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HIGH RESOLUTION RECORD OF PALEOCLIMATE SINCE THE LITTLE ICE AGE FROM THE TIBETAN ICE CORES

Tandong Yao,* Yafeng Shi* and L. G. Thompson†

**Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou 73000, China*
†Byrd Polar Research Center, The Ohio State University, Ohio, U.S.A.

Climate changes during the Little Ice Age were studied based on oxygen isotope values ($\delta\,^{18}O$) measured from ice cores recovered on, and nearby, the Qinghai–Tibetan Plateau. Three cold periods have been identified and are supported by three widely existing moraine ridges formed during the Little Ice Age. Importantly, the amplitude of the three cold periods differ in the cores studied. In the Dunde ice core, the coldest period occurred in the 17th century while it occurred in the 19th century in the Guliya ice core. All the ice cores recovered from the Tibetan Plateau and nearby regions show strong climatic warming in the 20th century. Copyright © 1996 INQUA/ Elsevier Science Ltd

INTRODUCTION

As the most recent glacial period, the Little Ice Age has been studied extensively, using various methods, in China. Historical records and tree ring records (Zhang, 1984) have aided the study of the Little Ice Age. As shown in Fig. 1 ice cores were recovered from the Tibetan Plateau, from the Dunde Ice Cap in the Qilian Mountains (Thompson *et al.*, 1989; Yao *et al.*, 1990), the Dongkemadi Glacier in the Tangula Mountain (Yao *et al.*, 1993) the Kangwure Ice Cap in the Xixiabangma area and the Guliya Ice Cap in the west Kunlun Mountain (Yao *et al.*, 1994). The Guliya Ice Cap and the Dunde Ice Cap, as the best natural archives, record a long time series and a high resolution history of past climate change. Based on data from the Guliya ice core and the Dunde ice cores the present paper will discuss climate change during, and after, the Little Ice Age.

RECONSTRUCTION OF PALEOCLIMATE

Interpreting proxy climate records is always a major issue for the study of paleoclimate. Oxygen isotope values ($\delta^{18}O$) from Tibetan ice cores are used as a paleotemperature indicator. There is a good correlation between oxygen isotope values in precipitation and air temperature, both on the Tibetan Plateau and at the northern margin of the plateau: oxygen isotopes in precipitation decrease with a decline in air temperature in winter, and increase with a rise in air temperature in summer. The correlation can be quantitatively described by a model (Yao *et al.*, 1995)

$$\delta^{18}O‰ = 0.66t - 13.5.$$

It has been calculated from the model that an increase (decrease) of 1‰ in oxygen isotope in precipitation corresponds to an increase (decrease) of 1.5°C in air temperature; or in other words, an increase (decrease) of 1.0°C in air temperature corresponds to an increase (decrease) of 0.66‰ in oxygen isotope. In order to accurately interpret ice cores, the dating of ice cores is a critical step. The dating of ice cores from the plateau was based on a combination of counting dirty layers and seasonal cycles of oxygen isotopes used by Yao *et al.* (1990). The uncertainty of the time series, since the Little Ice Age, using this method is estimated to be less than 5%.

Figure 2 shows the annual oxygen isotope fluctuation in the Guliya ice core and the Tanggula ice core since 1940. Although the distance between the two records is over 1000 km, the oxygen isotope records of these two cores shows similar trends. The important features of these two records are the warm periods in the late 1950s and the early 1960s and the warming beginning in the 1970s. These features are more obvious in the five year moving average curves (Fig. 2). The most impressive feature of the two ice cores is the dramatic warming of the

