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Apparent discrepancy of Tibetan ice core $\delta^{18}O$ records may be attributed to misinterpretation of chronology

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Abstract. Ice cores from the Tibetan Plateau (TP) are widely used for reconstructing past climatic and environmental conditions that extend beyond the instrumental period. However, challenges in dating and interpreting ice core records often lead to inconsistent results. The Guliya ice core drilled from the northwestern TP suggested a cooling trend during the mid-Holocene based on its decreasing $\delta^{18}O$ values, which is not observed in other Tibetan ice cores. Here we present a new high-resolution $\delta^{18}O$ record of the Chongce ice cores drilled to bedrock ~30 km away from the Guliya ice cap. Our record shows a warming trend during the mid-Holocene. Based on our results as well as previously published ice core data, we suggest that the apparent discrepancy between the Holocene $\delta^{18}O$ records of the Guliya and the Chongce ice cores may be attributed to a possible misinterpretation of the Guliya ice core chronology.

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1 Introduction

Global climate models simulate a warming trend during the Holocene epoch, typically attributed to retreating ice sheets and rising atmospheric greenhouse gases, while global cooling was inferred from proxy reconstructions obtained mainly from the analysis of marine sediment cores (Marcott et al., 2013). The apparent discrepancy is often referred to as the Holocene temperature conundrum, possibly due to the potentially significant biases resulted from both the seasonality of the proxy data and the high sensitivities of current climate models (Liu et al., 2014). Marsicek et al. (2018) recently presented temperature reconstructions derived from sub-fossil pollen across North America and Europe. These records show a general long-term warming trend for the Holocene until ~2 kaBP (thousand years before present), and records with cooling trends are largely limited to North Atlantic, implying varied regional climate responses to global drivers.

Given the significantly positive correlation between air temperature and $\delta^{18}O$ in precipitation over the central and the northern Tibetan Plateau (TP) (Yao et al., 1996, 2013), the stable isotopic records of ice cores recovered from this area were widely

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used as a temperature indicator (Tian et al., 2006; An et al., 2016). Among all the published Tibetan ice cores, the Guliya ice core drilled to bedrock (308.6 m) from the northwestern TP (Fig. S1) is unique due to the exceptional length of its temporal coverage, estimated to be >500 ka below the depth of 290 m (i.e., 18.6 m above the ice–bedrock interface), or up to ~760 ka at the ice–bedrock interface based on ^{36}Cl dead ice in the bottom section (Thompson et al., 1997). This makes it the oldest non-polar ice core up to now (Thompson et al., 2017). The Guliya record has been widely used as a benchmark for numerous studies since its publication (e.g., Fang et al., 1999; Rahaman et al., 2009; Sun et al., 2012; Hou et al., 2016; Li et al., 2017; Saini et al., 2017; Sanwal et al., 2019). Its stable isotopic record suggests a cooling mid-Holocene based on its decreasing $\delta^{18}O$ values during that period. However, this cooling mid-Holocene is not found in other Tibetan ice core records available so far. For instance, the Puruogangri ice core drilled from the central TP (Fig. S1) shows high $\delta^{18}O$ values during the period of ~4.8-4.0 kaBP (Thompson et al., 2006), and the Dunde ice core drilled from the Qilian mountains (Thompson et al., 1989; Fig. S1) shows a high stand of $\delta^{18}O$ values during the period of ~5-2 kaBP based on its updated chronology (Thompson et al., 2005). In order to investigate this apparent discrepancy between the Tibetan $\delta^{18}O$ records, we present a new $\delta^{18}O$ record of the Chongce ice cores that were recently drilled to bedrock at the Chongce ice cap on the northwestern TP, ~30 km away from the Guliya ice cap (Hou et al., 2018; Fig. S1).

