than that of the 1950s~ 1970s. But like the Medieval Warm Period in Europe interrupted by the occasional cold events[25], the Medieval Warm Period in China was not constantly warm which was divided into two warm stages by an about 100-year cold stage corresponding to the cold period in the South-Song Dynasty pointed by Chu (Table 2).

Table 2. The winter half-year temperature anomaly referring to 1951 ~ 1980 for the Medieval Warm Period in China

Stage	Warm stage 1	Cold stage	Warm stage 2
Beginning and ending time	930s~ 1100s	1110s~ 1190s	1200s~ 1310s
Duration (year)	180	90	120
Temperature anomaly (℃)	0.3	- 0.3	0.4
The warmest/coldest 30-year period and its temperature anomaly (℃)	1080s~ 1100s 0.5	1140s~ 1160s - 0.5	1230s~ 1250s 0.9

Another important warm period in the past 2000 years is the warm period in the Sui and Tang dynasties. Chu pointed out that the climate in the Sui and Tang dynasties (the 587~ 907 AD) was characterized as warm, because plum and citrus of the time were grown in Xi'an where they could not be planted

in 1931~ 1950 AD[1]. However, the later studies found that plum and citrus of that time in Xi' an could not implicate the existence of warm climate[21,26~28] because the plum in Xi' an was only an ornamental plant in the royal garden and the citrus was transplanted from southern China, and neither of them can be regarded as real "natural" evidence for warm climate. On the contrary, there were a lot of cold events recorded in the later Tang Dynasty, and some of extremely cold events were even colder than that recorded in the Little Ice Age. Although there are some debates on the existence of the warm period in the Sui and Tang dynasties, according to Fig. 1, there existed a warm period in the Sui and Tang dynasties, but it did not run through the whole Sui and Tang dynasties. And it was not warmer than that of the Medieval Warm Period, especially even lower than the second warm stage of the Medieval Warm Period. The winter half-year mean temperature in the 570s~ 770s was equal to that of the 1920s~ 1990s, and the temperature of the warmest 30 years (the 690s~ 710s) was 0.5 ℃ higher than that of the 1950s~ 1970s. The winter half-year mean temperature in the 780s~ 920s was 0.5 ℃ lower than that of the 1950s~ 1970s, and the temperature of the coldest 30 years (the 810s~ 830s) was 0.7 ℃ lower than that of the 1950s~ 1970s.

4 The magnitude and rate of temperature variation in China during the past 2000 years

It is necessary to define the temporal and spatial scale first because the magnitude and rate of temperature variation rely on them. Considering eastern China as a whole, the magnitude of the cold/warm change on centennial scale is usually more than 1 ℃ (winter half-year temperature), and the rate exceeds 1.0 ℃ per century. For example, in the three durations of the 480s~ 500s to the 570s~ 590s, the 870s ~ 890s to the 960s~ 980s, and the 1860s~ 1880s to the 1920s~ 1940s, when it changed from a cold period to a warm period, the warming magnitude was 1.3 ℃, 0.9 ℃, 1.0 ℃ respectively; in the two durations of the 690s~ 710s to the 810s~ 830s, the 1230s~ 1250s to the 1320s~ 1350s, when it changed from a warm period to a cold period, the cooling magnitude was 1.2 ℃ and 1.5 ℃ respectively. The magnitude of the alternation between cold and warm stages within a cold/warm period is big too. For example, in the Medieval Warm Period, the cooling from the 1080s~ 1100s to the 1140s~ 1160s and the warming from the 1140s~ 1160s to the 1230s~ 1250s is 1.0 ℃, 1.4 ℃ respectively; while in the Little Ice Age, the cooling magnitude from the 1380s ~ 1400s to the 1440s~ 1460s and from the 1740s~ 1760s to the 1800s~ 1820s was 0.8 ℃ and 0.9 ℃ respectively, and the warming magnitude from the 1440s~ 1460s to the 1500s~ 1520s and from the 1650s~ 1670s to the 1740s~ 1760s was 0.8 ℃ and 1.2 ℃ respectively. A change of about 1 ℃ even exists between two adjacent periods of 30 years. For example from the 1650s~ 1670s to the 1680s~ 1700s and from the 1620s~ 1640s to the 1650s~ 1670s, the temperature respectively increased by 0.9 ℃ and decreased by 1.0 ℃[3]. All the above indicates that the temperature change is characterized by a high rate from one status to another, and then, the climate tends to be stable in a new status.

5 The millennial scale periodicity of temperature change

Climatic change on the millennial scale is the background for understanding the climatic changes on the decadal to centennial scale. Recently, the existence of a periodicity of 1450~ 1500a has been reported according to the evidence from the GISP2 and GRIP ice cores in Greenland, ice core in the Antarctica, sediments in the North Atlantic Ocean and sediments in the Arabian Sea[29~34]. However, such a periodicity is still not sufficiently evidenced during the historical times.

The lagged autocorrelation coefficient of the winter half-year temperature changes during the last 2000 years in eastern China is most significant on the 1350a time lag (see Fig. 3 in Ref. [35]). The division of the cold/warm periods based on the proxy data derived from historical documents and natural evidences in China also indicates that the quasi-periodicity of temperature changes on the millennial scale of 1300~ 1380a is remarkable (see Table 1 in Ref. [35]). All the above shows that there is a re-occurring periodicity of 1350 years in temperature changes[19,35]. Further analysis on the structure of the 1350a period shows that it includes four warm or cold stages whose length is more than 100 years. They are the 200~ 250a warm stage, the 150~ 200a cold stage, the 350~ 400a warm stage and the 550~ 600a cold stage. Each cold or warm stage includes some relatively cold or warm phases on decadal scale. If the 150~ 200a cold stage is regarded as a stage in a warm period, the other three stages except the 550~

600a cold stage may be combined into one warm period. Then the 1350a period can be divided into two parts: a cold one and a warm one. The temperature during the cold one tends to decrease, while during the warm one the temperature tends to increase. The temperature alternates quickly between the warm dominant period and the cold dominant period.