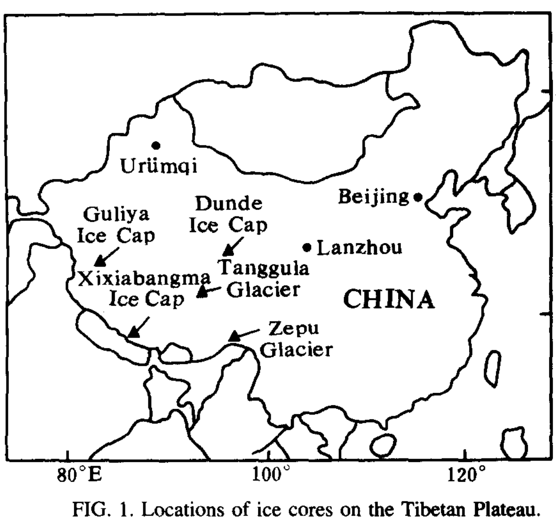

FIG. 1. Locations of ice cores on the Tibetan Plateau.

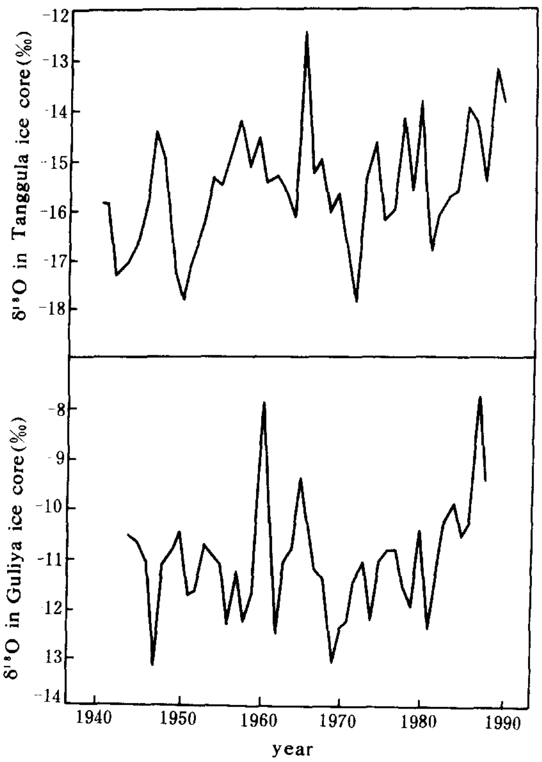

FIG. 2. The annual fluctuations of oxygen isotopes in the Tanggula ice core and in the Guliya ice core.

1980s. In Fig. 3, the warm period in the late 1950s and the warming beginning in the 1970s is also emphasized. It seems that the late 1980s warming, recorded in the Guliya ice core, is more rapid than in the Tanggula ice core.

Figure 4 shows annual, 10 year average and 100 year moving average values of oxygen isotopes reconstructed from the Guliya ice core. The annual fluctuations of

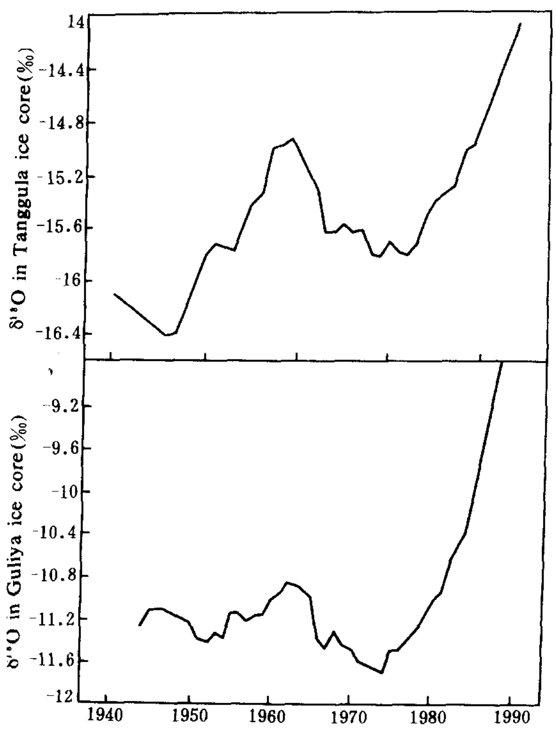

FIG. 3. Five year moving average of oxygen isotopes in the Tanggula ice core and in the Guliya ice core.