2 The Chongce ice cores and $\delta^{18}O$ measurements

In 2012, we drilled two ice cores to bedrock with the length of 133.8 m (Core 1) and 135.8 m (Core 2, 35º14′ N, 81º7′ E) and a shallow ice core (Core 3) of 58.8 m at an altitude of 6010 m above sea level (a.s.l.) from the Chongce ice cap (Fig. 1). The distance between the drilling sites of Core 2 and Core 3 is ~2 m. In 2013, two more ice cores to bedrock were recovered from the same ice cap with the length of 216.6 m (Core 4, 35°15′ N, 81°5′ E) and 208.6 m (Core 5) at an altitude of 6100 m a.s.l. (Fig. 1). More details about these ice cores can be found in Hou et al. (2018). For this study, measurements of stable isotopes were performed on the 135.8 m Core 2 and 58.8 m Core 3. In a cold room (−20 °C), Core 2 was cut into 1301 samples from the depth of 13.2 m to the bottom with a resolution of ~10 cm/sample. The bottom ~0.2 m above the ice-bedrock contact consists of a mixture of ice and sediment (Zhang et al., 2018), and is not analyzed for stable isotopes. The results were combined with the isotopic measurements of the top 13.2 m of Core 3 from An et al. (2016) to form a single profile as the two drilling sites are only ~2 m apart. Core 3 has a sampling resolution of 2-3 cm/sample. The samples were measured by a Picarro Wavelength Scanned Cavity Ring-Down Spectrometer (WS-CRDS, model: L2120-i) at Nanjing University. The stable isotopic ratio was calculated as:

$$\delta = \left[\frac{R_{sample}}{R_{reference}} - 1\right] \times 1000‰$$

where R is the ratio of the composition of the heavier to lighter isotopes in water ($^{18}O/^{16}O$ for $\delta^{18}O$), and the reference is the Vienna Standard Mean Ocean Water (V-SMOW). Each sample was measured eight times, with the first five measurements discarded in order to eliminate the effect of memory. The mean value of the last three measurements was taken as the measurement result. The analytical uncertainty is less than 0.1‰ for $\delta^{18}O$ (Tang et al. 2015).

3 Results

The $\delta^{18}O$ profile by depth of the Chongce ice core is shown in Fig. 2. For comparison, we also include the depth $\delta^{18}O$ profiles of the Guliya (Thompson et al., 1997), Puruogangri (Thompson et al., 2006) and Dunde (Thompson et al., 1989) ice cores. It is worth noting that the resolution of the $\delta^{18}O$ profiles varies from one ice core to another. The sampling resolution is ~10 cm/sample for the Chongce Core 2, and 2-3 cm/sample for the Chongce Core 3 (An et al., 2016). The 308.6 m Guliya ice core was cut into 12628 samples (~2.4 cm/sample) for $\delta^{18}O$ measurements (Thompson et al., 1997). However, the original Guliya data was not available. Instead, the Guliya data from the NOAA online repository have average resolutions of 10 m, 5 m, 3 m, 1 m and 0.6 m for the depth of 0-100 m, 100-150 m, 150-252 m, 252-308 m and 308-308.6 m respectively. The 214.7 m Puruogangri ice core was cut into 6303 samples (~3.4 cm/sample) for $\delta^{18}O$ measurements (Thompson et al., 2006), but its data from the NOAA online repository have an average resolution of 1 m for most of the core except the very top (0-1.05 m) and bottom (214.02-214.7 m) sections. The 139.8 m Dunde ice core was cut into 3585 samples (~3.9 cm/sample) for $\delta^{18}O$ measurements (Thompson et al., 1989). Data of the Dunde core are not publicly available, but we extracted the results from Fig. 3 of Thompson et al. (1989) using GetData graph digitizer software (https://docs.oracle.com/cd/E51711_01/DR/getdata.html). Although our digitized depth intervals are slightly different from their original values (i.e., 1 m and 0.5 m intervals for the depth ranges of 0-120 m and 120-139.8 m respectively) due to the pixel limit of the original figure, the general patterns of the Dunde $\delta^{18}O$ profile in the original Fig. 3 of Thompson et al. (1989) are largely preserved.

4 Discussion

A direct comparison of the Tibetan ice core $\delta^{18}O$ records could only be made based on a common time scale. The chronology of the Chongce, Guliya and Puruogangri ice cores was established by Hou et al. (2018), Thompson et al. (1997) and Thompson et al. (2006) respectively. The Dunde ice core was originally dated to be 40 kaBP at the depth of 5 m above the ice–bedrock interface, and was suggested to be potentially >100 kaBP at the ice–bedrock interface (Thompson et al., 1989). This chronology was subsequently revised to be within the Holocene (see details in Thompson et al., 2005).

