

Climatic variations since the Little Ice Age recorded in the Guliya Ice Core

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Abstract The climatic variations since the Little Ice Age recorded in the Guliya Ice Core are discussed based on glacial $\delta^{18}\text{O}$ and accumulation records in the Guliya Ice Core. Several obvious climate fluctuation events since 1570 can be observed according to the records. In the past 400 years, the 17th and 19th centuries are relatively cool periods with less precipitation, and the 18th and 20th centuries are relatively warm periods with high precipitation. The study has also revealed the close relationship between temperature and precipitation on the plateau. Warming corresponds to high precipitation and cooling corresponds to less precipitation, which is related with the influence of monsoon on this region.

Keywords: Guliya Ice Core, $\delta^{18}\text{O}$, glacial accumulation, monsoon.

The Little Ice Age has already been studied through various methods by different researchers. In eastern China, the Little Ice Age is studied mainly through historical document^[1-3]. In western China, progress was made through tree ring^[4, 5] and ice core study^[6]. Ice cores have been extracted on the Dunde Ice Cap, Tanggula Glacier, Xixiabangma Glacier and Guliya Ice Cap in the recent years. It is a great step to fill the blank of climate record on the Qinghai-Xizang Plateau. As the driest and coldest site of the Qinghai-Xizang Plateau, the "Third Pole of the Earth", the Guliya Ice Cap is the natural archives of high-resolution climate variations^[7-10]. The climatic variations since the Little Ice Age are discussed in this paper based on the recent data from the Guliya Ice cap.

Duration of the Little Ice Age is different according to different studies due to limitation of data series or difference in climatic conditions in different regions. This paper focuses on the period since the 17th century based on available data from the Guliya Ice Core.

1 Establishment of the time series

The dating of the ice core is based on two indexes, the seasonal variations of dust layers and $\delta^{18}\text{O}$. The stratigraphy of the ice core was described immediately after its extraction

based on the seasonal variations of dust layers. The seasonal variations of $\delta^{18}\text{O}$ can be used as a secondary index for the dating of the ice core. The variations of the dust layer thickness with depth of the Guliya Ice Core are set up based mainly on the stratigraphy of the dust layers (fig. 1). It can be seen that the amplitude of the annual layer variations is larger in the upper part, and become smaller gradually below a certain depth (about

