Decadal climatic variations recorded in Guliya ice core and comparison with the historical documentary data from East China during the last 2000 years *

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Abstract The high-resolution records of $\delta^{18}O$ and snow accumulation variations from the Guliya ice core provide valuable data for research on climatic variations at a decadal resolution during the past 2000 years in China. Based on the ice core data, five spells have been divided: the warm and wet period before 270 AD, the cold and dry period between 280 and 970 AD, the moderate and dry period between 970 and 1510 AD, the well-defined" Little Ice Age "with drastic cold-warm fluctuations between 1510 and 1930 AD and the warming period since 1930 AD. According to the combination of temperature and precipitation, cold events (55 times) surpass warm ones (26 times), and dry events (55 times) surpass wet ones (45 times). Cold-wet events (14 times) are less than cold-dry ones (16 times), while warm-wet events (10 times) are more than warm-dry ones (4 times). If the difference of 2‰ in $\delta^{18}O$ (corresponding to 3K in temperature) between two or three adjacent decades is taken as the criterion of it, the abrupt change has taken place 33 times or so since the 3rd century. Among them are four large ones, occurring in 250—280, 550—580, 1220—1260, and 1520—1560 AD respectively. Comparison of the ice core data with the latest comprehensive research results on historical documents of East China shows that the great climatic events appeared simultaneously or at the same age in the ice core record and in the documentary data, suggesting that consistences and similarities in climatic variation among different areas are far away from each other in the lower to mid-latitudes. However, there is a great difference between them during the Medieval Warm Period, which is conspicuous in the historical documents but not in the ice core. In addition, the first cold event of the Little Ice Age on East China was 60 years earlier than that of the Guliya Ice Cap, when the degree of cooling in West China is more intensive than that of East China. But the third cold event in East China lagged behind that in West China during the late 19th century. The 1820s cold event in both West and East China may be caused by the magnificent Tambora volcanic eruption in 1815.

Keywords: Guliya ice core, the last 2000 a, climatic variations, East China, comparison.

A time resolution of at least decade or ideally of year and season in the climatic and environmental changes during the last 2000 years plays an important role either in PAGES or climate variability and predictability (CLIVAR) of WCRP. Only on this basis is it feasible to research the predictability of climate variability and the persistence of special climate type. The best data for climatic variations during the last 2000 years are derived from ice core records. Guliya Ice Cap (35.2°N, 81.5°E, 6 200 m a.s.l.) lies on the western part of the Kunlun Mts. in the Qinghai-Tibet Plateau, where a 308.7 m long ice core which includes the last 2000 a spell on its upper part has been drilled. Yao

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et al.[1] have studied the climatic and environmental characteristics of the Guliya Ice Cap preliminarily and published two papers on the variations of decadal average and centennial-level (11-point running mean) since 3rd century[1,2]. Based on their work, the present paper studies the decadal climatic characteristics recorded in Guliya Ice Cap (fig. 1), and makes a comparison between the records of Guliya ice core and the historical documents from eastern China. The time scale is properly prolonged in this paper.

