$\delta^{18}O$ records from Tibetan ice cores reveal differences in climatic changes

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ABSTRACT. Observations of the $\delta^{18}O$ in precipitation from four ice cores (Puruogangri, Dasuopu, Guliya and Dunde) from the Tibetan Plateau (TP) provide additional important perspectives on climatic warming during the 20th century in a region where there is a lack of instrumental and observational climate data. The average $\delta^{18}O$ and surface air temperature over the TP show very similar fluctuations since 1955, which provides new evidence that the $\delta^{18}O$ in the ice cores is at least in part a temperature signal. Nevertheless differences and similarities exist among the four records. Some climatic events, particularly the major cooling episodes, are synchronously recorded in Puruogangri and Dasuopu and in the Bange meteorological air-temperature record. The major features of the ice cores allow them to be classified into two groups, the northern TP group (Dunde and Guliya) and southern TP group (Puruogangri and Dasuopu). This classification is determined by the different processes driving climate change between the northern and southern regions of the TP. Moreover, the $\delta^{18}O$ variability between the ice cores within each region further documents the smaller-scale regional variability.

INTRODUCTION

Although climatic records from the Tibetan Plateau (TP) are sparse, limited studies suggest that this region might be sensitive to the current global-scale warming, and it might also exert important large-scale influences (Thompson and others, 1989, 1997, 2000; Yao and others, 1990, 1995). Although continuous instrumental measurements rarely extend beyond the 19th century for many areas of the world, for the TP such records only begin in the late 1950s. It is thus imperative to obtain the best possible high-resolution data from proxy sources in order to address past climate changes, which can provide the basis from which to study present climate and to model future trends as demonstrated in previous studies of global climate trends (Mann and others, 1999; Jones and others, 2001; Esper and others, 2002).

Since the publication of the first Tibetan ice-core records, $\delta^{18}O$ has become better established as a reliable temperature recorder on the TP (Thompson and others, 1989, 1997, 2000; Yao and others, 1990, 1995, 1996, 1999; Tian and others, 2003). The recent enrichment in $\delta^{18}O$ on the TP, especially in the ice-core records from the highest altitudes, poses an interesting question concerning the rate of warming at higher elevations compared with lower elevations. Near sea level, isotopic values show strong linkages with sea surface temperatures (SSTs) across the equatorial Pacific (Vuille and others, 2005). However, it is unknown whether the International Atomic Energy Agency global network for isotopes in precipitation (GNIP) data collected near sea level and their interpretation as a function of the 'amount effect' (Hoffmann and others, 2004) are applicable to the interpretation of the mid-tropospheric $\delta^{18}O$ recorded in ice cores. This study also addresses the major differences in climate change in northern Tibet vs monsoon-dominated southern Tibet.

Some important features of climatic changes on the TP have been revealed by ice-core paleoclimatic studies from different sites and on different timescales (Thompson and others, 1989, 1997, 2000; Yao and others, 1990, 1995). However, the central region of the TP, a key area for understanding climate variability in the region as a whole, has been difficult to access until recently. Between 1999 and 2000, we successfully drilled ice cores from the Puruogangri ice field located in the central TP (Fig. 1). The record from these new cores makes it possible to study the spatial differences in paleoclimatic changes recorded in glaciers across the TP. In addition, 10 years of data from the continuously running meteorological stations in Delingha and Tuotuohe have been used for $\delta^{18}O$ studies. It is now possible to interpret more reliably the $\delta^{18}O$ in glacier ice and in precipitation on the TP.

TEMPERATURE SIGNAL OF $\delta^{18}O$ IN PRECIPITATION ON THE TIBETAN PLATEAU

Although early studies (e.g. Yao and others, 1996) indicated that the $\delta^{18}O$ signal in the northern TP is a proxy for temperature, a comprehensive study was needed to make a definitive conclusion. Starting in 1991, a systematic observation and sampling program was initiated at two meteorological stations, Delingha (4500 m a.s.l.) and Tuotuohe (2981 m a.s.l.) (Fig. 1). A longer database now exists that allows further confirmation of the relationship between $\delta^{18}O$ and temperature. Figure 2 shows the annually averaged $\delta^{18}O$ between 1991 and 1999 based on 480 and 790 samples collected at the Delingha and Tuotuohe stations, respectively. Most of the samples were collected during the spring, summer and fall because there is little precipitation during the winter. The altitude difference between the two stations results in different mean values of temperature and $\delta^{18}O$. During the observation and sampling period, average temperature and $\delta^{18}O$ are 4.3°C