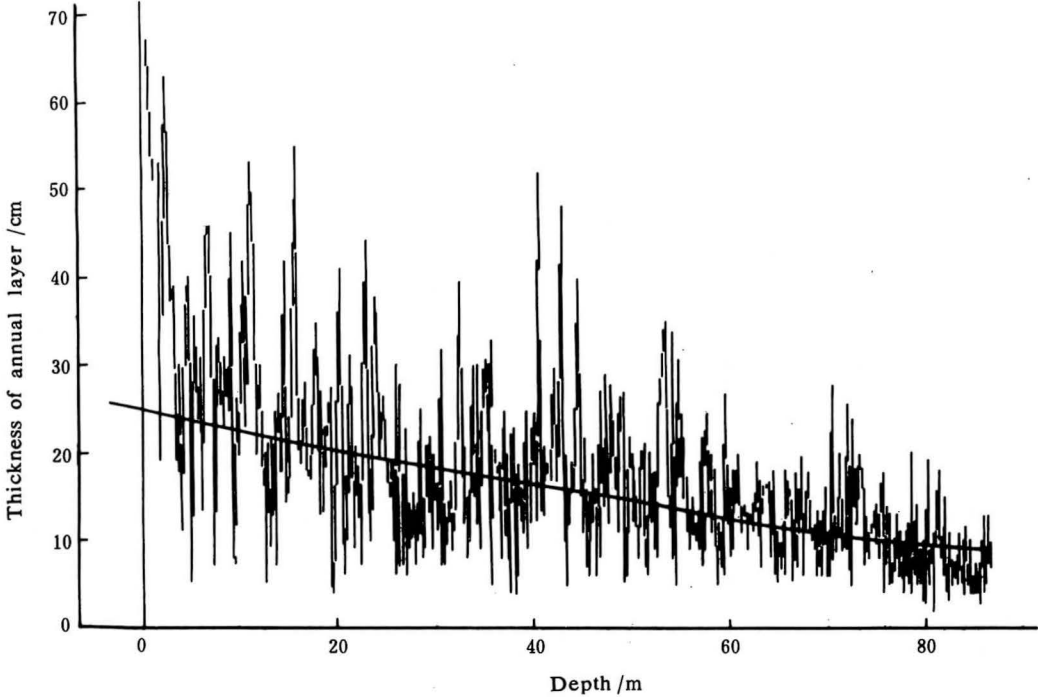


Fig. 1. Variations of annual layer thickness of the Guliya Ice Core with depth.

30 m). In order to calculate the time series of the ice core, appropriate glacial flow model must be selected at first. Of all the flow models, the most favorable model for the Guliya Ice Core is Bolzan model. According to this model, the vertical velocity $V(y)$ with depth can be expressed as

$$V(y) = b(1 - y/H)^{p+1}, \quad (1)$$

where b is average accumulation rate in m/a, y is ice-equivalent depth and p is a constant.

The relationship between annual layer thickness and the depth of ice core shown in fig. 1 is simulated with eq. (1) using reasonable strain rate, where $b=0.252$ ice equivalent, $p=2.369$, and $H=323$ m. The time-model can be expressed as

$$T(y) = 541.05[(1 - y/323)^{-2.369} - 1]. \quad (2)$$

The result from the above time-model is corrected by a time series based on dust layers, so the dating precision of this model can be improved. The model result agrees well with the time series based on stratigraphy since the Little Ice Age. At 100, 300, 400, 500 a depth obtained through counting dust layers, the corresponding ages are 104, 301, 401

and 501 a respectively according to the model result, with the maximum error of 4 a, less than 1%.