The $\delta^{18}O$ profiles for the Tibetan ice cores are shown in Fig. 3. The $\delta^{18}O$ profiles of the Chongce and Dunde ice cores show an increasing trend from 6-7 kaBP to ~2.5 kaBP, while the Guliya $\delta^{18}O$ profile shows a decreasing trend from 7 kaBP to ~3 kaBP. For the Puruogangri ice core, its highest $\delta^{18}O$ value (~ -12 ‰) occurs around ~7 kaBP (Fig. 3) at a depth of ~211 m according to Thompson et al. (2006). However, this high $\delta^{18}O$ value is not observed around the depth of ~211 m in the Puruogangri depth $\delta^{18}O$ profile (Fig. 2). Indeed, all $\delta^{18}O$ values in the depth profile of the Puruogangri core are well below -12‰. Therefore, the high $\delta^{18}O$ value around ~7 kaBP of the Puruogangri core (Fig. 3) needs further verification. From ~6.5 kaBP to ~4 kaBP, the $\delta^{18}O$ profile of the Puruogangri core also shows an increasing trend, and remains relatively stable since ~4 kaBP. In addition, the Grigoriev ice core drilled from the western Tienshan Mountains (see Fig. S1 for location) also shows a rapid increasing trend of $\delta^{18}O$ since ~8 kaBP (Takeuchi et al., 2014). This warming trend during the mid-Holocene is similar to recent paleoclimatic reconstructions in other parts of the world (Samartin et al., 2017; Marsicek et al., 2018). By comparison, it seems that the $\delta^{18}O$ profile of the Guliya ice core, especially for the period of 6-7 kaBP to ~3 kaBP, is at odds with this warming trend during the mid-Holocene. It is possible that this anomaly is not caused by the dramatic difference in local climate conditions, but linked to the equally anomalous length of Guliya's temporal coverage, which is over one order of magnitude greater than that of the surrounding ice cores (Hou et al., 2018).

Cheng et al. (2012) are one of the first to question the chronology of the Guliya ice core, and argued that it should be shortened by a factor of two (Fig. 4) in order to reconcile the difference in the $\delta^{18}O$ variations between the Guliya ice core and the Kesang stalagmite records (see Fig. S1 for location). However, if compressed linearly by a factor of two, the revised chronology (Guliya-Cheng in Fig. 4) would place the high Guliya $\delta^{18}O$ values below the depth of 266 m (i.e., 110 kaBP, Fig. 2; Guliya-original in Fig. 4) in the cold glacial period (North Greenland Ice Core Project members, 2004). This is very unlikely, given the significantly positive relationship between temperature and $\delta^{18}O$ in precipitation over the northwestern TP (Yao et al., 2013; An et al., 2016). We believe the Guliya chronology needs to be further compressed until the high $\delta^{18}O$ values below the depth of 266 m (i.e., 110 kaBP, Guliya-original in Fig. 4) fall within a warm period (Guliya-New in Fig. 4), which is likely to be the mid-Holocene based on the age range of surrounding ice cores (Hou et al., 2018). Since the complete dataset of the Guliya core, as well as its detailed depth-age relationship, is not made available, a detailed comparison between the Guliya and Chongce ice cores is difficult. Therefore, we attempt to make a direct comparison between the depth-$\delta^{18}O$ profiles of the Guliya and Chongce ice cores. We first divided the depths of each $\delta^{18}O$ data points by the total core length to get the relative depths, and compared the $\delta^{18}O$ profiles of the Guliya and the Chongce ice cores based on their same relative depth (Fig. 5). The Chongce $\delta^{18}O$ profile has much higher sampling resolution than the publically available Guliya record. In order to account for this difference, we averaged Chongce $\delta^{18}O$ values based on the same relative depth intervals of the Guliya record as shown in Fig. 2a. After averaging, the Guliya and Chongce $\delta^{18}O$ profiles share much similarity (Fig. 5), and have a highly significant positive correlation (r=0.57, n=110, p=0.00), whereas their correlation is significantly negative (r=-0.79, n=16, p=0.00) based on Guliya's original chronology (Fig. 3b). Correlations between the $\delta^{18}O$ profiles of Chongce/Guliya-original and other Tibetan ice cores during their common period (i.e. 0-6 kaBP) are largely non-significant (Table 1). The highly significant correlation between the Guliya and Chongce $\delta^{18}O$ profiles based on their relative depth suggests the possibility that the Guliya core covers a similar time span as the Chongce core, which is reasonable given their close proximity (~30 km in direct distance). Consequently, the apparent discrepancy between the $\delta^{18}O$ records of the Guliya and other Tibetan ice cores (Fig. 3) may be attributed to a possible misinterpretation of the Guliya ice core chronology. This would also cast doubt on the notion of asynchronous glaciation on the TP on Milankovitch timescales (Thompson et al., 2005), which is developed based on the original chronology of the Guliya ice core.