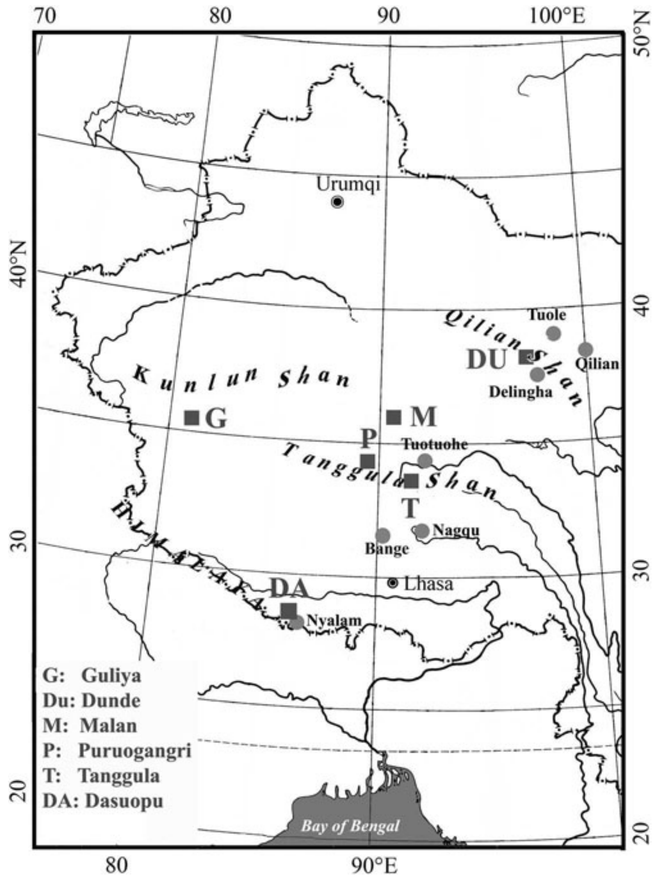

Fig. 1. Locations of the ice-core sites and meteorological stations on the TP.

and –11.57‰, respectively, at the Tuotuohe station, and 8.4°C and –8.63‰, respectively, at the Delingha station. However, the two stations show very similar fluctuations in both $\delta^{18}O$ and air temperature during the measurement period, which indicates a large-scale coherence of $\delta^{18}O$ and temperature changes on the TP. It is also clear from Figure 2e that there is strong positive correlation between $\delta^{18}O$ and air temperature at the sites. According to previous studies (Dansgaard and others, 1969; Lorius and Merlivat, 1977; Lorius and others, 1979; Jouzel and others, 1983; Jouzel and Merlivat, 1984; Mosley-Thompson and others, 2001), there is a positive correlation between $\delta^{18}O$ and air temperature in the polar regions with linear regression slopes that vary from 0.5 to 0.7‰ °C^{-1}. Rozanski and others (1992) found that slopes at European sites ranged from 0.25 to 1.1‰ °C^{-1}. The first study of $\delta^{18}O$ on the TP (Yao and others, 1995, 1996; Thompson, 2001) also indicated slopes ranging between 0.25 and 1.1‰ °C^{-1}. Further research (Yao and others, 1999) in the Ürümqi river basin, northwest China, has indicated that the correlation and the positive slope of $\delta^{18}O$ values vs temperature increases with elevation for monthly averages. In Figure 2e, the slopes both for Delingha and Tuotuohe are about 1‰ °C^{-1}.

The positive relationship between $\delta^{18}O$ and temperature based on spatial studies in the polar regions has long been used as a temperature proxy in ice-core records (Dansgaard and others, 1969; Lorius and Merlivat, 1977; Lorius and others, 1979). The accumulated $\delta^{18}O$ data from the TP now make it possible to study the relationship between $\delta^{18}O$ and temperature on longer timescales. Figure 2f shows the linear regression between the ice temperature at 10 m depth below the surface and $\delta^{18}O$ for six glaciers. The Tibetan ice-core records are of high resolution, with some being annually dated back nearly 2000 years BP. However, the Tanggula ice core is very short and only a 40 year record of $\delta^{18}O$ has been reconstructed. The $\delta^{18}O$ values for each of the six glaciers are therefore the averages of the past 40 years. A previous study by Huang (1999) revealed that the ice temperature at 10 m depth for glaciers on the TP offers an estimate of the annual air temperature. The correlation between $\delta^{18}O$ and ice temperature for the six glaciers gives a slope of 1.14‰ °C^{-1}, very close to the slope of 1.10‰ °C^{-1} obtained from the Delingha and Tuotuohe stations.

