Anonymous Referee #1

The manuscript entitled "Apparent discrepancy of Tibetan ice core $\delta^{18}O$ records may be attributed to misinterpretation of chronology" by Hou et al. presents a new high resolution $\delta^{18}O$ record from the Chongce ice core from the Tibetan Plateau (TP) on the basis of the previously published timescale (Hou et al., 2018). The record covers the middle and late Holocene (the past ~7 kyr). Although the Chongce ice core is very close to the Guliya ice core (~30 km away), the Holocene pattern in the Chongce $\delta^{18}O$ record is clearly different from the original Guliya $\delta^{18}O$ record (Thompson et al., 1997). As such, the authors attributed the observed discrepancy between the Holocene $\delta^{18}O$ records of the Guliya and the Chongce ice cores to a misinterpretation of the Guliya ice core chronology. Given the fact that the Guliya record (covering the past ~130 kyr based on its original timescale) has been widely used as an important climate reconstruction/benchmark (cited nearly 1000 times), even after its chronology was questioned by Cheng et al. (2012), the new observational data obtained near Guliya and the new insights about Guliya chronology are fascinating and thus deserve to be published. However, I have a few suggestions for improvement pending on which I recommend acceptance of this paper.

(1) The authors imply that they could not get the original dataset of the Guliya and other Tibetan ice core records that were used in several published papers. Please contact the authors of the original papers again to get the original datasets, instead of using digitizer software or other approximate approaches.

Response:

I sent an email on 3 April to the corresponding author of the original papers regarding the possibility of sharing the original datasets of the Guliya and other Tibetan ice core records, and got responses from Prof. Lonnie Thompson on 13 April, and Prof. Ellen Mosley-Thompson on 15 April. They said they would provide a web link for downloading the Dunde ice core $\delta^{18}O$ datasets. We are very grateful for their willingness to share the datasets, and will update the figures accordingly with the datasets. It is worth pointing out that, even without the original datasets, the general patterns of the Guliya and Dunde $\delta^{18}O$ profiles are sufficiently preserved in the summary data to support our conclusions.

(2) The interpretation of Tibetan ice core $\delta^{18}O$ data solely as a temperature proxy needs to be further validated. The apparent positive relation observed between ice core $\delta^{18}O$ and local temperature from instrumental records cannot be mechanically extrapolated to explain the relation on much longer timescales, for example, the Holocene (e.g., Liu et al., 2015; Shao et al., 2017). This claim is crucial to Tibetan ice core researches, including this paper, and should be more rigorously backed up with empirical data and/or model simulations.

Response:

Many studies have shown a significant positive correlation between local temperature and isotopic composition in precipitation in the northern Tibetan Plateau (e.g., Yao et al., 1996; Tian et al., 2003). This positive correlation is also observed between local temperature from instrumental records and isotopic composition in ice cores from Tibetan Plateau (e.g., Tian et al., 2006; Kang et al., 2007; An et al., 2016). Specifically, An et al (2016) established a statistically significant correlation between annual (not seasonal) $\delta^{18}O$ of Chongce ice core and annual temperature record at Shiquanhe (the nearest climate station). In addition, simulations by the LMDZ4 general circulation model indicate that this positive correlation between local temperature and precipitation isotope has persisted during the Holocene (Risi et al., 2010).

Although changes in moisture source (as indicated by Liu et al., 2015) or large-scale atmospheric circulation (as indicated by Shao et al., 2017) could influence precipitation isotopic composition in the Tibetan Plateau, such changes often lead to concurrent temperature change with the same effect on the precipitation isotopes. Therefore, we believe that the isotopic variability of Chongce ice core primarily reflects local temperature signals.