Recently, Ritterbusch et al. (2018) applied ^{81}Kr dating, with the updated laser-based detection method of Atom Trap Trace Analysis (ATTA), to the bottom ice samples collected at the terminal of the Guliya ice cap. The resulting ^{81}Kr ages are <50 kaBP. The exact age is likely to be even younger than 50 kaBP because this age lies at the

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low limit of the ATTA method and serves as an upper constraint for the actual age. The ^{81}Kr dating results are more than 1 order of magnitude younger than the original Chronology of the 1992 Guliya ice core (Thompson et al., 1997), and roughly in line with the age ranges of the other Tibetan ice cores (Zhang et al., 2018; Hou et al., 2018).

From September to October of 2015, several new ice cores were recovered from the Guliya ice cap, including a core to bedrock (309.73 m) and a shallow core (72.40 m) adjacent to the 1992 Guliya core drilling site, as well as three cores to bedrock (50.72 m, 51.38 m, 50.86 m) from the summit (35º17′ N, 81º29′ E, ~6700 m a.s.l.) of the Guliya ice cap (Thompson et al., 2018). The Guliya summit 50.80 m ice core (note that the depth 50.80 m is given in Zhong et al., 2018, which is slightly different from 50.86 m given in Thompson et al., 2018) was dated to be ~20 kaBP at the depth of 41.10–41.84 m and ~30 kaBP at the depth of 49.51 to 49.90 m by matching the δ^{18}O values with those from the 1992 Guliya ice core (Zhong et al., 2018). We made use of the two age points above, as well as the density profile of the 2015 Guliya summit core (Kutuzov et al., 2018), to estimate the basal age of the Guliya summit core by applying a two-parameter flow model (2p model) (Bolzan, 1985), and obtained 76.6 kaBP, 48.6 kaBP and 42.1 kaBP at the depth of 1 cm w.e. 20 cm w.e., 40 cm w.e. above the ice–bedrock contact (Fig. S2). Although these estimates have great uncertainty due to limited data, the results are still one order of magnitude younger than the original Chronology of the 1992 Guliya ice core (Thompson et al., 1997) despite the fact that the two age points (i.e. ~20 kaBP and ~30 kaBP) used by the 2p model are deduced from the original chronology of the1992 Guliya ice core (Zhong et al., 2018). This casts further doubt on the original Guliya chronology.

5 Conclusions

In this study, we provided a new high-resolution $\delta^{18}O$ record of the Chongce ice cores drilled from the northwestern TP. Our results show a warming trend for the mid-Holocene on the TP, which is largely consistent with the Dunde and, to a lesser degree, Puruogangri ice cores, but much different from the Guliya ice core. It is possible that the cooling mid-Holocene derived from the Guliya $\delta^{18}O$ record resulted from its erroneous chronology, rather than the unique boundary conditions on the TP

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as previously suggested, such as decreasing summer insolation and weakened Indian monsoon (Hou et al., 2016; Li et al., 2017). Our study highlighted the urgent need for more ice core records with reliable chronologies, especially results from the 309.73 m Guliya ice core drilled in 2015 close to the 1992 Guliya core drilling site (Thompson et al., 2018) to verify past temperature variation on the TP, which serves as important baseline information for many other studies, and based on which various scientific hypotheses such as asynchronous glaciation on the Milankovitch timescales (Thompson et al., 2005) could be further tested.

Data availability. The $\delta^{18}O$ data of the Chongce ice core will be provided in the Supplement. At this stage, please refer to the corresponding author for the data.