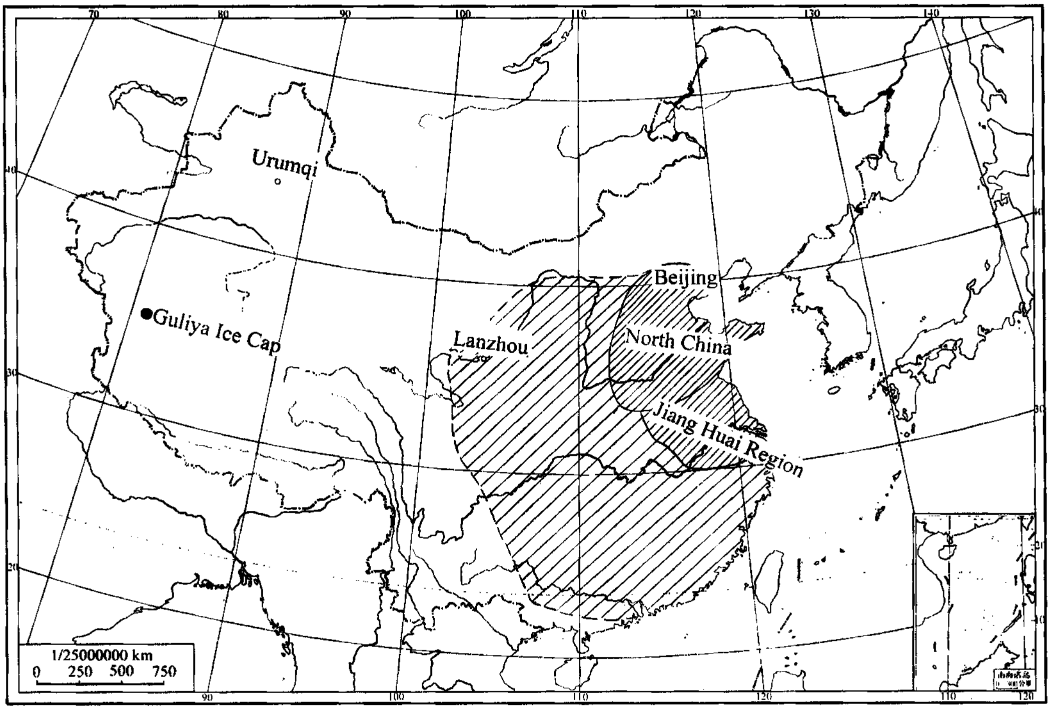

Fig. 1. The site of Guliya Ice Cap and documentary source regions in East China.

1 The characteristics of decadal climatic variations recorded in Guliya ice core during the last 2000 years

1.1 Decadal temperature change reflected by $\delta^{18}O$

The ice temperature at 10 m depth is −15.5℃, which suggests that the Guliya Ice Cap has some features similar to the glaciers in south Greenland and southwest Antarctica. There is a good positive-correlation between $\delta^{18}O$ and air temperature, which shows that temperature is higher in summer or at lower elevation and lower in winter or at higher elevation. For lack of stationary meteorological stations near Guliya ice core, the relationship between $\delta^{18}O$ and air temperature cannot be observed for a longer period. The relationship of $\delta^{18}O$ and air temperature shows that an increase (decrease) of 1‰ in $\delta^{18}O$ corresponds to an increase (or decrease) of 1.5℃ in air temperature at Delingha Meteorological Station[3,4]. The calculated temperature increases from the 1970s to the 1990s[5] in Tanggula and Guliya glaciers are 1.8℃ and 3.3℃ respectively. $\delta^{18}O$ values in precipitation are related not only to the air temperature in precipitation sites, but also to other factors such as the moisture source, the moisture path, condensation altitude and so on. $\delta^{18}O$ value might be the same in different precipitation events with different temperatures. This should be taken into consideration when calculating temperature by $\delta^{18}O$ in ice core. As far as Antarctica and Greenland are concerned, where $\delta^{18}O$-Ta relationships are good using currently measured $\delta^{18}O$-Ta relationships to reconstruct temporal variations in Ta from $\delta^{18}O$ may result in errors of 20 to 30%, as pointed out by Joussaume an Jouzel[6]. Therefore, we infer that Ta errors for $\delta^{18}O$ may be greater than these values in Guliya ice core.

Decadal $\delta^{18}O$ variations without being treated by mean method in Guliya ice core, as shown in fig. 2(a), ranges from the lowest value (−18.4‰) in the 1 220s AD to the highest value (−10.69‰) in the 220s AD. The $\delta^{18}O$ average value during the past 2000 years is −15.25‰, while the one in the 20th century is −13.89‰. The difference between the highest value and the lowest value is 7.7‰ (corresponding to about 11.5℃ in temperature) according to Delingha $\delta^{18}O$-Ta relationships. The $\delta^{18}O$ values during the past 2000 years are divided into five classes, which have been demonstrated in fig. 2 and table 1.