(3) In the past decade, more and more evidences demonstrate that the temporal pattern of the precipitation $\delta^{18}O$ changes on orbital-scale, including the Holocene, broadly follows Northern Hemisphere summer insolation (NHSI) inversely in the westerlies (e.g., Bar-Matthews et al., 2003; Cheng et al., 2012a, 2016a; Cai et al., 2017; Mehterian et al. 2017), Indian Monsoon (e.g., Zhang et al., 2011; Cheng et al., 2012b; Cai et al., 2015; Kathayat et al., 2016; Han et al., 2017), East Asian Monsoon (e.g., Cheng et al., 2016b) climatic regimes, as well as within the Tibetan Plateau (e.g., Cai et al., 2010, 2012; Zhang et al., 2011). Cheng et al. (2012) proposed two possibilities: (1) Both the Guliya and Kesang relationships (nearly opposite on orbital-scale) could be valid, with differences related to the different elevations and localities of the sites. (2) Alternately, differences could be reconciled if the low excursions in Guliya $\delta^{18}O$ were, instead, correlated to high excursions in $CH_4$ (or higher NHSI). Notably, all aforementioned precipitation $\delta^{18}O$ records show a consistent inverse $\delta^{18}O$–NHSI relationship on orbital (possibly millennial) timescale with rather similar amplitudes, in line with the latter possibility. As such, the authors should take the above observations into consideration. In other words, a detail comparison of the Guliya ice core record with the NHSI or a large number of precipitation $\delta^{18}O$ records remains one of valid (or better) approaches to establish a more reliable Guliya ice core chronology. Additionally, the new dates from the bottom of the Guliya ice cap indeed show some last glacial ages (Thompson et al., 2018; Zhang et al., 2018; as well as the data in Figure S2), which are consistent with the chronology of the 'Guliya-Cheng' (rather than

the 'Guliya-New') reconstructed on the basis of a comparison with other precipitation $\delta^{18}O$ records from both Westerlies and Asian Monsoon climatic domains.

Response:

We think that the Guliya-New chronology is more reasonable than Guliya-Cheng for several reasons. (1) The Guliya-Cheng chronology would put the high stands of $\delta^{18}O$ values of the Guliya profile from the depth 266 m to the ice core bottom (Fig. 4 in our manuscript) in the cold glacial period. This is very unlikely, given the significantly positive relationship between temperature and $\delta^{18}O$ in precipitation over the northwestern TP (see the response above). (2) The ages established in Zhang et al (2018) and Ritterbusch et al. (2018) only serve to provide upper constraints, and the actual bottom age of the ice cores is likely to be younger. Thompson et al. (2018) did not provide any new estimates of the bottom age of the Guliya ice cores (both 1992 and 2015 cores), as they wrote that "Future analyses will include $^{14}C$ on organic material trapped in the ice, and $^{36}Cl$, beryllium-10 ($^{10}Be$), $\delta^{18}O$ of air in bubbles trapped in the ice, and argon isotopic ratios ($^{40}Ar/^{38}Ar$) on deep sections of 2015PC2 to determine more precisely the age of the ice cap." (3) The data in Fig. S2 in our manuscript is based on Zhong et al. (2018), who established the chronology of the 2015 Guliya summit ice core by matching its $\delta^{18}O$ values with those from the 1992 Guliya ice core (Thompson et al., 1997). There is still much inconsistency between the age ranges of the 2015 Guliya summit ice core and the1992 Guliya ice core despite the fact that the two age points of the 2015 Guliya summit ice core are deduced from the original chronology of the1992 Guliya ice core. This casts further doubt on the original 1992 Guliya chronology. Consequently, the chronology of the 2015 Guliya summit ice core might also suffer from this questionable original 1992 Guliya chronology. (4) Hou et al. (2018) provided convincing evidence that the bottom age of the Chongce ice cores is likely within the Holocene, consistent to the other Tibetan ice cores except the Guliya ice core. Given the similarity between the Guliya and Chongce depth $\delta^{18}O$ profiles (Fig. 5 in our manuscript), it is reasonable to suggest that the Guliya core covers a similar time span as the Chongce core, though a more detailed comparison (Fig. 4 in our manuscript) would be necessary when more evidence and the original datasets of the Tibetan ice cores become available in order to confirm the Guliya-New chronology.