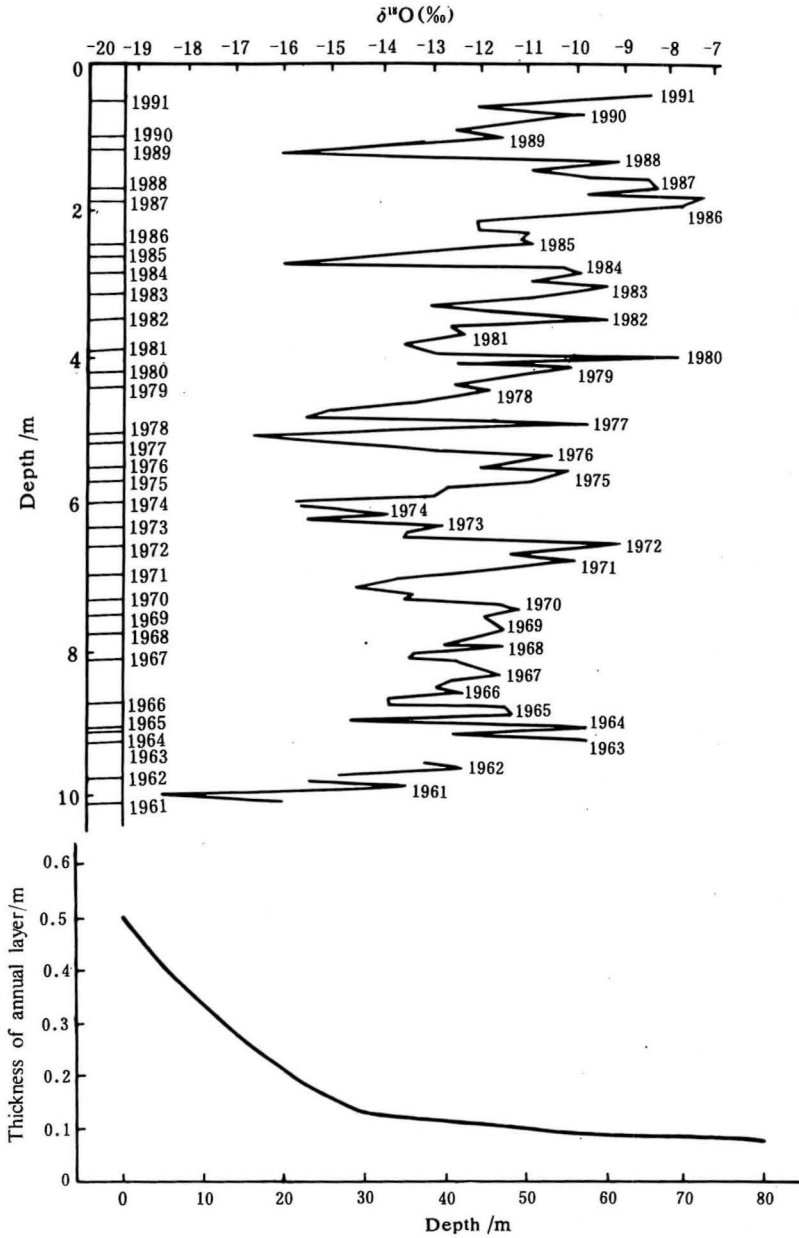


Fig. 2. Comparison between $\delta^{18}\text{O}$ time series and the time series derived from the model along the upper 10 m of the Guliya Ice Core.

In addition, the time model result is also compared with $\delta^{18}\text{O}$ time series. As shown in fig. 2, there are 30 annual layers by counting the oxygen isotope peaks from the surface to 10 m deep along the ice core. According to the dust layer model result, there are 31 annual layers from the surface to the same depth, with a precision of one year, less than 2.5%.

According to the above comparison, high-resolution time series can be established using any of the three methods. As the dust layer method is the easiest to discern, the time series used in this paper are based preferentially on the dust layer method.

2 $\delta^{18}\text{O}$ and glacial accumulation — indexes of temperature and precipitation

$\delta^{18}\text{O}$ in ice core record is a reliable temperature index reflecting the long-term climatic change. This has been verified from the following aspects. i) The seasonal variation of $\delta^{18}\text{O}$ in precipitation parallels the air temperature variation observed at meteorological stations. Whether at Tuotuohe Station, in the interior of the plateau, or at Delingha Station, in the north of the plateau, the variations of air temperature are closely related with that of $\delta^{18}\text{O}$ in precipitation. Lower temperature in winter corresponds to low $\delta^{18}\text{O}$ in precipitation, and higher temperature in summer corresponds to higher $\delta^{18}\text{O}$ in precipitation. ii) The relationship between the seasonal variation of $\delta^{18}\text{O}$ in precipitation and that of air temperature can be expressed quantitatively. Air temperature will increase (or decrease) by 1.6°C where $\delta^{18}\text{O}$ in precipitation increases (or decrease) by 1‰ , or $\delta^{18}\text{O}$ in precipitation will increase (or decrease) by 0.6‰ when air temperature increases (or decreases) by 1°C . iii) $\delta^{18}\text{O}$ in precipitation has linear relationship to altitude. $\delta^{18}\text{O}$ in precipitation increases with decreasing altitude and decreases with increasing altitude. This relation can be observed not only in the Guliya Ice Cap, but also in the whole northern part of the Qinghai-Xizang Plateau. The relationship between $\delta^{18}\text{O}$ in precipitation and altitude reflects actually the temperature dependence of $\delta^{18}\text{O}$ in precipitation, because the change of altitude can lead to the change in temperature.

Accumulation in ice core is a direct record of precipitation on the glaciers. Precipitation is received by rain gauge at meteorological stations to record the precipitation amount. On the glacier, the whole glacier can serve as a receiver to record the precipitation. At the meteorological station, the record of precipitation can be influenced by accidental error and systematic error due to the small receiving area of rain gauge, wind direction or the forms of precipitation. The accumulation on the ice cap can also be affected by snow drifting. Nevertheless, many studies have already verified that the accumulation on ice cap is closest to the actual precipitation among all kinds of glaciers.