The $\delta^{18}O/T$ slope exceeding 1.0‰ °C^{-1} was obtained from the long-term $\delta^{18}O$ data from precipitation samples

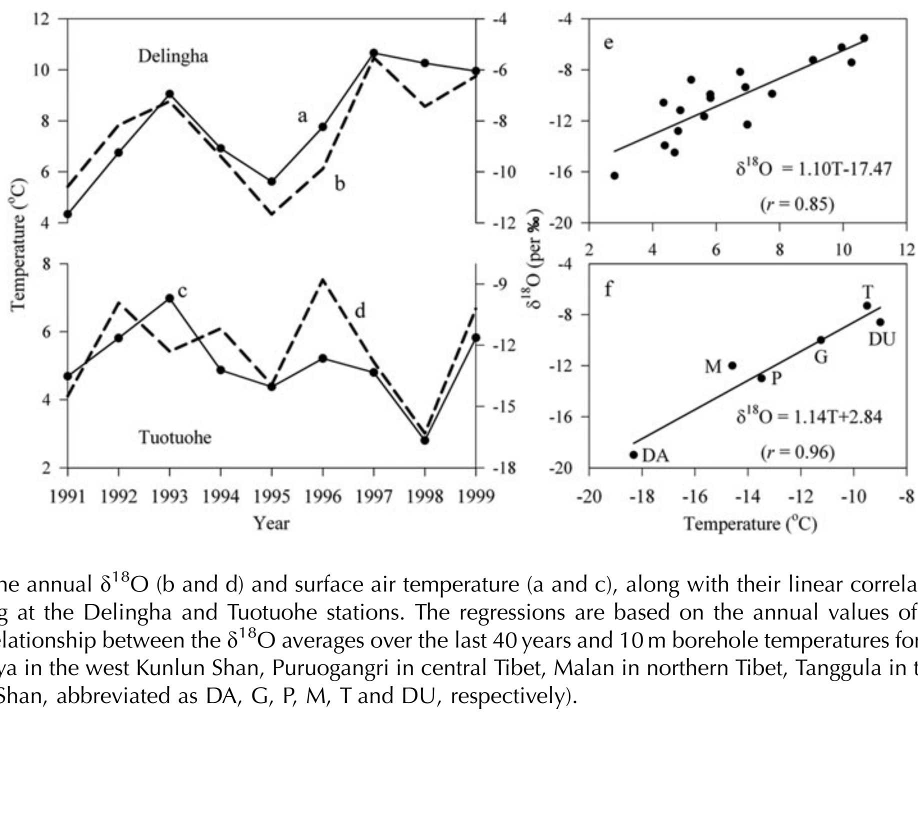

Fig. 2. (a–e) Plots of the annual $\delta^{18}O$ (b and d) and surface air temperature (a and c), along with their linear correlation (e), vs the time of precipitation sampling at the Delingha and Tuotuohe stations. The regressions are based on the annual values of $\delta^{18}O$ and surface air temperature. (f) The relationship between the $\delta^{18}O$ averages over the last 40 years and 10 m borehole temperatures for six glaciers (Dasuopu in Xixiabangma, Guliya in the west Kunlun Shan, Puruogangri in central Tibet, Malan in northern Tibet, Tanggula in the Tanggula Shan and Dunde in the Qilian Shan, abbreviated as DA, G, P, M, T and DU, respectively).

and ice-core samples, and is much higher than the previously observed slope of ~0.5–0.7‰ °C^{-1}. This likely reflects different moisture sources and air-mass trajectories as well as changes in the seasonal input (Davis and others, 2005) at sites in northern and southern Tibet. The δ^{18}O in precipitation and ice cores on the southern side of the TP is influenced more strongly by monsoon precipitation, with more depleted δ^{18}O. Over the northern TP, where there is more local recycling of water vapor, the δ^{18}O values of precipitation and ice-core samples are more enriched.