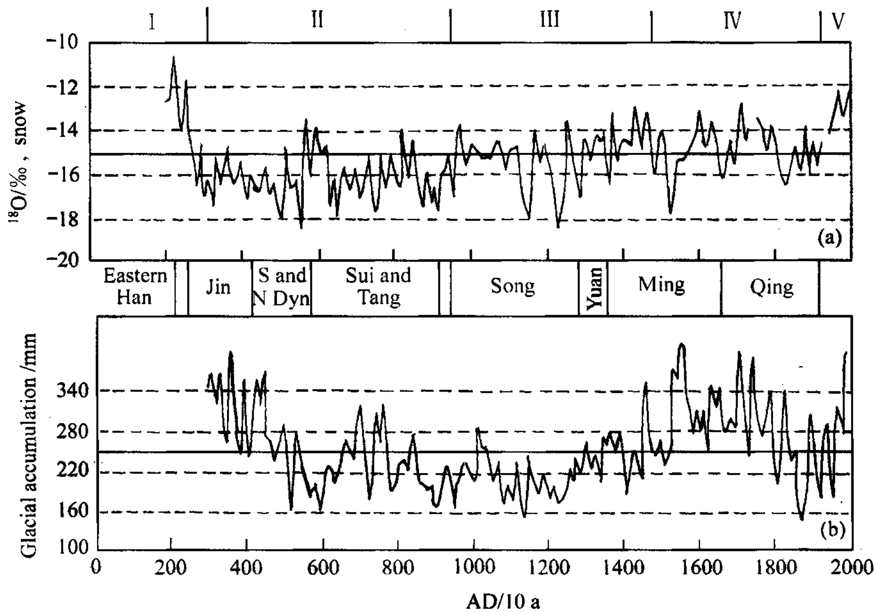

Fig. 2. Variations of $\delta^{18}O$ and glacial accumulation in the past 2000 years recorded in Guliya ice core (decadal average). (a), $\delta^{18}O$; (b), glacial accumulation; I referring to the first temporal stage, the rest are similar. Eastern Han, Jin, South and North are dynasties in Chinese history.

Table 1 The statistical table of temperature classes indicated by $\delta^{18}O$ variations

$\delta^{18}O$ Class	$\delta^{18}O$ interval	Frequency (time)	Frequency(%)	Distribution features
A: Highest Ta	> −12‰	2	1.10	mainly before 270 AD
B: Higher Ta	−12‰— −14‰	31	17.30	mainly beofre 270 AD, 18 and 20 century
C: Moderate	−14‰— −16‰	93	51.1	scattered distribution
D: Lower Ta	−16‰— −18‰	54	29.67	mainly between 3 and 9 century
E: Lowest Ta	< −18‰	2	1.10	occurred in the 550s and 1 220s

Figure 2(a) shows that the decadal $\delta^{18}O$ variations have some drastic abrupt changes. If a difference of 2‰ in $\delta^{18}O$ (corresponding to 3K in temperature) between two or three sequential decades is taken as the criterion of it, the abrupt change had taken place 33 times or so since 3rd century. Among them were several large ones, such as occurred in 250—280 AD with a decrease of 4.8‰ in $\delta^{18}O$ (corresponding to 7℃ or so in temperature), in 550—580 AD with an increase of 4.78‰ in $\delta^{18}O$ (corresponding to 7℃ or so), and in 1120—1260 AD with an increase of similar scale. Such decadal abrupt changes could have resulted in serious natural disasters.

1.2 Decadal precipitation variations reflected by snow accumulation

Snow accumulation in the ice core is the direct record of the precipitation on glacier; it, on ice cap, may be influenced by wind-blown snow; the latter can thicken or thin the former, making it somewhat different from the actual precipitation. But it excels any other indices of precipitation. Among all sorts of glaciers, the accumulation on the ice cap is closest to real precipitation. The thickness of annual accumulation zone thins with an increase in depth. Therefore, a proper model should be established so as to calculate the long-period accumulations accurately. Yao et al. have discussed the model in detail. Decadal accumulation data in Guliya ice core were reconstructed from 300 AD. The average annual accumulation was 252.6 mm. The highest values of annual accumulation, 426.5 mm and 426.7 mm, occurred in the 350s and the 1 550s AD respectively, while the lowest value, only 148 mm, appeared in the 1870s. According to the difference between the highest and the lowest accumulation, five classes with an interval of 60 mm have been classified. Table 2 presents their specific characteristics.

Table 2 The statistical annual precipitations indicated by accumulation variations

Accumulation class	Scope /mm·a^{-1}	Frequencies (time)	Frequency (%)	Distribution features
A: Highest precipitation	> 340	16	9.4	mainly before 440 AD and after 1 550 AD
B: Higher precipitation	280—340	29	17.0	mainly before 490 AD and after 8 and 16 century
C: Moderate precipitation	220—280	71	41.8	scattered distribution
D: Lower precipitation	160—220	50	29.4	mainly between 6 and 15 century, 19 century
E: Lowest precipitation	< 160	4	2.4	Occurred once in 6,10,12,19 century respectively

1.3 The combination of decadal temperature and precipitation

Three types of temperature and precipitation have been classified. As far as $\delta^{18}O$ is concerned, A and B indicate warmth, C moderate, and D and E coldness. Similarly, for accumulation, A and B indicate wetness, C moderate precipitation, and D and E dryness. Thus there are nine types of combination: warm/wet, warm/moderate, warm/dry; moderate/wet, moderate/moderate, moderate/dry; cold/wet, cold/moderate, cold/dry ones. Preliminary statistical results since 300 AD are shown in table 3.