Another factor which needs to be considered is that the relative humidity is different at different altitudes. Therefore, it is impractical to compare the absolute precipitation amount between different stations. The distribution of relative humidity with altitude on the Qinghai-Xizang Plateau is different from that in the plain region of East China (fig. 3). On the Qinghai-Xizang Plateau, the relative humidity increases with altitude at first, and then decreases, rather than increases all the time as observed in the plain region of East China. As a result, the thickness and intensity of the high-moisture layer reach the maximum of about 400 hPa. In addition, summer is the rainy season on the plateau, and the average

height of the strongest convection is also about 400 hPa. The high-moisture layer is inductive to the formation of ice crystals and cloud. Therefore, the 400 hPa level is an important height for convection and condensation on the plateau, and precipitation at this level is higher than that at low altitude. The top of the Guliya Ice Cap is about 7000 m, just in the high-moisture layer, and therefore precipitation there is higher than that at the meteorological stations at low altitude. This can be observed clearly in table 1.

Based on the above, we can see that, as far as the Guliya Ice Core is concerned, $\delta^{18}\text{O}$ and glacial accumulation are the most appropriate indexes of air temperature and precipitation.

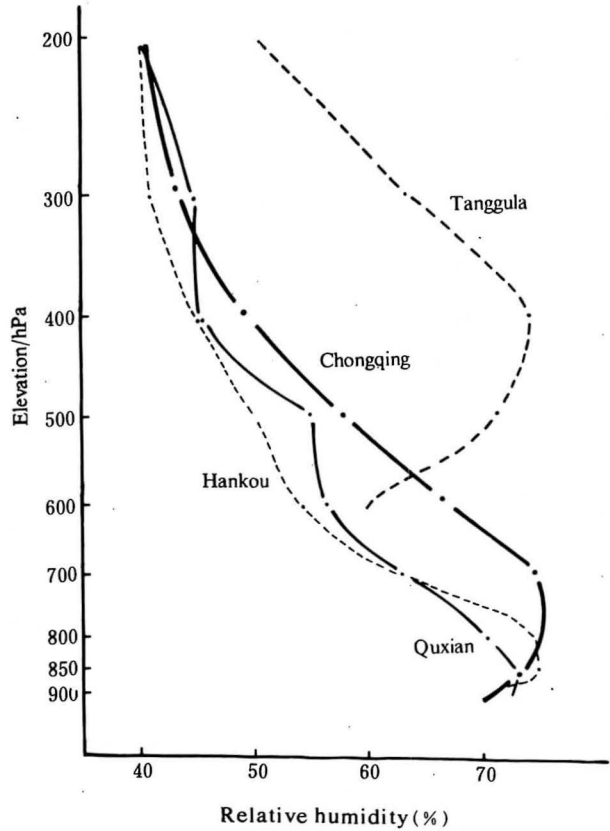


Fig. 3. Variations of relative humidity with altitude on the Xizang Plateau and in the eastern plain region.

Table 1 Comparisons of temperature and precipitation between Guliya Ice Cap and surrounding meteorological stations

Station	Latitude	Longitude	Altitude/m	Annual precipitation/mm (1570—1991)	Air temperature/°C		
					Average	January	July
Guliya			6 700	200	-19	< -24	
Tianshuihai	35° 21'N	79° 33'E	4 860	23.8	-7.7	-21.2	6.0
Kangxiwa	36° 12'N	78° 46'E	3 986	36.6	-0.6	-11.3	9.8
Tianwendian			5 171	46.7	-9.8	-21	3.0
Kongkeshanko			5 278	30.1	-9.3	-19.9	4.2
Hetian	37° 08'N	79° 56'E	1 374	35.0	12.1	-5.7	25.5

3 Reconstruction of $\delta^{18}\text{O}$ and accumulation since the Little Ice Age in the Guliya Ice Core

The variation of $\delta^{18}\text{O}$ with depth has been converted to the variation with time according to the above method (fig. 4). Annual variation and the decadal average variation of $\delta^{18}\text{O}$ are given in fig. 4. The decadal average has been smoothed by 11-point running average in order to study the trend of climatic change. The abnormal warm and abnormal cold years can be observed from the annual $\delta^{18}\text{O}$ record, and their occurrences are rather regular. The abnormal warm years generally occurred in the warm periods, whereas the abnormal cold