Author contributions. SH conceived this study, drilled the Chongce ice cores and wrote the paper. WZ performed the $\delta^{18}O$ measurements. All authors contributed to a discussion of the results.

Competing interests. The authors declare that they have no conflict of interest.

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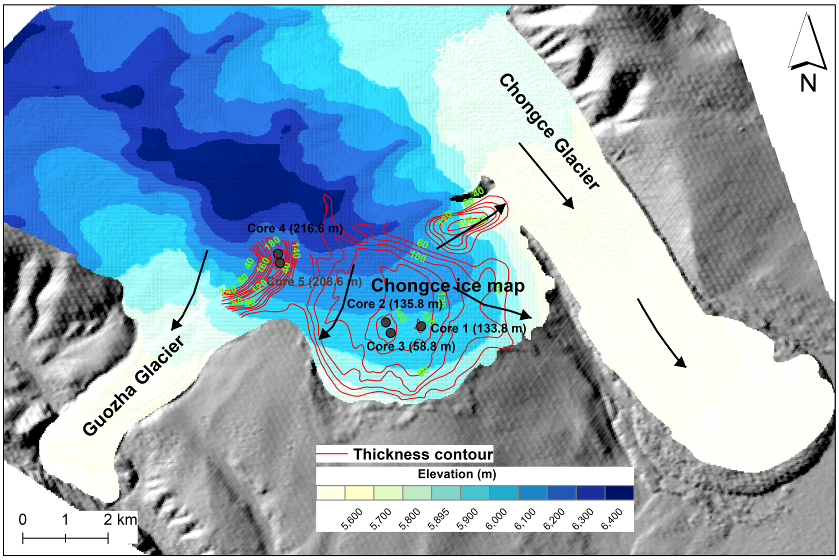

Figure 1. Map showing the topography (red contour lines) and ice thickness (blue color ramp) of the Chongce ice cap with the drilling sites (black dots). The black arrows show the ice flow direction. The effects of the Chongce Glacier surging on the mass balance of the Chongce ice cap is limited, if any (Wang et al., 2018), because the ice flows from the Chongce ice cap into the Chongce glacier, and the surged area is confined within the Chongce Glacier (Yasuda and Furuya, 2015).

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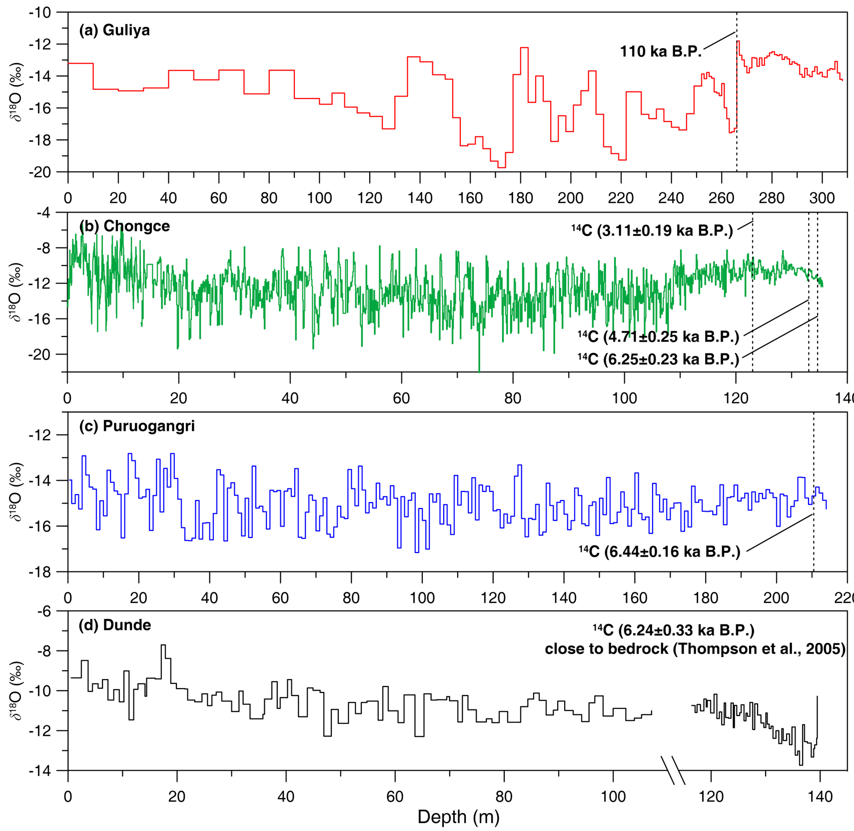