Consistent with all other precipitation $\delta^{18}O$ records in the westerlies regime, the Chongce ice core $\delta^{18}O$ record also shows an inverse $\delta^{18}O$-NHSI relationship at the precession time scales. There are two possible explanations for this inverse $\delta^{18}O$–NHSI relationship. First, some studies suggest this inverse relationship is caused by the possible incursions of the Asian summer monsoon moisture (with low $\delta^{18}O$) into central Asia during the high NHSI summers. For example, the speleothem $\delta^{18}O$ record from Kesang Cave in northwestern China was much depleted at times of high NHSI (Cheng et al., 2012, 2016), a feature closely resembling speleothem records in Asian summer monsoon regime. The second explanation suggests that one would expect an inverse $\delta^{18}O$–NHSI relationship if winter precipitation (with low $\delta^{18}O$) in the westerlies region increased during the low Northern Hemisphere winter insolation (NHWI, which has a reverse phase with NHSI) (Tzedakis, 2007; Kutzbach et al., 2014). At present, there is no consensus on what caused the inverse $\delta^{18}O$-NHSI relationship, and additional studies are needed for unravelling the underlying mechanisms. Here, we compared the Chongce isotopic record with other records of precipitation $\delta^{18}O$ in the westerlies regime, including speleothem $\delta^{18}O$ records from the Kesang Cave in the northwestern China (Cheng et al., 2012), the Ton Cave in Uzbekistan (Cheng et al., 2016), the Kinderlinskaya Cave in the southern Ural Mountains (Baker et al., 2017), and the Soreq Cave from Central Israel (Bar-Matthews et al., 2003), and a record of the oxygen isotope composition of permafrost ice wedges from the Lena River Delta in the Siberian Arctic (Meyer et al., 2015) (Fig. 1). All of these records show a consistent rising trend during the middle to late Holocene, in contrast with decreasing trend observed in the isotopic record of the Guliya ice core during this period.