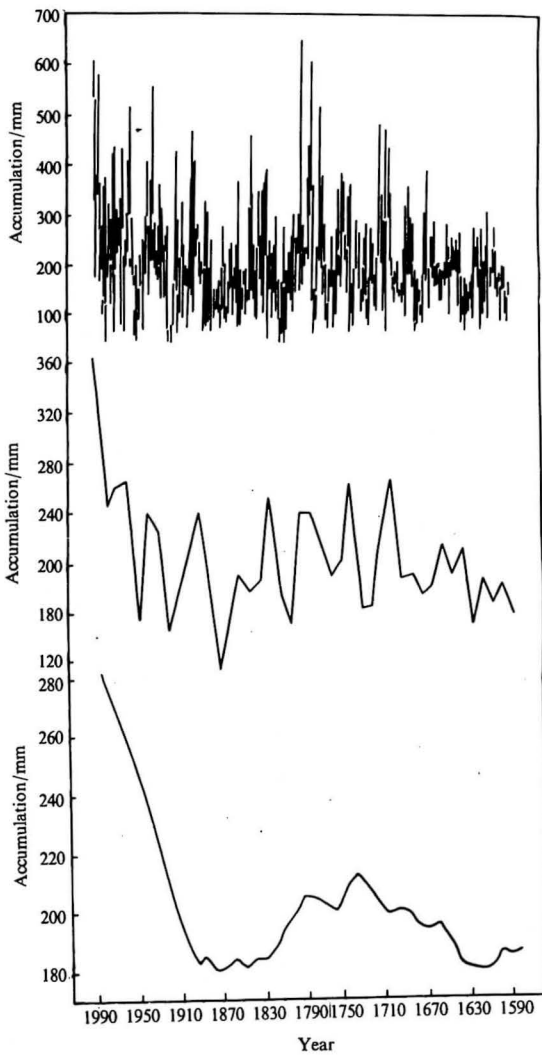


Fig. 4. Variations of $\delta^{18}\text{O}$ versus time in the Guliya Ice Core. Upper, annual variation; middle decadal variation; lower 11-point running average of the decadal average.

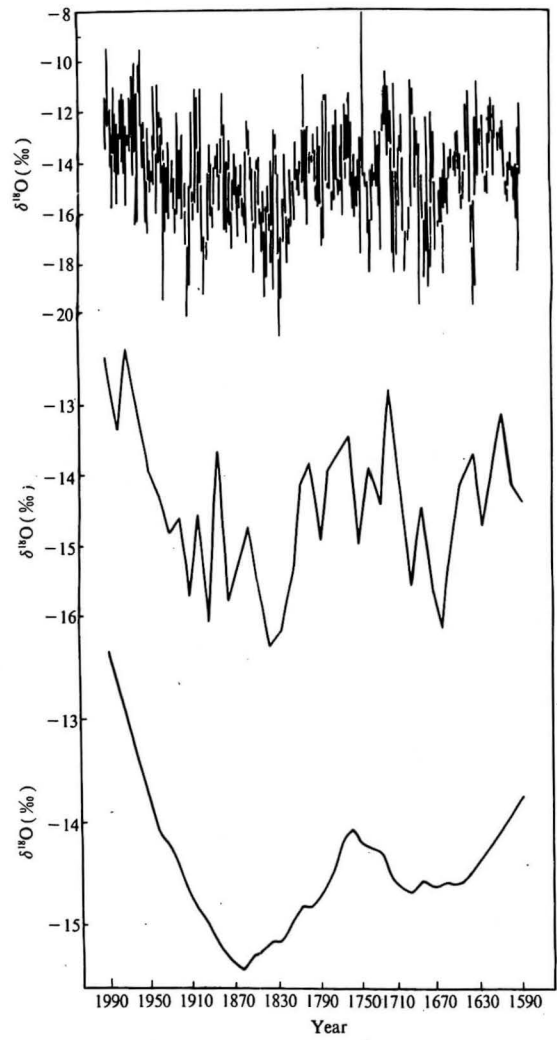


Fig. 5. Variations of glacial accumulation versus time in the Guliya Ice Core. Upper, annual variation; middle, decadal variation; lower, 11-point running average of the decadal average.