Table 3 The statistical characteristics of combined types of decadal temperature and precipitation

Frequencies of combined types	Warm	Moderate-warm	Cold	Total number
Wetness	10	21	14	45
Moderate-wetness	12	34	25	71
Dry	4	35	16	55
Total number	26	90	55	171

The statistics of combined types begin with 300 AD.

As shown by table 3, cold events (55 times) surpass warm ones, and dry events (55 times) surpass wet ones (45 times). Among the combinations of temperature and precipitation, cold-wet events (14 times) are less than cold-dry ones (16 times). However, the times of cold-wet types are slightly less than the ones of cold-dry types in cold events, while the times of warm-wet types (10 times) are far more than the ones of warm-dry types (4 times) in warm events. As for temporal distribution of all combined types, high-accumulation events are far more than low-accumulation ones during the high-temperature period before 270 AD, and it is primarily characterized by wetness according to annual-accumulation departure curve of the Guliya ice core published by Thompson[7]. But the termination of wet period lagged the termination of high-temperature period by one century or so. Fig. 2 (b) shows that the accumulation in the 440s was 364 mm/a, after which accumulation rapidly decreased to 232 mm/a in the 470s. From 470 AD to 1 510 AD, the accumulation had been lower than average value except for a few ages. In addition, three extremely-low accumulation ages as well as 47 ones out of 50 low accumulations existed in this spell. To our knowlege, all cold-dry and warm-dry events are found in this period. Afterwards, in the 1450s and the 1530s there appeared the high accumulations of 351.8 mm/a and 366 mm/a, and then in the 1550s the accumulation rose to 426.7 mm/a which obviously indicated a great climatic change. From the 1550s to the end of the 18th century, the accumulation and temperature were higher than their average, but in the 19th century the temperature and precipitation were lower than their average. Temperature and precipitation increase dramatically in the 20th century.

1.4 Distinguished sub-stages based on climate change during the last 2000 years

Generalizing the above results, five stages may be distinguished:

1) The warm and wet period before 270 AD. A series of extremely high-temperature events ($\delta^{18}O$ higher than − 12‰) with higher precipitation occurred in the period, the termination time of which lied in the early 4th century.

2) The cold and dry period between 280 and 970 AD. During the 680-year-long period, there were 41 events with $\delta^{18}O$ higher than − 16‰, one event of $\delta^{18}O$ lower than − 18‰ which belonged to extremely low-temperature class, and only three events of $\delta^{18}O$ higher than − 14‰. The $\delta^{18}O$ values of a majority of events were lower than average value. In addition, 24 $\delta^{18}O$ values were lower than 220 mm/a, among which three accumulations were only 160 mm/a or so.

3) The moderate and dry period between 970 and 1510 AD. During the 530-year-long period, a majority of $\delta^{18}O$ values are between − 14 and − 16‰, and between 1220 and 1250 AD there appeared the maximum change: $\delta^{18}O$ value increased from − 18.3‰ to − 13.6‰. In summary, $\delta^{18}O$ values in the early period tended to stabilize, in mid-period fluctuated drastically, and in final period tended to warmth.

4) The well-defined " Little Ice Age " with drastic cold-warm fluctuations between 1510 and 1930 AD. The 410-year long period is divided into five sub-periods a, b, c, d, and e. In a- sub-period the temperature reached the lowest point (as low as − 17.74‰ in the 1520s AD) and the precipitation in the 1550s AD reached 427 mm/a. b was characteristic of temperate climate, during which warm peak ($\delta^{18}O$ − 13.16) occurred in the 1600s AD. c was the second cold event, but the degree of coldness was the minimum among the three cold periods. For example, $\delta^{18}O$ was only − 16.21‰ in the 1600s in c, which was different from the most intensive cold period in East China at the same spell. d was warmer, and $\delta^{18}O$ value in the 1710s reached − 12.77‰. In addition,

precipitation in this spell was abundant, reaching 407.6 mm/a in the 1700s. Cold period ($\delta^{18}O$ −16.45) in e (1800—1910 AD) occurring in the 1830s was a little lower than that of c sub-period, and the temperature in esub-period increased discontinuously from the 1830s to the 1920s. The precipitation in esub-period was the lowest in all stages of "Little Ice Age", and reduced to 148 mm/a or so in the 1870s. At the same time a cold event in the 1820s happened in e sub-period, which was related to volcanic activity. We will address it below.