Inferred from the temperature change on the millennial scale, the most possible analogue for the warm period in the 20th century would be the warm period in the Sui and Tang dynasties (570s~ 770s), instead of the Medieval Warm Period. The result can also be validated by analysis on the alternation of cold and warm period. In fact, the warming in the early 20th century is a transformation from a centennial scale cold period (the Little Ice Age) to a warm period. Among the other three warm periods in the past 2000 years, only the cold period before the warm period in the Sui and Tang dynasties is comparable with the Little Ice Age on cold magnitude and duration, while the cold period before the Medieval Warm Period was very different from the Little Ice Age (see Fig. 3 in Ref. [36]). Correlation analysis indicated that the correlation coefficient of the series of the 1500s~ 1990s (including the warm period in the 20th century and two cold stages of the Little Ice Age) and the 150s~ 650s (including the warming of the warm period in the Sui and Tang dynasties and two cold stages of the cold period before the warm period) is 0.72 ($p < 0.01$); but the correlation coefficients between the series of the 1500s~ 1990s and the 540s~ 1040s (including the warming of the first warm stage of the Medieval Warm Period and the cold stage before), and the 1500s~ 1990s and the 810s~ 1310s (including the warming of the second warm stage of the Medieval Warm Period and the cold stage before) are small. So the most possible analogue for the warm period in the 20th century is the warm period in the Sui and Tang dynasties (the 570s~ 770s), instead of the Medieval Warm Period[19].

6 The warming in the 20th century seen from temperature change in the last 2000 years

One of the purposes of reconstructing temperature change is to test whether the warming in the 20th century has exceeded the maximum magnitude in the past 2000 years. For this, the warming of the 20th century was analyzed from the view of warm magnitude, the rate of temperature change and the historical analogue in the past 2000 years based on the winter half-year temperature series of eastern China[36]. Compared with the other three centennial scale warm periods in the past 2000 years in eastern China (Table 3), the temperature of the 20th century in eastern China is still within the threshold of the variability of the last 2000 years although it has been critically warm. At the centennial scale, the temperature anomaly of the 20th century is not only lower than that of the later warm stage of the Medieval Warm Period (the 1200s~ 1310s), but also slightly lower than that of the warm period in the Sui and Tang dynasties (the 570s~ 770s) and the early warm stage of the Medieval Warm Period (the 930s~ 1100s). On a 30-year scale, the warmest 30-year temperature anomaly in the 20th century is roughly equal to the warmest 30-year one in the Sui and Tang dynasties warm period, but a little lower than that of the Medieval Warm Period. On the decadal scale, the warmest decadal temperature anomaly in the 20th century is approximately at the same level of the warmest decade of the early stage of the Medieval Warm Period. Although the warming rate in the early 20th century has reached 1.1 ℃ per century, such a rapid change is not unique during the alternation from the cold period to the warm period (see Table 3 in [36]). This gives a different viewpoint from that "the 20th century is the warmest century in the past 1000 years", presented by IPCC[37], and is of great significance for better understanding the phenomena of the greenhouse effect and global warming etc. induced by human activities.

Table 3. Comparison between the warm period in the 20th century and other warm periods in the past 2000 years in eastern China

Warm period duration	Temperature anomaly (℃)	The warmest 30-year and its temperature anomaly (℃)		The coldest 30-year and its temperature anomaly (℃)	
0s~ 200s	0.14	91~ 120	0.4	31~ 60	- 0.2
570s~ 770s	0.23	691~ 720	0.5	601~ 630 751~ 780	0.0
930s~ 1310s, including	0.18	1231~ 1260	0.9	1141~ 1170	- 0.5
930s~ 1100s	0.27	1081~ 1110	0.5	931~ 960	0.0
1200s~ 1310s	0.43	1231~ 1260	0.9	1291~ 1320	0.0
1920s~ 1990s	0.20	1981~ 1999	0.5	1951~ 1980	0.0

7 Conclusions

We draw the following conclusions: (1) The Little Ice Age (LIA) in China began in the early 14th century (the 1320s) and ended in the beginning of the 20th century (the 1910s), which was composed of four evident cold stages and three short warming stages. The cold period in the Wei, Jin and South-North dynasties (the 210s~560s) is the only one comparable with LIA in the past 2000 years. (2) The Medieval Warm Period (MWP) in China began in the 930s and ended in the 1310s. But it is not a constant warm period, which was composed of two warm stages of over 100 years and a cold stage of less than 100 years. (3) The climate in the Sui and Tang dynasties should be divided into two stages: the climate in the 570s~770s was as warm as that in the 20th century; while the temperature in the 780s~920s was lower than that in the 1950s~1970s. (4) The winter half-year temperature variation was above 1 ℃ between the cold and warm stages on the centennial scale in eastern China as a whole, while the changing rate used to exceed 1.0 ℃ per century. (5) There exists an about 1350-year periodicity in the historical temperature changes. Inferred from the periodicity, the most likely historical analogue for the warming in the 20th century is the warm stage of the Sui and Tang dynasties (the 570s~770s) instead of the Medieval Warm Period. (6) Although it has been critically warm, the temperature of the 20th century in eastern China is still within the threshold of the variability of the last 2000 years. This conclusion put forward a different viewpoint from that "the 20th century is the warmest century in the past 1000 years"[37].

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