years generally occurred in the cold periods or the transitional periods from warm to cold or from cold to warm period. The occurrence of the abnormal cold years in the transitional periods can result in intensive climatic fluctuation and instability. The general change trend of temperature since the 17th century can be observed in both time series of decadal average and 11-point running average of decadal average. The climate became cool at the end of the 16th century and the beginning of the 17th century. The middle of the 17th century was coldest in this period. Climate became warmer quickly at the beginning of the 18th century, which is mainly a warm period though there are quite a few weak cold intrusions. Temperature dropped abruptly from the beginning of the 19th century and the cold climate

lasted to the beginning of the 20th century. The cold period reached its maximum in about 1820, the coldest period since the 17th century in the Guliya Ice Core record. From the beginning of the 20th century, warming is the dominant trend of climatic change.

The reconstruction of precipitation index, the glacial accumulation, is based on the variation of annual layers in ice core (fig. 1). The annual layers become thinner downwards with increasing ice thickness. Therefore, the original annual layers should be reconstructed through calculation. Because the thinning of annual layers is affected by ice temperature and ice stress ratio and so on, different reconstruction formulas are used for different glaciers. The formula applied for the Guliya Ice Core is as follows:

$$\lambda = \lambda_1 / (1 - y/H)^{3.369}, \quad (3)$$

where λ is the annual thickness at depth y , H is the thickness of the glacier, and λ_1 is the average accumulation rate. Thus, the variation of annual thickness with depth can be converted to the variation of annual thickness with time (see the upper part of fig. 5). The decadal average (see the middle part of fig. 5) and 11-point running average (see the lower part of fig. 5) of annual thickness are also given in order to study the trend of precipitation change. The 17th century is a low-precipitation period, with average annual precipitation less than 200 mm. Precipitation increased in the 18th century and there were three obvious high-precipitation periods: 1700—1720, 1730—1750 and 1770—1790. The whole 19th century is also a low-precipitation period, and the average annual precipitation is less than 180 mm except in about 1830 when precipitation had a little increase. Precipitation increases abruptly in the 20th century. Though the maximum annual precipitation during the 20th century is not as high as that during the 18th century, precipitation in the 20th century is constantly high. As a result, the average precipitation in the 20th century is much higher than that in the 18th century, which can be seen more clearly in the running average curve (the lower part of figure 5).

4 Discussion

Figure 6 shows the long-term variation of accumulation and $\delta^{18}\text{O}$ in the Guliya Ice Core record. Temperature and precipitation are clearly correlated in the Guliya Ice Core record. Low temperature corresponds to less precipitation and high temperature corresponds to high precipitation. The average annual precipitation in the cold period of the 17th century is less than 200 mm. Temperature increased in the 18th century and the annual precipitation increased to 210 mm. Precipitation in the 19th century, the coldest century since the Little Ice Age, decreased abruptly to about 180 mm. Temperature increases intensively in the 20th century, and the annual precipitation increases intensively to 280 mm which is the highest value since the Little Ice Age. The correlation coefficient of $\delta^{18}\text{O}$ and precipitation is up to 0.86. The high correlation between them is shown in figure 7.