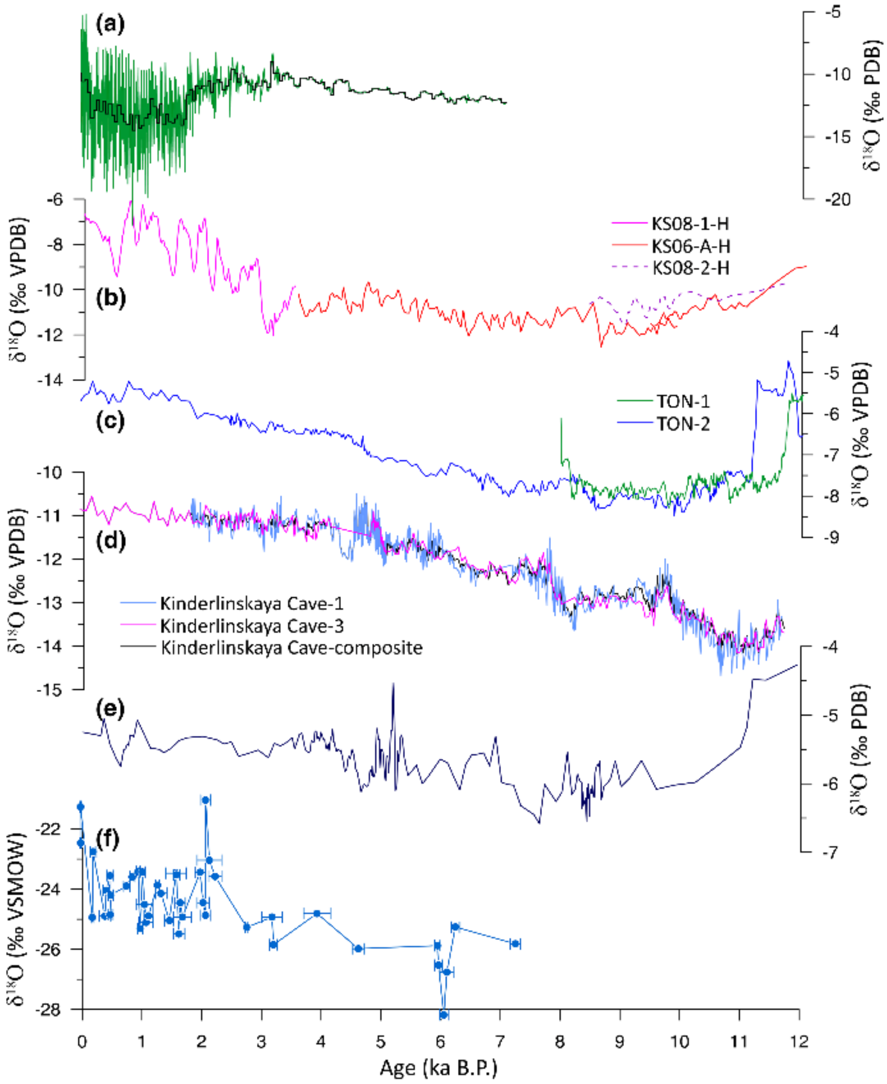



**Fig. 1:** Comparison of oxygen isotopic records during the Holocene from the Chongce ice core (a), the Kesang Cave (Cheng et al., 2012) (b), the Ton Cave in Uzbekistan (Cheng et al., 2016) (c), the Kinderlinskaya Cave in the southern Ural Mountains (Baker et al., 2017) (d), the Soreq Cave from Central Israel (e) and permafrost ice wedges from the Lena River Delta in the Siberian Arctic (Meyer et al., 2015) (f).

(4) Broadly, the amplitude of $\delta^{18}O$ variations on orbital (or glacial-interglacial) scale is about ~8 ‰ in the Westerlies (e.g., Bar-Matthews et al., 2003; Cheng et al., 2012a, 2016a; Mehterian et al., 2017) and Indian Monsoon (e.g., Cai et al., 2010, 2012, 2015; Kathayat et al., 2016) domains, and ~4 ‰ in the East Asian Monsoon domain (e.g., Cheng et al., 2016b). In addition, the climate during the interglacial time periods, including the Holocene, is fairly stable as inferred by a wide range of proxy records, including various precipitation $\delta^{18}O$ records. Provide the 'Guliya-New' chronology was factual, the prominent multi-millennial changes around the mid-Holocene as characterized by ~10 ‰ $\delta^{18}O$ change (larger than

the large regional glacial-interglacial amplitude) would be an unconceivable anomaly (Figure 4), which requires a proper explanation.

Response: Large amplitudes of $\delta^{18}O$ variations are often observed in the Tibetan core cores during the Holocene, such as ~8 ‰ for the Guliya ice core (Fig. 2 in the manuscript) (or ~6‰ based on its original chronology, Fig. 3 in the manuscript), ~6.5 ‰ for the Chongce ice core (Fig. 5 in the manuscript), and ~6 ‰ for the Puruogangri ice core (Fig. 3 in the manuscript). This is largely attributed to the elevation dependency of temperature change observed in many studies, i.e. high altitude regions experience larger temperature changes than low elevation regions (Beniston et al. 1997; Liu and Chen, 2000; Mountain Research Initiative EDW Working Group, 2015). In addition, prominent changes in water vapor sources associated with northward and southward shifts of the westerly circulation on longer timescale (e.g., from multi-millennial to orbital timescales) may also contribute to the large amplitude of $\delta^{18}O$ variation in core cores on the Tibetan Plateau.

References cited:


An, W., Hou, S., Zhang, W., Wu, S., Xu, H., Pang, H., Wang, Y., and Liu, Y.: Possible recent warming hiatus on the northwestern Tibetan Plateau derived from ice core records, Sci. Rep., 6:32813, doi:10.1038/srep32813, 2016.

Baker, J. L., Lachniet, M. S., Chervyatsova, O., Asmerom, Y., and Polyak, V. J.: Holocene warming in western continental Eurasia driven by glacial retreat and greenhouse forcing, Nat. Geosci., doi:10.1038/NGEO2953, 2017.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., and Hawkesworth, C. J.: Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the eastern Mediterranean region and their implication for paleorainfall during interglacial intervals, Geochim. Cosmochim. Acta, 67, 3181–3199, 2003.