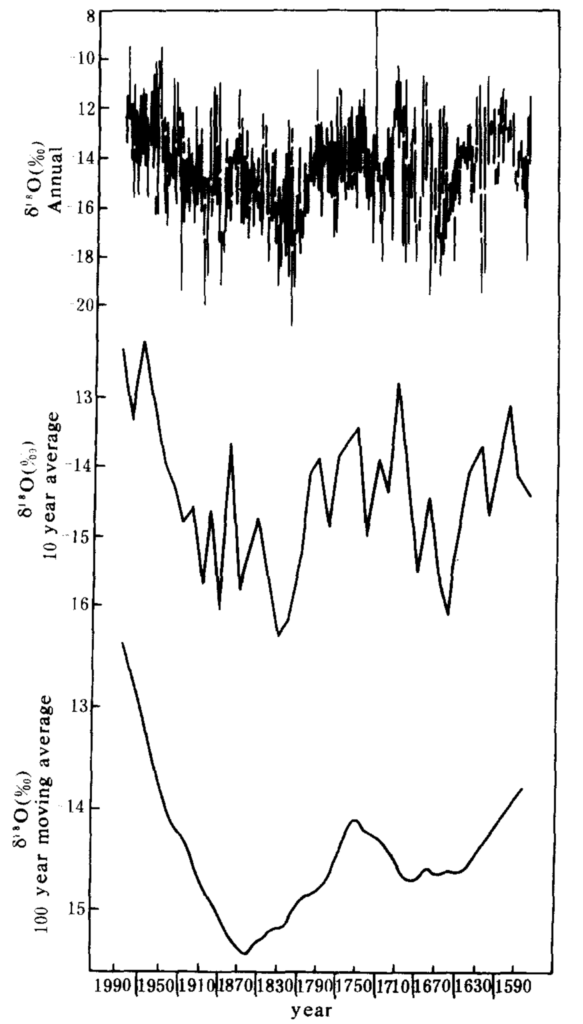

FIG. 4. Oxygen isotope record, since 1570 A.D. reconstructed from the Guliya ice core. The three curves from the top to the bottom in the figure are the annual, the 10 year average and the 100 year moving average curves, respectively.

oxygen isotope values reveal the appearance of abnormal warm year and abnormal cold year values. Basically, abnormal warm years occur during warm periods and abnormal cold years occur during colder periods and interestingly, both are fairly abundant during the transitional stage from cold to warm. Both the 10 year average and 100 year moving average reveal the basic trend of climate change since the 17th century: in the early 17th century, it was becoming colder and reached the climax of that cold period in the middle of the 17th century. Although there are some minor cold events, climatic warming is a dominant feature of the 18th century. Temperature abruptly declines during the late 18th century and reached the coldest climate during the mid-19th century. In the 20th century, climatic warming is a major feature.

Figure 5 shows the 10 year average and 100 year moving average of oxygen isotope values from the Dunde ice core. There are three obvious cold periods and three obvious warm periods since 1400 A.D. The warm periods occurred in the 16th, the 18th and the 20th centuries while the cold periods occurred in the 15th, the 17th and the 19th centuries, respectively. Some interesting features can be identified from Fig. 5.

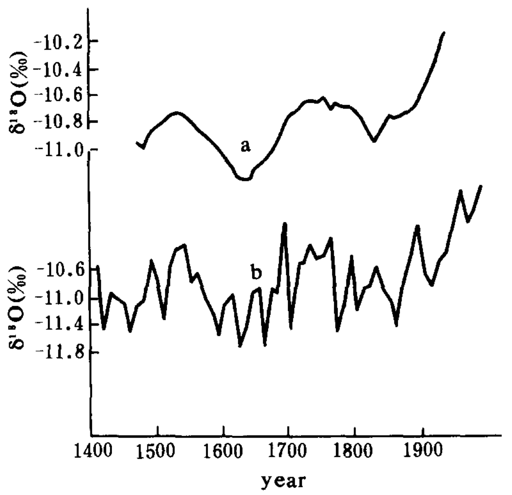

FIG. 5. Oxygen isotope record reconstucted from the Dunde ice core. In the figure, (a) stands for the 10 year average and (b) for the 100 year moving average.