5) The warming period since 1930 AD. The temperature rise was discontinuous in North Hemisphere, and so was it in Guliya Ice Cap. In the 1950s, the $\delta^{18}O$ in Guliya rose to −14‰, and in the 1970s to −12.6‰. According to the increase of artificial CO_2 greenhouse gases, the temperature will continue to rise. On the other hand, the precipitation in this area increased, and was more than 300 mm/a in the 1960s and the 1970s, and then reached 409 mm/a in the 1 990s.

2 Preliminary comparison between the records in Guliya ice core and other sources from East China

Guliya Ice Cap lies on the western part of the Kunlun Mts. in the Qinghai-Tibet Plateau. The special geographic position makes it somewhat differ from the climate of East China, where there are rich documentary records. A comparison has been made between Guliya ice core records and the research results derived from the documentary records of North China and East China.

Since the publication of famous article by Zhu Kezhen in 1973, there have been great advances in the research of historical climate in East China using phenological and archaeological data. Zhang Peiyuan's research group have made great efforts on the historical climate over most of the eastern China in the last 2000 years, which covers North China and Jiang-Huai Region to the east of Lanzhou and Chengdu City. *The Variations of Historical Climate in China* was published in 1996. After that, new progress has been made under the cooperation of Zhang Lansheng, Zhang Peiyuan and Zou Yiling. In order to compare it with the records in Guliya ice core, figs. 3 and 4 are drawn from the two above-mentioned research results.

Zhu found in 1973 that the first stage of the last 2000 years was warmer and wetter than the present[10], Zhang (1996) pointed out that the 280s was a turning point from warm period to cold period[9], which agreed with the great abrupt change (the temperature reduced by 7℃) in 250—280 AD in Guliya ice core. The research results on East China show that the coldest time was in 310 AD, which is in close proximity to the record of the 320s in Guliya ice core. The minute difference in time may lie in different dating techniques, but not the phase shift.

There was a special cold event around 500s (fig. 3(a)), which lasted from 485 to 580 AD and was 2℃ lower than average temperature and was the coldest event in the last 2000 years. In correspondence with it, the event occurred in the 480s ($\delta^{18}O$ departure is −3.94‰) and the 550s ($\delta^{18}O$ departure is −4.42‰) in Guliya ice core, and its accumulation was very low with very high Ca content peak, showing strong wind-force, poor vegetation and formidable natural environment. Fig. 4 shows that the drought-flood index during the time in North China was about 2.5, and the one in Jianghuai Region was 3 or so. Moreover, many floods occurred in 480—535 AD and many droughts occurred in 535—590 AD. These show that East China was wetter than West China in the spell of the cold event and the climatic fluctuations were very dramatic. Fig. 3(b) indicates that the frequency

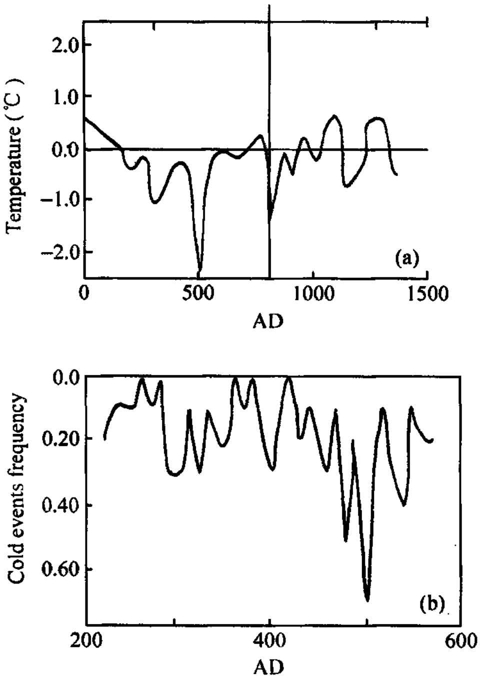

Fig. 3. The temperature change curve in the last 2000 years derived from the research results on historical materials and phenology in East China. (a) The change of temperature departures from 0 to 1500 AD, (b) The frequency change of cold events from 200 to 600 AD, (by Zhang Lansheng, Zhang Peiyuan and Zou Yiling, 1997)[8]; (c) The change of temperature departures from 1750 to 1900 AD, (d), The change of temperature departures from 1500 to 1900 AD, (by *The Variations of Historical Climate in China* edited by Zhang Peiyuan, see p. 436 of reference [9].

fluctuations of cold events in 200—600 AD was similar to $\delta^{18}O$ fluctuations at the same spell in figure 2(a).