The above feature is found not only in the Guliya Ice Core, but also in the Tanggula

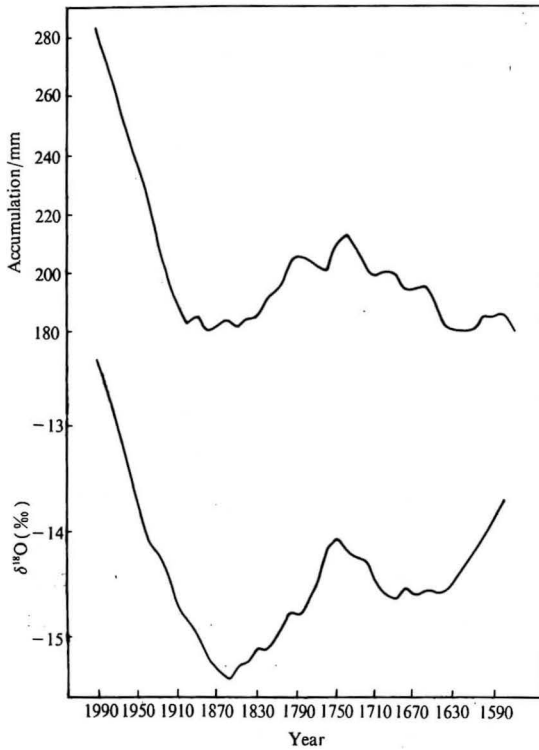


Fig. 6. Trend of $\delta^{18}\text{O}$ and glacial accumulation variation since the Little Ice Age as recorded in the Guliya Ice Core (11-point running average of the decadal average).

maputra River with abundant moisture. After the Great Turn of the Yarlung Zangbo River, the air mass entered the plateau as a "wet tongue" and reached as far as Yigong and Jiali. Afterwards, the air mass moved northwestwards as far as the north margin of the plateau. This moisture channel supplies the main precipitation moisture for the southern Xizang Plateau. Another moisture source is the Arabian Sea. In summer, because the frequent heat flow on the Indian Peninsula and Arabian Sea, a large amount of convective cloud and cumulonimbus enter the west of the plateau following the strong divergent westerly and divergent southerly winds in front of the southern trough. In winter, the extensive jet clouds on the Arabian Sea extend to the Pamir Plateau at the western end of the Qinghai-Xizang Plateau. Thus, the vortex cloud system is formed and precipitation occurs in area from the edge of the basin of southern Xinjiang to Ali area. This moisture trajectory probably leads to a large amount precipitation in the Guliya area. In summer, the Qinghai-Xizang Plateau is a strong heat origin, and the intensive convection results in the maximum wet layer at about 400 hPa, and precipitation is formed at this level (fig. 3). This moisture origin is of our specific interest because the ice core drilling altitude is at about 6000—7000 m on the Guliya Ice Cap. Another possible moisture transport path to the

Ice Core^[11]. Comparing the Tanggula Ice Core accumulation record with that of the Guliya Ice Core, we can find the pronounced correlation between the two records (figure 8).

Now that the accumulation records from two ice cores 1000 km away have the identical variation trends, and there exists a close correlation between $\delta^{18}\text{O}$ and accumulation in the two ice cores, it is reasonable to believe that this phenomenon is caused by the same process, rather than by accidental factors. This process results in not only the same temperature variation trend but also the same moisture supply of the two regions. Monsoon is just a process to control the variations. There are several possible moisture origins on the glaciers of the Qinghai-Xizang Plateau: the Bay of Bengal, Indian Ocean, southwest of the Arabian Sea^[12], regional convective transport and the westerly. The air mass from the Bay of Bengal moved along the Brah-