Beniston, M., Diaz, H. F., and Bradley, R. S.: Climatic change at high elevation sites: an overview, Clim. Change, 36, 233-251, doi: 10.1023/A:1005380714349, 1997.

Cheng, H., Zhang, P., Spötl, C., Edwards, R. L., Cai, Y., Zhang, D., Sang, W., Tan, M., and An, Z.: The climatic cyclicity in semiarid-arid central Asian over the past 500,000 years, Geophy. Res. Lett., 39, L01705, doi:10.1029/2011GL050202, 2012.

Cheng, H., Spötl, C., Breitenbach, S. F. M., Sinha, A., Wassenburg, J. A., Jochum, K. P., Scholz, D., Li, X., Yi, L., Peng, Y., Lv, Y., Zhang, P., Votintseva, A., Loginov, V., Ning, Y., Kathayat, G., and Edwards, R. L.: Climate variations of central Asia on orbital to millennial timescales, Sci. Rep., 6, 36975, doi:10.1038/srep36975, 2016.

Hou, S., Jenk, T., Zhang, W., Wang, C., Wu, S., Wang, Y., Pang, H., and Schwikowski, M.: Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains, The Cryosphere 12, 2341 – 2348, doi: 10.5194/tc-12-2341-2018, 2018.

Kang, S., Zhang, Y., Qin, D., Ren, J., Zhang, Q., Grigholm, B., and Mayewski, P.: Recent temperature increase recorded in an ice core in the source region of Yangtze River. Chin. Sci. Bull., 52, 825–831, doi:10.1007/s11434-007-0140-1, 2007.

Kutzbach, J. E., Chen, G., Cheng, H., Edwards, R. L., Liu, Z.: Potential role of winter rainfall in explaining increased moisture in the Mediterranean and Middle East during periods of maximum orbitally-forced insolation seasonality, Clim. Dyna., 42, 1079-1095, 2014.

Liu, X. and Chen, B.: Climatic warming in the Tibetan Plateau during recent decades, Int. J. Climol. 20, 1729–1742, 2000.

Liu, X., Rao, Z., Zhang, X., Huang, W., Chen, J., and Chen, F.: Variations in the oxygen isotopic composition of precipitation in the Tianshan Mountains region and their significance for the Westerly circulation. J. Geography Sci. 25, 801–816, 2015.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., and Finkelnburg, R.: Precipitation seasonality and variability over the Tibetan Plateau as resolved by the high Asia reanalysis, J. Clim., 27, 1910-1927, 2014.

Meyer, H., Opel, T., Laepple, T., Dereviagin, A., Hoffmann, K., and Werner, M.: Long-term winter warming trend in the Siberian Arctic during the mid-to late Holocene, Nat. Geosci., doi:10.1038/NGEO2349, 2015.

Mountain Research Initiative EDW Working Group.: Elevation-dependent warming in mountain regions of the world, Nat. Clim. Change, 5, 424-430, doi: 10.1038/nclimate2563, 2015.

Risi, C., Bony, S., Vimeux, F., and Jouzel, J.: Water stable isotopes in the LMDZ4 General Circulation Model: Model evaluation for present day and past climates and applications to climatic interpretation of tropical isotopic records, J. Geophys. Res., 115, D12118, doi:10.1029/2009jd013255, 2010.

Ritterbusch, F., Chu, Y., Dong, X., Gu, J., Hu, S., Jiang, W., Landais, A., Lipenkov, V., Lu, Z., Shi, G., Stenni, B., Taldice team, Tian, L., Tong, A., Yang, G., and Zha, L.: Revealing old ice with $^{81}$Kr, Geophysical Research Abstracts. 20, EGU2018-2350-5, 2018.

Shao, L., Tian, L., Cai, Z., Cui, J., Zhu, D., Chen, Y., and Palcsu, L.: Driver of the interannual variations of isotope in ice core from the middle of Tibetan Plateau, Atmos. Res., 188, 48–54, doi: 10.1016/j.atmosres.2017.01.006, 2017.

Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J. F.: Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821-1825, doi: 10.1126/science.276.5320.1821, 1997.

Thompson, L., Yao, T., Davis, M., Mosley-Thompson, E., Wu, G., Porter, S., Xu, B., Lin, P., Wang, N., Beaudon, E., Duan, K., Sierra-Hernάndez, M., and Kenny, D.: Ice core records of climate variability on the Third Pole with emphasis on the Guliya ice cap, western Kunlun Mountains, Quat. Sci. Rev., 188, 1 – 14, doi: 10.1016/j.quascirev.2018.03.003, 2018.

Tian, L., Yao, T., Schuster, P. F., White, J. W. C., Ichiyanagi, K., Pendall, E., Pu, J., and Yu, W.: Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau, J. Geophys. Res., 108(D9), 4293, doi:10.1029/2002JD002173, 2003.

Tian, L., Yao, T., Li, Z., MacClune, K., Wu, G., Xu, B., Li, Y., Lu, A., and Shen, Y.: Recent rapid warming trend revealed from the isotopic record in Muztagata ice core, eastern Pamirs, J. Geophys. Res., 111, D13103, doi: 10.1029/2005JD006249, 2006.

Tzedakis, P. C.: Seven ambiguities in the Mediterranean palaeoenvironmental narrative, Quat. Sci. Rev., 26, 2042 – 2066, doi:10.1016/j.quascirev.2007.03.014, 2007.

Yao, T., Thompson, L. G., Mosley-Thompson, E., Yang, Z., Zhang, X., and Lin, P.: Climatological significance of $\delta^{18}O$ in north Tibetan ice cores, J. Geophys. Res., 101(D23), 29531-29537, doi: 10.1029/96JD02683, 1996.

Zhang, Z., Hou, S., and Yi, S.: The first luminescence dating of Tibetan glacier basal sediment, The Cryosphere, 12, 1-6, doi: 10.5194/tc-12-1-2018, 2018.

Zhong, Z. P., Solonenko, N.E., Gazitúa, M. C., Kenny, D. V., Mosley-Thompson, E., Rich, V. I., Van Etten, J. L., Thompson, L. G., and Sullivan, M. B.: Clean low-biomass procedures and their application to ancient ice core microorganisms, Front. Microbiol., 9, 1-15, doi: 10.3389/fmicb.2018.01094, 2018.

Dear Prof. Lonnie Thompson,

Many thanks for your thoughtful referee comments. Below is a point-to-point response to your comments. The original comments are in black, and our response is marked in blue.

---

Referee Comments on the paper by Hou et al., Apparent discrepancy of Tibetan ice core $\delta^{18}O$ records may be attributed to misinterpretation of chronology, for The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-295.

First, it is certainly good to see the recent interest in our work on the Guliya ice core record that was conducted in the 1990s. The community has come a long way since that time when the greatest challenge that Tandong Yao and I faced when drilling in that part of the world was the question of whether or not it would be possible to drill an ice core at those elevations and then keep it frozen during its transit across the Gobi desert. We didn't know at the time how that work would set the stage for all of those who have come along since those early days.

Regarding the time scales on the early Guliya cores, they raised as many questions as they answered and therefore our team returned to Guliya in 2015 where we successfully recovered 5 ice cores, 4 of which were drilled to bedrock. A recently published paper highlights the geophysical work conducted in the field (Kutuzov *et al.*, 2018). A primary goal of the 2015 drilling campaign was to better constrain the time-scale on the Guliya ice cap by taking advantage of additional, newer analytical approaches and applying them to the freshly drilled ice cores. A number of these analyses are focused specifically on dating the ice and are now underway.

Kutuzov, S., L. G. Thompson, I. Lavrentiev, and L. Tian. 2018. Ice thickness measurements of Guliya ice cap, western Kunlun Mountains (Tibetan Plateau), China, *Journal of Glaciology*, 64(248) 977–989, doi: 10.1017/jog.2018.91.