Taking the bamboo, cypress and persimmon in Xian City and the frozen date of Shuzhou's canal as markers, the second cold event which occurred around 800 AD in Zhang Lansheng's temperature curve (fig. 3(a)) was 1.5℃ lower than the average value and next to the first cold event. But in the Guliya ice core of the western China it was a sub-warm period.

Zhang Peiyuan et al. pointed out that the climate after 910 AD tended to warmth; the winter temperature around 960 AD was 0.5℃ higher than at present; during the period (1060—1080 AD) winter temperature was 0.3—1℃ higher than at present; in 1190—1269 AD winter temperature was 1℃ higher than at present, and that the annual average temperature inferred by Zhang De'er in middle-China in the mid-13th century was 0.9—1℃ higher than at present[11]. The three periods made up the Medieval Warm Period of East China. But the records on the Medieval Warm Period are not conspicuous in Guliya ice core. Instead, cold events were frequent and intensive in 800—1300 AD.

Zhang Peiyuan et al. paid much attention to the climatic change occurring around 1230 AD, and believed that it is a global abrupt change. The climatic system before 1230 AD was in unstable state that was characterized by rapid transition and more fluctuations, while the one after it was characterized by slow transition and the decrease in temperature tended to stabilize. Fig. 2(a) shows that the coldest event in Guliya ice core took place in the 1220s, after which temperature rose with some oscillations. Fig. 2(b) shows that low precipitation appeared in the 1230s, before which there was a

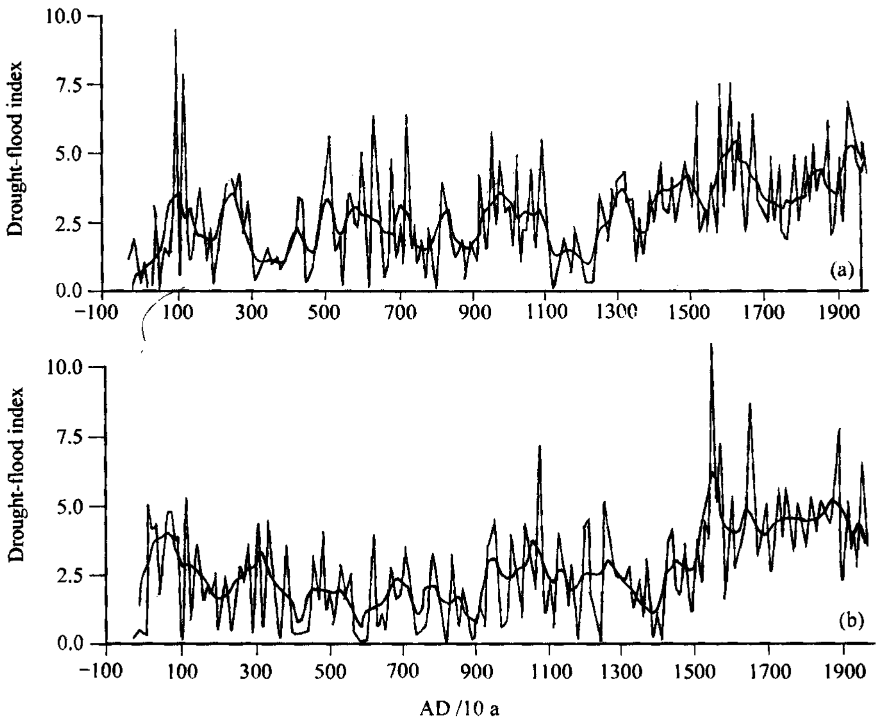

Fig. 4. Drought-flood index in the last 2000 years in East China (processed by running mean and twice calibration). (a) Jianghuai Region; (b) North China (by Zhang Peiyuan et al., 1996).

longer dry perid and after which the precipitation increased with some fluctuations. Obviously, the 1230s was also a turning point in West China.