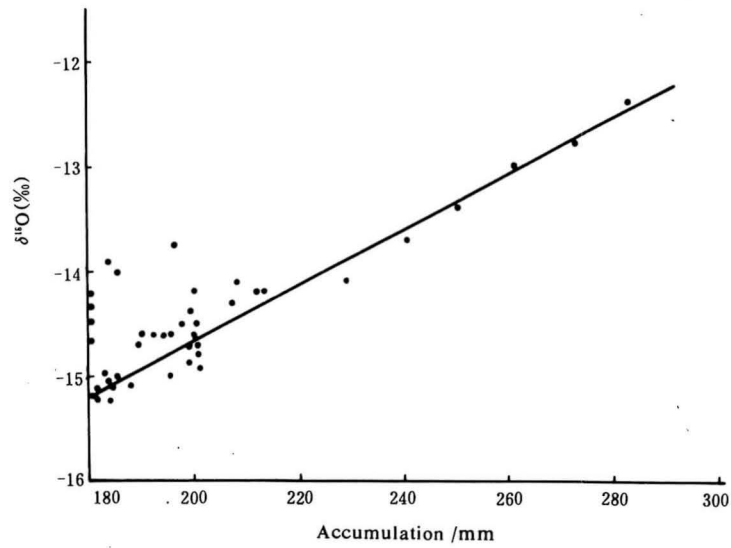


Fig. 7. Correlation between $\delta^{18}\text{O}$ and glacial accumulation in the Guliya Ice Core record.

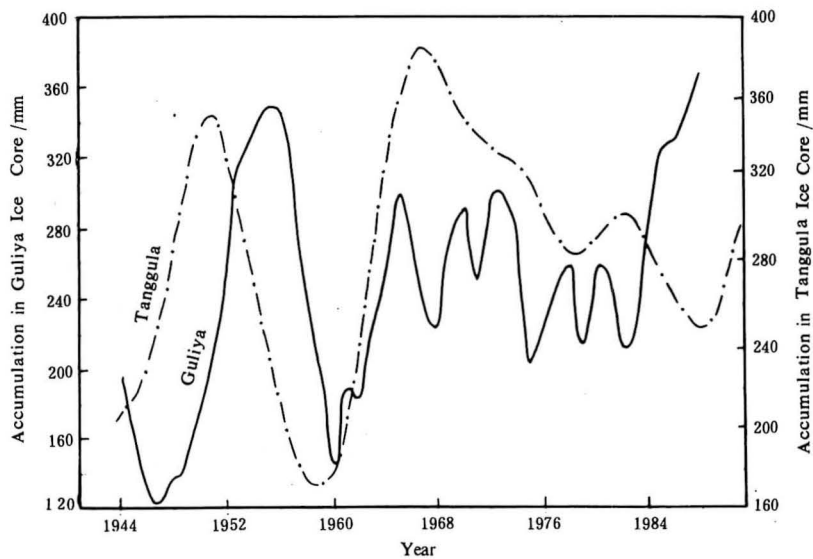


Fig. 8. Comparison of glacial accumulation records between the Guliya Ice Core and the Tanggula Ice Core.

Qinghai-Xizang Plateau is the westerly current. According to the available data, however, the possible influence of this moisture path is limited to Guliya area concerning the two regions discussed in this paper.

The following conclusions can be drawn from the above discussion. There are four main moisture origins affecting the precipitation on the glaciers across an extensive area from Guliya Ice Core to Tanggula Glacier on the Qinghai-Xizang Plateau, from the Bay of Bengal, the Arabian Sea, regional convection and westerly. It seems that the

major moisture source on the Guliya Ice Cap is connected with the oscillation of the monsoon. In the different researches, precipitation and temperature changes are undoubtedly two main factors to reflect monsoon process. After the onset of the summer monsoon, temperature increases on continent. The large temperature discrepancy between continent and ocean results in the movement of marine air mass toward continent with abundant moisture and rich precipitation is formed on the plateau. After the onset of the winter monsoon, temperature decreases on the continent, and dry and cold continental air mass moves toward ocean, resulting in a little precipitation on the continent. The long-term variations of the monsoon is in the same mechanism of the seasonal variations of the monsoon. When it is warm, the temperature of the continent and ocean increases, resulting in intensified evaporation on the ocean surface, intensified transport of moisture and intensified convection on the Qinghai-Xizang Plateau and thereby more precipitation on the plateau. When it is cold, temperature of the continent and ocean decreases, resulting in weak evaporation on the ocean surface, weak transport of moisture, weak convection and therefore less precipitation on the plateau. Though the direct moisture origins may be different on the Guliya Ice Cap and the Tanggula Glacier, the moisture origins are controlled by monsoon mechanism. This can help us understand why there exists good correlation of the temperature and precipitation changes between the Guliya Ice Cap and the Tanggula Glacier.

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