As mentioned above, over southern Tibet the variation in the δ^{18}O of precipitation is related to monsoon activity. Strong monsoons during summer bring abundant precipitation with depleted δ^{18}O. The result is a higher correlation between δ^{18}O and precipitation amount and a lower correlation between variations in δ^{18}O and temperature (Kang and others, 2000; Tian and others, 2001). This relationship persists in the annual signal (Tian and others, 2003). The ice-core δ^{18}O record from the Himalaya is weakly and negatively correlated with the amount of precipitation that is reflective of monsoon activity (Qin and others, 2000, 2002). However, over longer timescales, the ice-core δ^{18}O data represent a temperature signal. Thompson and others (2000) reported a strong positive correlation between δ^{18}O in the Dasuopu ice core and Northern Hemisphere temperature reconstructions. However, δ^{18}O in the Dasuopu ice core, unlike that in the Dunde and Guliya ice cores, is not a direct indicator of atmospheric temperature over the glacier during monsoon snowfall, but rather is an indicator of SSTs on decadal timescales (Zhang and others, 1999; Bradley and others, 2003; Davis and others, 2005; Vuille and others, 2005). This mechanism is different from that over the northern TP (Yao and others, 2002). Bradley and others (2003) and Vuille and others (2005) report that although there is a statistically significant (negative) relationship between δ^{18}O in ice cores and precipitation, isotopic records from tropical ice fields reflect the 'amount effect', because δ^{18}O is strongly related to the large-scale atmospheric circulation that is driven in large measure by tropical SSTs.

δ^{18}O RECORDED IN THE PURUOGANGRI ICE CORE OVER THE PAST 100 YEARS

The Puruogangri ice field (Fig. 1; 33°44′–34°44′ N, 89°20′–89°50′ E), which is composed of several ice caps, has an area of 422.6 km^2, with a wide and flat plateau of 150 km^2. In 1999, we investigated the Puruogangri ice field for the first time. In 2000, four ice cores were drilled (214.7, 150, 118.6 and 86 m, respectively). The results in this paper are from the 214.7 m ice core, which was cut into ~6000 samples and analyzed for δ^{18}O. The δ^{18}O measurements on melted water samples were made by isotope-ratio mass spectrometry (MAT-252), with a precision of 0.2‰.

The Puruogangri ice field is in close proximity to the desert, and annual dust layers in the ice core are clear; the core was dated by counting the visible dust layers. Gross beta radioactivity has been measured for the ice core to check the dating accuracy of this layer-counting method (Thompson and others, 2006). Beta-radioactivity measurements identified the 1963 atmospheric nuclear testing horizon and confirmed the accuracy of the dating by dust layer counting. While the entire ice-core record extends back several thousand years, here we discuss only the past

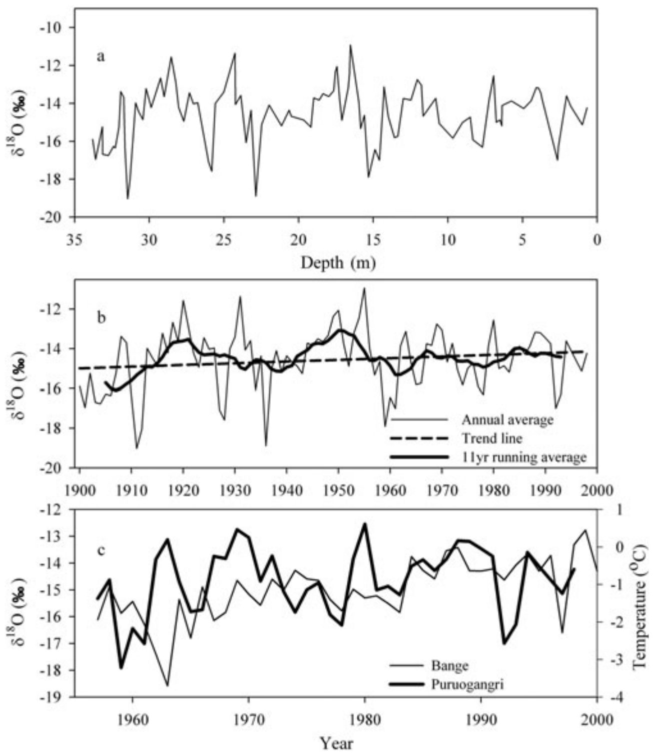

Fig. 3. (a, b) The Puruogangri ice-core δ^{18}O record is shown with depth for each sample of the upper 34.8 m of the 214.7 m ice core drilled in 2000 (a) and with corresponding time for the annual averages (b). In (b) the fine solid line shows annual fluctuations of δ^{18}O, the thick solid line is the 11 year running average and the dashed thick line provides the long-term trend in δ^{18}O. (c) The annual average of the Puruogangri δ^{18}O (thick solid line) compared with the Bange meteorological station annual air temperature (fine solid line) since 1957.

100 years and compare the δ^{18}O data with the meteorological records on the TP from ~1950 to the present.