Figure 2. The $\delta^{18}O$ profiles of the ice cores against each respective depth. The age of 110 kaBP at the depth 266 m of the Guliya ice core is from Thompson et al. (1997). The top 13.2 m of Chongce Core 3 profile (An et al., 2016) is combined with Core 2 to form a single profile because the distance between their drilling sites is only ~2 m (Fig. 1). Data of Guliya and Puruogangri were obtained from the NOAA online repository, and the data of Dunde were extracted from the Fig. 3 in Thompson et al. (1989) using GetData graph digitizer software.

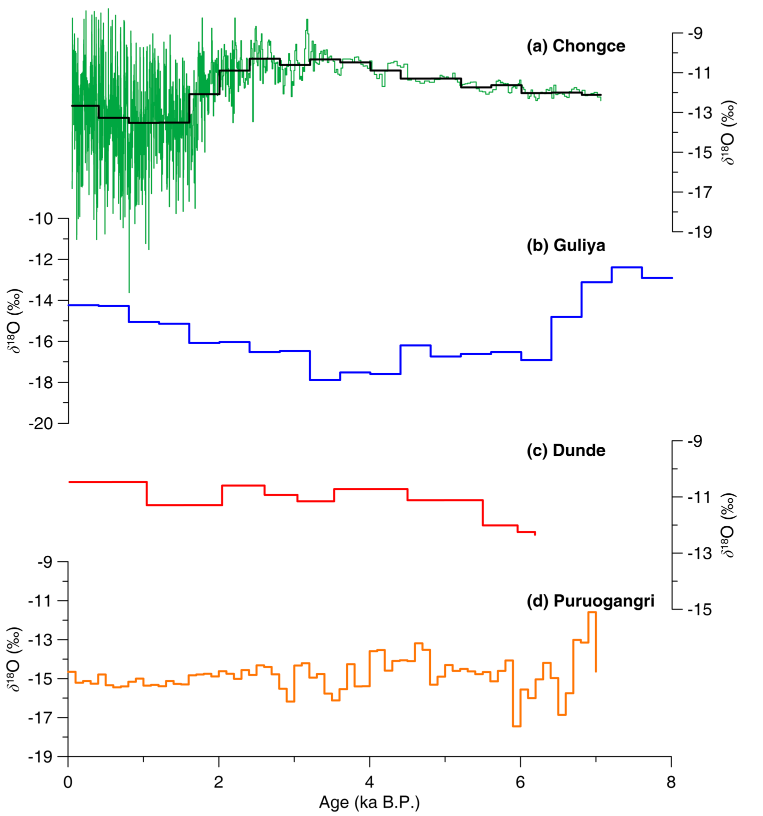

Figure 3. The $\delta^{18}O$ profiles of the Chongce (a), Guliya (b), Dunde (c) and Puruogangri (d) ice cores by age. We combined the $\delta^{18}O$ profiles of Core 2 and Core 3 into a single time series. The black line of the Chongce $\delta^{18}O$ profile represents 400-year averages to match the temporal resolution of the Guliya ice core data that are available from the NOAA online repository. The 100-year averages of the Puruogangri ice core are also available from the NOAA online repository, but the multi-centurial averages of the Dunde ice core were extracted from Figure 3 of Thompson et al. (2005) plotted based on its updated chronology instead of its original chronology (Thompson et al., 1989).