Response:

We share the same experience and challenge of drilling ice cores at such high elevations. An additional challenge is to set up a reliable chronology for these mountain ice cores, especially for their bottom sections due to the rapid thinning of the ice layers and the dynamic nature of mountain glaciers. At present, tens of ice cores to the bedrock have been recovered from the Tibetan Plateau, but so far only three of them (i.e., Dunde, Guliya and Puruogangri) have provided a continuous time series beyond the last two millennia. Even for these three ice cores, there is much inconsistency among their $\delta^{18}O$ records

(Fig. 3 of our TCD manuscript). Therefore, more Tibetan ice core $\delta^{18}O$ records with reliable chronologies, including the Chongce and the new 2015 Guliya ice cores, are extremely necessary to reconcile the inconsistency among the Tibetan ice core $\delta^{18}O$ records.

As an invited referee for the paper by Hou *et al.*, I have addressed a number of the specific issues raised in the manuscript but in short the paper lacks sufficient quantitative support for the authors' conclusions. I hope that the following points will help the authors improve their manuscript.

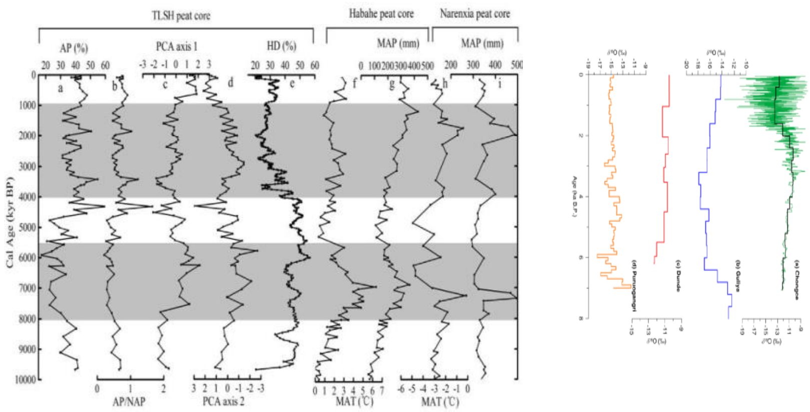
Response:

Many thanks for the thoughtful comments below. We believe that our detailed responses to your questions/comments show that our conclusion is reasonable and based on solid evidence.

**Specific comments:**

Lines 50-55*: "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."*

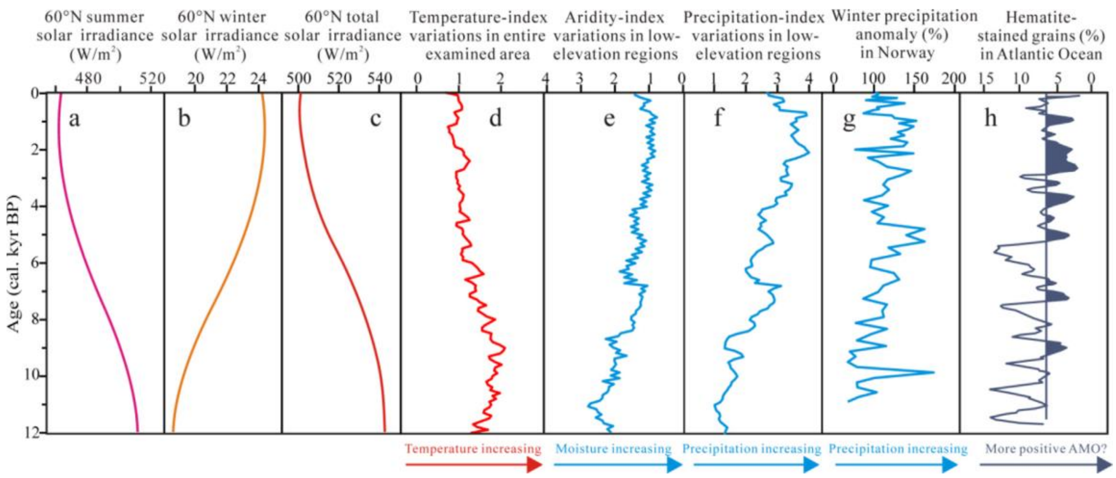
The first sentence will be addressed below. The third sentence is misleading. The mid-Holocene cooling is very noticeable in Tibetan climate records that are not from ice cores. For example, the regional vegetation and climate changes during the Holocene have been reconstructed from a high-resolution pollen record preserved in a peat sequence from the Altai Mountains of Xinjiang, China (Zhang *et al.*, 2018, *Quaternary Science Reviews*, 201, 111-123). These vegetation phases indicate that the regional climate changed from a cold and dry early Holocene to a warmer and wetter early-mid Holocene followed by a cold and dry mid-Holocene, which transitioned to a cool and wet late Holocene with warm and dry conditions characterizing the last millennium. Below is a figure comparing the data in Figure 6 of the Zhang *et al.* paper (left) with Figure 3 (right) from the Hou *et al.* paper. Note that the Guliya $\delta^{18}O$ record (blue) is more similar to the mean annual temperature (Figure 6, panel f, red star) than the Chongce $\delta^{18}O$ record. It is also important to note that the Guliya ice core was not used to help establish the chronology of the pollen record.