Figure 3 presents the results from the Puruogangri ice field. Figure 3a shows δ^{18}O vs depth and Figure 3b shows δ^{18}O changes over the past 100 years. The length of the ice core corresponding to the past 100 years is 34.8 m. From 34.8 m to the top of the core, the δ^{18}O record shows abrupt warming and cooling events. Three major low-δ^{18}O events at depths of 32, 24 and 15 m correspond to three cool periods. All of the major warming events (δ^{18}O enrichment) appear below 15 m. The dashed line in Figure 3b illustrates the δ^{18}O trend since 1900.

The closest meteorological station to Puruogangri ice field is the Bange meteorological station which has been in operation since 1957. Figure 3c compares the Bange temperature record and the Puruogangri δ^{18}O record. These records show a consistent pattern over their period of overlap, and the linear regression has a correlation coefficient of $r = 0.4$ and $p < 0.02$ based on their 5 year running average from 1957 to 1998, suggesting that the Puruogangri ice-core δ^{18}O record provides a reasonable proxy for temperature and captures the general climatic changes over an extensive area.

The annual fluctuations of δ^{18}O show some prominent features, including a warming trend from 1900 to 2000 (Fig. 3b) which is also observed in the 11 year running average. Climatic changes before the 1960s were more dramatic, characterized by large-amplitude fluctuations

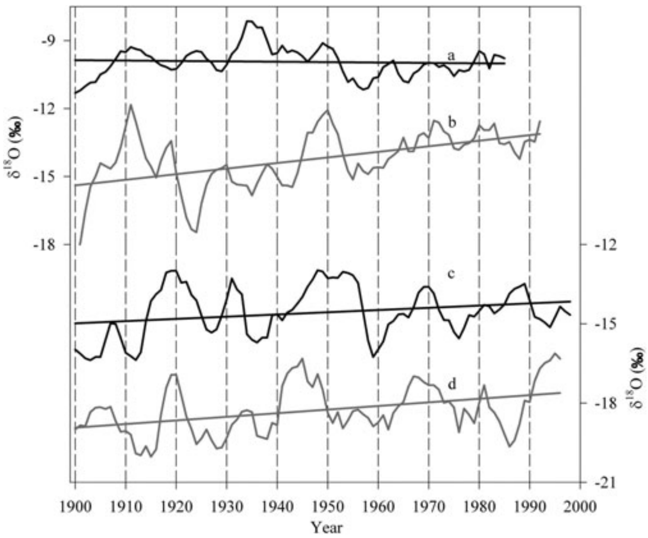

Fig. 4. The 3 year running averaged $\delta^{18}O$ records for the four ice cores from the TP presented in the paper: (a) Dunde, (b) Guliya, (c) Puruogangri and (d) Dasuopu. The trend lines of Guliya, Puruogangri and Dasuopu show obvious warming since 1900, but the Dunde warming is less obvious because the record ends in 1985.

in $\delta^{18}O$. Four major cooling events, in 1911, 1928, 1936 and 1959, have a $\delta^{18}O$ that is 5‰ below the average and there are no major cooling events after the 1960s. The major warming events also occurred before the 1960s (in 1908, 1921, 1931 and 1955) and each occurred just prior to a major cooling. It is interesting that the warming during the 1980s in the record is not as strong as in 1921, 1931 and 1955. The average temperature derived from the ice-core $\delta^{18}O$ record after the 1960s is higher than that before the 1960s. A linear regression shows that $\delta^{18}O$ increased by 0.81‰ from 1900 to 1998, corresponding to a temperature increase of 1.4°C based on our previous study (Yao and others, 1996).

MAJOR FEATURES IN $\delta^{18}O$ RECORDS IN TIBETAN ICE CORES

Figure 4 shows $\delta^{18}O$ records in the Puruogangri ice field, Dasuopu glacier, Dunde ice cap and Guliya ice cap. We are limiting our discussion to the period between 1900 and the present, as the dating for this period is more accurate. Air-temperature records from stations on the TP begin in the 1950s.

As shown in Figure 4, $\delta^{18}O$ in the four ice-core records shows apparent spatial differences, reflecting the spatially varying character of climate changes across the TP. There are also similarities among these records and especially between the Puruogangri and Dasuopu ice-core records. These two cores record all of the major warming and cooling events before 1980, and the linear regression of the 3 year running average of $\delta^{18}O$ in the two ice cores has a value of $r = 0.42$ and $p < 0.001$.

Differences between the Dasuopu and Puruogangri ice-core records are also apparent and there is an obvious discrepancy after 1980 when the two records are out of phase. The main reason for the differences between the $\delta^{18}O$ records over the past 100 years is the spatial difference of climate change patterns. Dasuopu is located along the southern margin of TP in the Himalaya, while Puruogangri is located in the center of the TP.