The records in East China indicate that the Little Ice Age began in the 15th century, including cold period in 1430—1590 AD, warm one in 1510—1620 AD, cold period in 1630—1700 AD, warm one in 1710—1790 AD and cold one in 1800—1900 AD. Then the warming 20 century arrives[8,9] (fig. 3(c), (d)). In comparison with the records in Guliya ice core, the first cold event (1460—1470 AD) of the Little Ice Age on East China was 60 years earlier than that (1520—1530 AD) of the Guliya Ice Cap, while the degree of cooling in West China was much larger than in East China. By estimation, the temperature of the second cold period (1650—1660 AD) was (1.5—2)℃ lower than at present and in agreement with Guliya ice core in time, when the relative cooling of the second cold period was lower than that of the first and third periods in Guliya. The temperature of the third cold period in East China (1870—1880 AD) was about 1℃ lower than at present, while in Guliya ice core the lowest temperature occurred in the 1830s ($\delta^{18}O - 16.45‰$). In our opinion, the cold event in the 1820s may be related to the most magnificent Tambora (in Indonesia) volcanic eruption in 1815, which resulted in "no summer" in 1816, snowfall on June (Dongliu in Anhui Province), serious cold-winter weather, deeper frozen-ice on ground in Taiwan and climatic stability lasting 15 years. Meanwhile, the eruption had influence on $\delta^{18}O$ value in Greenland ice core, for example, the temperature in GISP2 reduced 1.5℃ in 4 years. Stuiver et al. (1995) pointed out that the influence was maintained till the 1820s in annual $\delta^{18}O$ curve[12]. Therefore, the cold event with more precipitation (336 mm/a) in the 1820s which occurred in Guliya ice core results from the Tambora volcanic eruption.

3 Discussions and conclusions

Based on the high-resolution record of $\delta^{18}O$ and snow accumulation variations from the Guliya ice core in the western part of the Kunlun Mts, decadal climatic variations during the last 2000 years can be profoundly discussed. The results shows that the period before 270 AD was characterized by higher temperature, in 250—290 AD temperature reduced by 7℃ and the precipitation reduced from 340 to 220 mm/a, and that the abrupt climatic change appeared in 550—580 AD and 1220—1260 AD with dramatic temperature oscillations ($\delta^{18}O$ difference of 4%). In addition, Guliya ice core shows that temperature was at a normal state with a little lower precipitation in the "Medieval Warm Period" (1000—1200 AD) obviously which occurred in Europe. The 1220s was a turning point, after which temperature and precipitation rose with some fluctuations. Between 1500 and 1930 AD, although the average temperature and precipitation were higher, their fluctuations were dramatic. Among the three cold periods of the so-called the Little Ice Age, there were two warm periods. The first cold period (1520—1530 AD) had the lowest temperature and very high accumulation, and the second cold period had moderate precipitation and the smallest cooling while the third cold period had moderate cooling and the lowest precipitation. The 1820s cold event corresponded to the prelude of the third cold period, originating from the global cooling caused by Tabora volcanic eruption in Indonesia. Since the 1920s, temperature rise has been intensive and continuous, suggesting that the Little Ice Age comes to an end.

The comparison of the ice core data with the latest comprehensive research results from historical documents of East China shows that some major climatic events, such as the warm-wet climate before the 270s, the rapid and large cooling in the 250—280s, cold events in the 310s and the 320s, the extremely-cold events and drastic fluctuations lasting almost 100 years since 500 AD, the abrupt change in 1230 AD (a significant climatic turning point), the turn-up time of the second cold valley in the Little Ice Age, the following cold event resulting from Tambora volcanic eruption in 1815 and the warming period since 1920 AD, occurred essentially synchronously among different areas which were 4 000 km apart at similar latitudes during the last 2000 years. The obvious difference lies in the "Medieval Warm Period", which is conspicuous in the East China but not in West China. Instead, there was a wider cold valley in the 9th century and the two extremely cold-dry events in the 1150s and 1220s AD respectively in Guliya ice core. After it temperature and precipitation rose with some fluctuations, but tended to decrease in East China. East China enterd the Little Ice Age earlier than West China. The first cold event of the Little Ice Age in East China was 60 years earlier than that of the Guliya ice core, when the cooling degree in West China was much larger than that of East China. The intensive-cooling and high-precipitation events in Guliya ice core at the beginning of the 16th century were confined to West China and never spread to East China.

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