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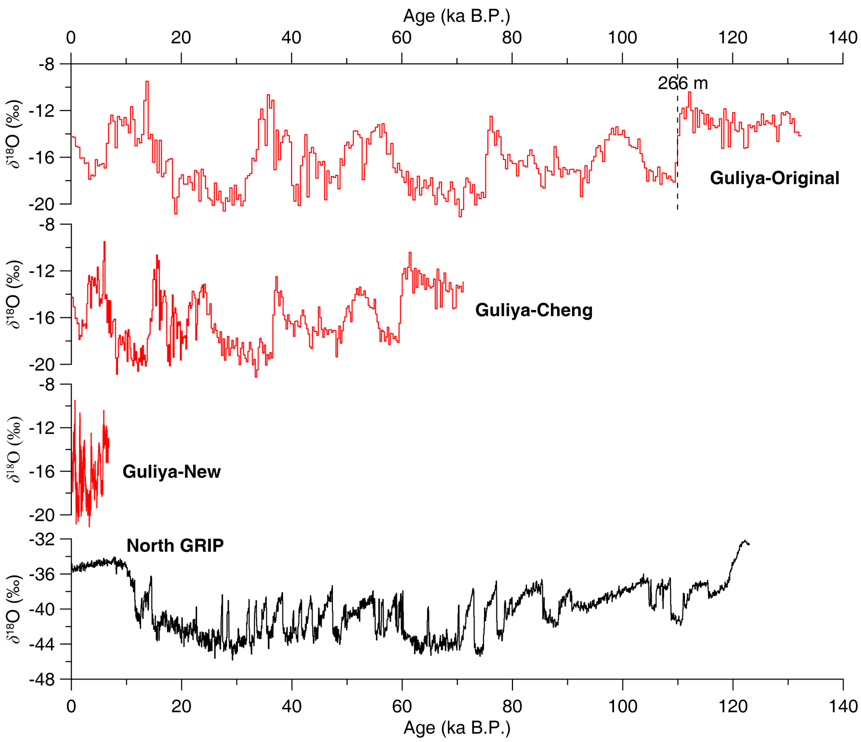

Figure 4. The $\delta^{18}O$ profiles of the Guliya and North GRIP ice cores. The Guliya-Original is plotted on its original chronology (Thompson et al., 1997). The Guliya-Cheng profile is the original Guliya record linearly compressed by a factor of two, as suggested in Cheng et al. (2012). The Guliya-New profile is the original Guliya record further compressed linearly so that the high $\delta^{18}O$ values fall within the warm Holocene.

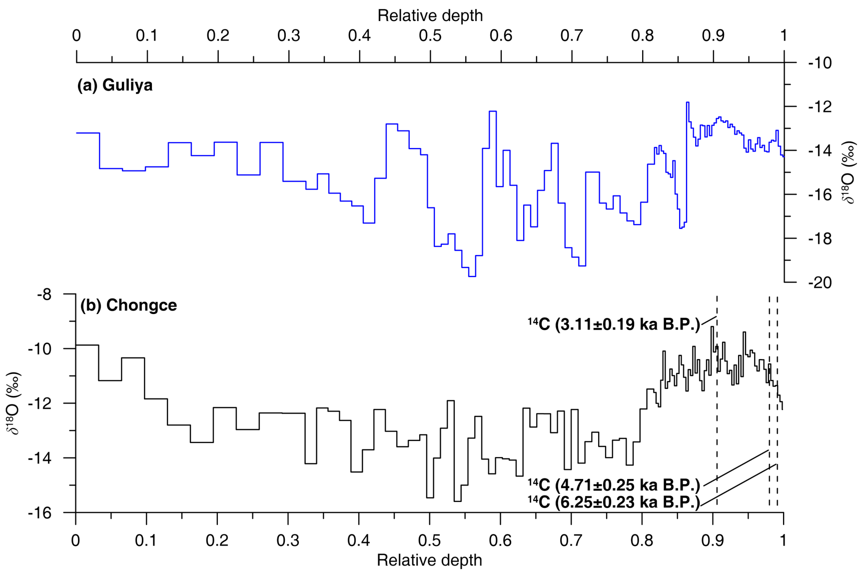

Figure 5. The $\delta^{18}O$ profiles of the Guliya (a) and Chongce (b) ice cores, plotted against their relative depth. The Chongce profile was averaged to match the temporal resolution of the published Guliya record as shown in Fig. 2a (Thompson et al., 1997).

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Table 1. Correlation coefficients (n=16) between the $\delta^{18}O$ profiles of the Tibetan ice cores.

	Chongce	Guliya	Puruogangri
Guliya	-0.79 [a]		
Puruogangri	0.22	-0.10	
Dunde	0.11	0.24	-0.11

[a] $p < 0.001$