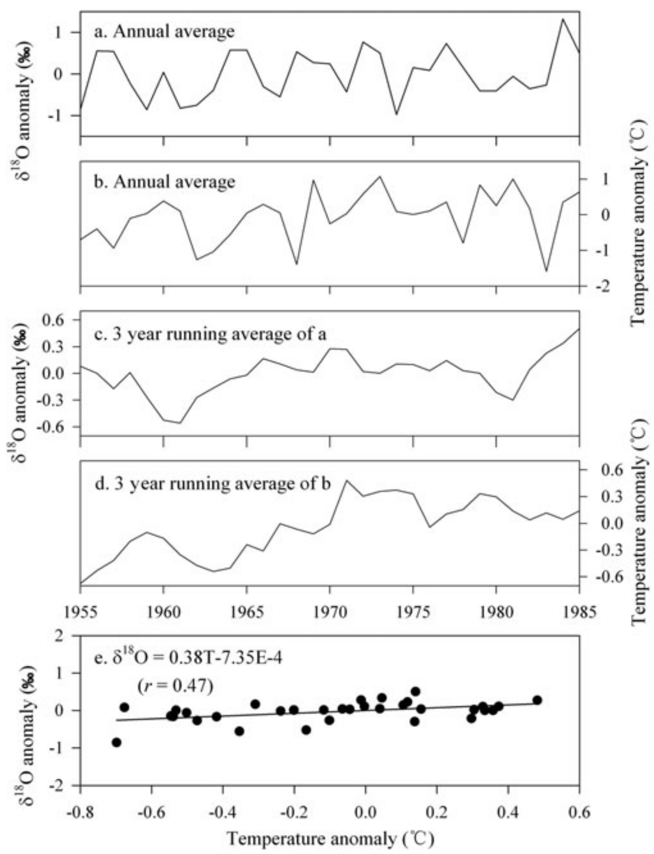

Fig. 5. (a, b) The annually averaged $\delta^{18}O$ record based on the $\delta^{18}O$ anomaly records in four ice cores (a) and the average surface air temperature recorded at 160 meteorological stations (Liu and Chen, 2000) (b) from 1955 to 1985. A positive correlation exists between them. (c–e) The 3 year running averages of $\delta^{18}O$ (c) and surface air temperatures (d) and their correlation (e).

The $\delta^{18}O$–temperature relationship suggests that the average $\delta^{18}O$ should be related to averaged instrumental temperature records as mentioned above. It is reasonable to compare the averaged $\delta^{18}O$ record of the four ice cores with the averaged surface air temperature. Liu and Chen (2000) have studied the surface air temperature on the TP and averaged the temperatures from 197 stations in and around the TP since 1955. Based on the work by Liu and Chen (2000), Figure 5 shows the comparison between averaged $\delta^{18}O$ and averaged surface air temperature. All the values are deviations from the long-term average. Because most of the meteorological data only go back to 1955, the deviations of the $\delta^{18}O$ values have been taken from a 31 year (1955–85) average (–7.54‰). A positive correlation exists between averaged annual $\delta^{18}O$ deviation and averaged annual surface air-temperature deviation from 1955 to 1985 (Fig. 5a and b). The correlation is better for the 3 year running average (Fig. 5c and d) as illustrated by the regression model shown in Figure 5e, with a regression coefficient of $r = 0.47$ and $p < 0.01$. This result argues that the spatially averaged ice-core $\delta^{18}O$ record reflects larger-scale climatic change and especially the temperature trends across the TP.

A very important feature in the Dasuopu ice-core $\delta^{18}O$ record is the greater magnitude of the temperature change than is observed in other records. For example, the increase