(1) The amplitudes of the cold periods differ. The weakest cold period occurred during the 19th century and the coldest period, occurred during the 17th century.
(2) The degree of warmth of the three warm periods has been increasing gradually since 1400 A.D. In the 16th century warm period, isotope values are about −10.7‰, in the 18th century warm period, −10.6‰ and in the 20th century warm periods values increased to −10.2‰.
(3) Beginning in the early 20th century, especially after the 1950s, climatic warming became dramatic.

It is instructive to identify similarities and discrepancies by comparing the Guliya and the Dunde climatic records. Figure 6 reveals similar trends of long-term climatic change. In both records, we see that cold periods occurred during the 17th and the 19th centuries while warm periods occurred during the 18th and 20th the centuries. The most obvious discrepancy is that the coldest periods did not occur at the same time in the two records. In the Dunde ice core, the coldest period occurred in the 17th century. However, it occurred in the 19th century in the Guliya ice core. Because of this important discrepancy, the general trend of these two records appears different. In the Dunde ice core there is a very general increase in oxygen isotope values from the 17th century to the 20th century. In the Guliya ice core, oxygen isotope values generally decrease from the 17th century to the 19th century. Both records reveal dramatic increases during the 20th century.

DISCUSSION

The three cold periods indicated by the Dunde ice core should be considered major climatic events. We cannot distinguish, from the Guliya record in Fig. 4, the cold period of the 15th century however, we believe it does exist based on field evidence.

Field evidence can be found in China for the three Little Ice Age cold periods. Three moraine ridges exist at the terminous of glaciers in west China. By using various

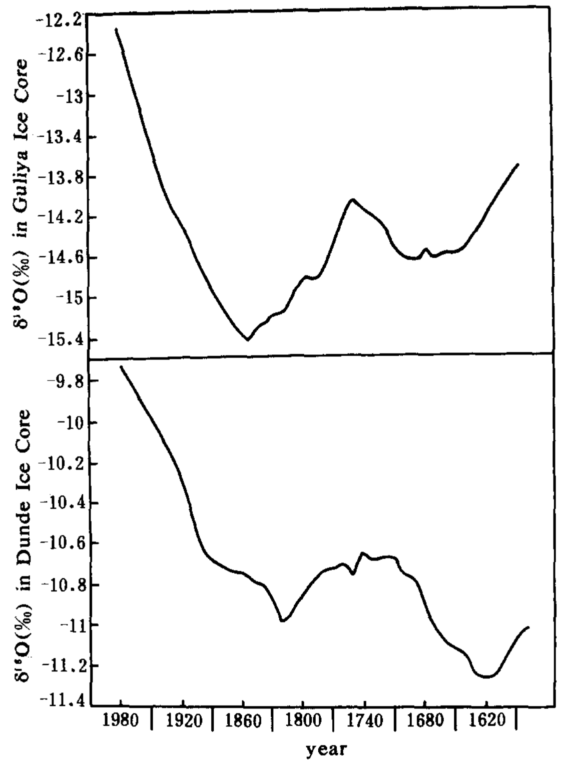

FIG. 6. A comparison of oxygen isotope records between the Dunde ice core and the Guliya ice core.

dating methods, such as tree rings from moraines, we have determined that the three moraines belong to the Little Ice Age and are direct evidence for three cold periods. The scales of the three moraines differ from region to region. In the Qilian Mountains the youngest moraine of the Dunde Ice Cap (formed in the 19th century cold period) is the smallest, while the 17th century moraine is the largest. The 17th century moraine overlies the oldest moraine, formed during the 15th century cold period. Additionally, a 17th century lateral moraine almost completely covers a 15th century lateral moraine.