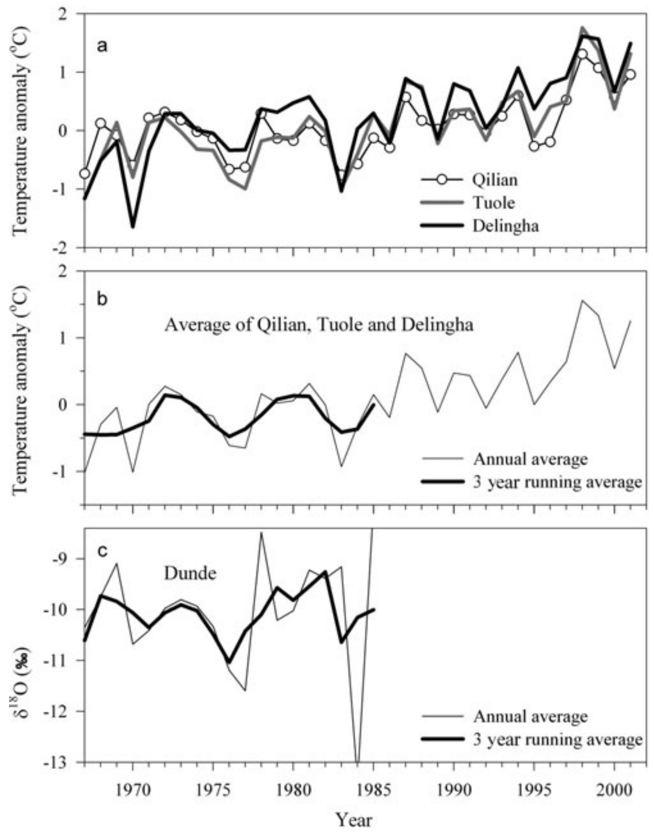

Fig. 6. Air temperatures at three meteorological stations (Qilian, Tuole and Delingha) on the northern TP (a) averaged (b) and compared with the Dunde ice-core δ^{18}O record (c).

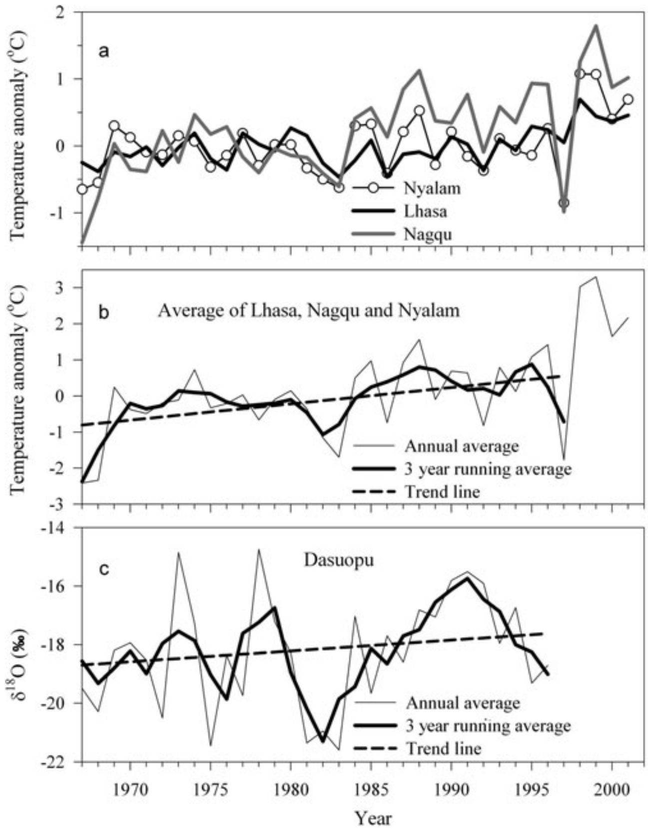

Fig. 7. Air temperatures at three meteorological stations (Nyalam, Lhasa and Nagqu) on the southern TP (a) averaged and smoothed (b) and compared with the Dasuopu ice-core δ^{18}O record (c).

of average δ^{18}O during the 20th century is 3‰ in the Dasuopu record, ~2‰ less in the Puruogangri, Dunde and Tanggula (the latter not shown) records and a little higher than 2‰ in the Guliya record. Earlier studies (Yao and others, 1990; Thompson and others, 2000) suggested that the TP is sensitive to global climatic change and the sensitivity of the TP to climatic change is amplified at the higher-elevation sites. This conclusion can also be argued by the climatic warming in the 20th century.

In Figure 4, the four cores provide very clear evidence that there are differences in the climatic changes between the southern and northern TP. From the above discussion, it is concluded that the Dasuopu and Puruogangri ice-core records show some reasonable similarity, so we have grouped them as representative of the southern TP.

The Dunde and Guliya ice cores are from the northeast and northwest TP, so it is not surprising that the two records are quite different from the Puruogangri and Dasuopu ice-core records. The Dunde and Guliya records are similar after 1940 but different prior to 1940. The differences between the two records are more obvious if they are compared year by year (not shown in the figure). For example, although the abrupt cooling events in the 1930s, early 1950s, mid-1960s and early 1980s were recorded at the same time in both cores, some warming events did not occur contemporaneously. In addition, the magnitude of the air-temperature change derived from the ice-core δ^{18}O record in each event is also different, suggesting that the nature of the climate changes is different on the western and eastern sides of the TP.

Meteorological records on the northern and southern TP also indicate significant differences. Figures 6 and 7 present six air-temperature records from meteorological stations from the north to the south of the TP. As shown in Figure 6a, the three meteorological records (Tuole, Qilian and Delingha) on the northern TP reveal very similar features over the past 35 years. The meteorological record from Nagqu differs from the northern TP meteorological records, but is similar to the meteorological records in Nyalam and Lhasa on the southern TP (Fig. 7a).

According to the correlation coefficients, the meteorological records can be classified as two groups: the northern and southern Tibetan groups. In the northern TP, the correlation coefficients between Delingha and Tuole, between Delingha and Qilian, and between Tuole and Qilian are 0.90, 0.83 and 0.91, respectively, suggesting that the three stations form one group. The correlation coefficients in the southern TP are 0.51, 0.68 and 0.41 for Nyalam and Lhasa, Nyalam and Nagqu, and Lhasa and Nagqu, respectively. Although not as high as for the northern TP stations, they clearly classify the three stations as another group.

Taking the average of the three stations in the north (Fig. 6b and c) and of the three stations in the south (Fig. 7b and c), good relationships between meteorological record and δ^{18}O record in ice core in the northern TP are illustrated in Figure 6b and c. In Figure 6b and c, both the Dunde ice core, the northernmost ice core, and the average air temperature of the three meteorological stations in the northern TP show temperature decreases in 1970, 1977 and 1984, and temperature increases before 1970, between 1970 and 1977, and after 1984. The agreement between the ice-core record and meteorological record also confirms the reliability of the δ^{18}O record in ice core as a temperature proxy.

In Figure 7b and c, the southernmost ice core, Dasuopu, is compared with the average temperature from the three meteorological stations on the southern TP. Due to the monsoon precipitation, the annual variations of $\delta^{18}O$ and the regional air temperature show large differences. Nevertheless, a large decrease (more negative) of $\delta^{18}O$ and abrupt cooling are still coincident around 1983. The trend lines of the Dasuopu ice-core $\delta^{18}O$ and the instrumental air-temperature records show a gradual increase in both $\delta^{18}O$ and air-temperature record, indicating the longer-term response of the ice-core $\delta^{18}O$ record to regional temperature changes over the southern TP.

CONCLUSIONS

The study of $\delta^{18}O$ in both precipitation and ice cores on the TP has provided key links to climatic warming in the 20th century. The long and continuous study at Delingha and Tuotuohe stations reveals the influence of temperature changes on the $\delta^{18}O$ in precipitation and hence in the ice-core records. The good comparison between the ice-core $\delta^{18}O$ record and air temperature at the nearest meteorological station confirms the reliability of $\delta^{18}O$ in ice core as temperature proxy. The plateau-scale averaged $\delta^{18}O$ and surface air temperature show similar fluctuations since 1955 and this argues once again that variations in $\delta^{18}O$ of the precipitation and hence in the ice-core record across the TP reflect predominantly variations in air temperature. The positive relationship based on a spatial correlation between $\delta^{18}O$ and ice temperature verifies the validity of temperature proxy of $\delta^{18}O$.

The Puruogangri record provides a critical link to other ice-core records on the TP and indicates that a warming trend began early in the last century. Although there were cool periods in the late 1920s, 1950s and late 1980s, the longer-term warming trend is clear. Comparing the Bange air temperature and Dasuopu isotope records reveals that some climatic events, particularly the major cooling events, were synchronously recorded in the three records. The present study indicates that the Dasuopu ($\sim$7000 m a.s.l.) and Puruogangri ($\sim$6000 m a.s.l.) records show some similarities, probably due to common moisture sources.

The four ice-core (Puruogangri, Dasuopu, Guliya and Dunde) $\delta^{18}O$ records show a gradual warming since 1900, which is related to the plateau-scale climate change. The northern ice-core $\delta^{18}O$ record reflects temperature changes on both annual and longer timescales. On the southern TP, the annual relationship between $\delta^{18}O$ and air temperature is weak, but on longer timescales they show similar variations. This difference implies that different climatic change mechanisms are operating on the northern and southern parts of the TP.

Significant differences exist in the four records, showing the diversity of climate change east–west across the TP. In the north, the differences between the Dunde and Guliya ice-core records reflect their differing climatic regimes. In the south (Puruogangri and Dasuopu), there are some similarities in the $\delta^{18}O$ variations, but also differences that reflect local to regional effects.

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