At the terminous of the Guliya Ice cap, three moraine ridges are also evident. The oldest moraine (corresponding to the 15th century cold period) extends the longest distance which indicates that a relatively strong cold event may have occurred during that time. However, the 19th century moraine is the highest and largest of the three moraines, which may also suggest a strong cold event. Compared to the moraine formed during the 19th century cold period, the 17th century moraine is much smaller. In the Qilian Mountains the 17th century terminal moraine (coldest) overlies the 15th century moraine while the 19th century moraine separates from the older moraines. At Guliya the large 19th century moraine overlies the 17th century moraine, whereas the 15th century moraine separates from the younger two. Based on the above discussion, we conclude that both the ice core record and terminal moraines of the Guliya Ice Cap demonstrate that climatic cooling in the Guliya and nearby areas were stronger in the 19th century than in the 17th century.

The scale of moraine is controlled by the glacier while the scale of the glacier is dependent on temperature and precipitation. In a given region, or a given glacier, temperature and precipitation effects are variable. Based on a previous study, Yao and Shi (1990) deduced that continental glaciers are more sensitive to precipitation while maritime glaciers are more sensitive to temperature. In a cold period, like the Little Ice Age, the key factor controlling glacial development was certainly temperature. Otherwise, it is difficult to explain why glacial fluctuations during the Little Ice Age are so similar on such a spatially large scale. It is evident that the three moraine ridges correspond to the three cold periods from the ice core record. Furthermore, the greater the degree of cold, the larger the moraine ridges. At Dunde the 15th century cold period was not as cold as the 17th century cold period as revealed in ice cores (Fig. 5), therefore, the corresponding moraine ridge is smaller. The 19th century cold period was weak and of short duration, consequently the corresponding moraine ridge is the smallest. Also, at Guliya, the 19th century was the coldest period and, consequently, its' moraine is the largest of the three.

The three cold periods and three warm periods recorded in the Tibetan ice cores are also evident in the tree ring record. The three cold periods from tree ring records have a similar age range to those from the ice core record at Dunde (Table 1). Also the three cold periods recorded in Tibetan are indicated in literature from east China (Yao *et al.*, 1990).

Although the three cold periods are evident in the tree ring records there are discrepancies at the beginning and the end of these periods. The most obvious difference occurs during the 20th century. The Dunde, Guliya and the Tanggula ice core records reveal a warm period beginning in the 20th century. This is also evident in the Shanghai temperature record (Zhang, 1984). In the tree ring record, a cold period occurred between the 1920s and the 1970s (Zhang, 1981). This record also differs from temperatures recorded at meteorological stations in this region. The growth rate of tree rings is partly controlled by temperature and precipitation. Although it is generally considered that the growth rate of tree rings at the upper limit of forest development reflects temperature fluctuation and that the lower limit reflects fluctuating precipitation, the reverse must also be true. The age difference between the tree ring record, the Tibetan ice core record, the Shanghai temperature record and the local temperature record from meteorological stations my be explained by fluctuating temperature and precipitation from region to region. The above discussion implies that the ice core record may more accurately reveal high resolution climatic change.

The most impressive feature of the Guliya ice core and the Dunde ice core record is the dramatic temperature increase in the 20th century. This feature is evident on both the 100 year moving average and on the 10 year average curve. What are the reasons that caused the dramatic temperature increase during the 20th century in this region? An interesting aspect that may concern scientists, is whether or not global warming is already recognizable in this region. Almost all climate models give similar estimations for the inland area of middle latitudes. The mid-latitude inland area is most sensitive to temperature increases in the atmosphere. The Tibetan ice cores are recovered in the inland area of middle latitudes and at an altitude above 500 mb where climatic records are rarely disturbed by other factors. Therefore, the anomalous climatic warming in the 20th century, recorded in the Tibetan ice cores, may provide strong evidence for the study of global warming.

CONCLUSION

(1) Three cold periods and three warm periods have been recorded in the Tibetan ice cores since 1400 A.D. In the Dunde ice core, the coldest among the three occurred in the 17th century and the degree of warming increased gradually. The time series in the Guliya ice core is limited to 1570 A.D. which only allows us to distinguish two cold periods. We believe that the third cold period exists in the Guliya Ice Cap based on the observation of moraines at the terminous of the ice cap. Unlike the Dunde ice core, the coldest period in the Guliya ice core occurred in the 19th century.

TABLE 1. Comparison of cold periods Recorded in Tibetan Ice cores and other archives

Dunde ice core (1400–1980)		Tree ring in Qilian mountains (1400–1970)		Winter temperature in Shanghai (1471–1980)		Guliya ice core (1570–1990)	
Cold period	Warm period	Cold period	Warm period	Cold period	Warm period	Cold period	Warm period
Ist	Ist	Ist	Ist	Ist	Ist	Ist	Ist
1420–1520	1521–1570	(1428–1537) 1428–1532	(1538–1621) 1533–1621	?	?–1575	?	?–1620
2nd	2nd	2nd	2nd	2nd	2nd	2nd	2nd
1570–1690	1681–1770	(1622–1740) 1622–1740	(1741–1796) 1741–1796	1576–1690	1691–1780	1621–1710	1711–1810
3rd	3rd	3rd	3rd	3rd	3rd	3rd	3rd
1770–1890	1891–1980	(1797–1870) 1797–1866	(1871–1923) 1866–1923*	1781–1895	1896–1980	1811–1910	1911–1990

*There is another cold period after 1923 in the tree ring record.

(2) The three cold periods evident in the Tibetan ice core are also revealed in other proxy records, such as the three moraine ridges in west China, the winter temperature record since 1471 in Shanghai and the tree ring record of the Qilian Mountains.
(3) The high oxygen isotope values during the 20th century, recorded in the Tibetan ice cores, indicates that recent climatic warming of the Qinghai–Tibet Plateau is remarkable and may provide evidence for global warming.
(4) The Tibetan ice core records have not only revealed climatic change on a regional scale but, importantly, also revealed differences in climatic change on a local scale.

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REFERENCES

Thompson, L.G., Mosley-Thompson, E., Davis, B.E., Bolzan, J.F., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L. and Xie, Z. (1989). Pleistocene climate record from Qinghai–Tibetan ice cores. *Science*, **246**, 474–477.

Yao, T., Xie, Z., Wu, X. and Thompson, L.G. (1990). The Little Ice Age as recorded in the Dunde Ice Cap. *Science in China*, **11B**, 1196–1201.

Yao, T. and Shi, Y. (1990). Fluctuation and future trend of climate, glaciers and discharge of Urumqi River in Xinjiang. *Science in China*, **4B**, 504–512.

Yao, T., Pu, J. and Liu, J. (1993). Climatic study of an ice core from Tanggula on Tibet. *In:* Yao, T. and Ageta, Y. (eds), *Glacial Climate and Environment on Qinghai–Tibetan Plateau*, pp. 16–21. Academic Press.

Yao, T., Jiao, K., Tian, L., Li, Z., Shi, W., Li, Y., Liu, J., Huang, C. and Xie, C. (1994). Climatic and environmental records in the Guliya Ice Cap. *Science in China*, **24B**, 245–252.

Yao, T., Thompson, L.G., Jiao, K., Mosley-Thompson, E. and Yang, Z. (1995). Recent warming as recorded in the Tibetan cryosphere. *Annals of Glaciology*, **21**, 196–200.

Zhang, D. (1984). Synoptic and climatic analyses of dust deposition during historical period in China. *Science in China*, **No. 27B**, 278–282.

Zhang X. (1981). Tree ring in the Qilian Mountains and climatic changes in China. *Proceedings of symposium on climatic change in China*, pp. 26–35. Academic Press (in Chinese).