☆

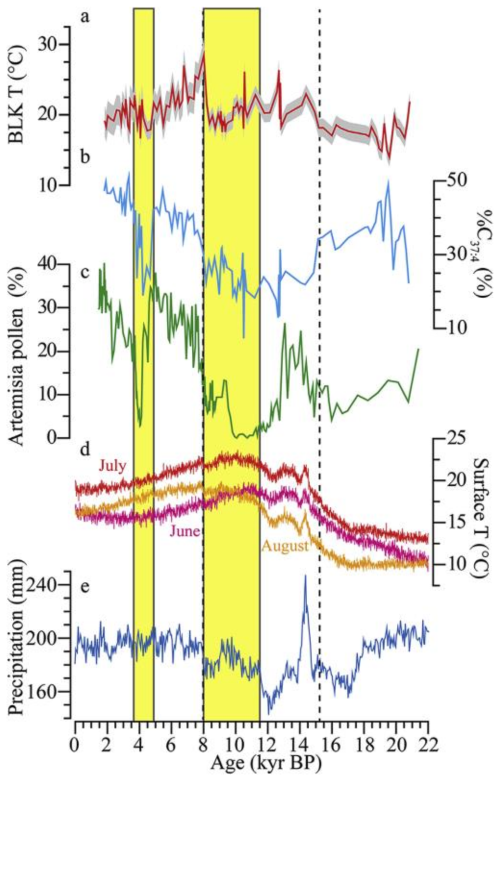
The figure is a composite of Figure 6 (Zhang *et al.*, 2018) and Figure 3 (Hou *et al.*, unpublished). The records above, along with other examples given below, dispute Lines 136-140 *("This warming trend during the mid-Holocene is similar to recent paleoclimatic reconstructions in other parts of the world (Samartin et al., 2017; Marsicek et al., 2018). By comparison, it seems that the δ$^{18}$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.")*. Here the authors are picking records from regions thousands of miles away in much different climate regimes to confirm the Chongce δ$^{18}$O record (and time scale). The Samartin *et al*. records are from the Mediterranean while the Marsicek *et al.* records are from Europe and North America. Hou *et al.* (Lines 35-40) state that *"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")*. There are several publications that link North Atlantic climate to the climates of Central Asia and China. Although most of them discuss the linkages between precipitation and westerlies influenced by North Atlantic atmospheric and oceanic processes, papers such as Feng and Hu (2008, *Geophysical Research Letters* 35 doi: 10.1029/2007GL032484) present an argument that North Atlantic SST anomalies strongly affect the TP surface temperature and heat sources, at least in the last century.

There are other records that call into question their conclusions regarding Holocene climate variability as inferred from the Chongce cores. For example, Zhang and Feng (*Earth-Science Reviews*, 2018, 185, 847-869) presented a compilation of pollen records from the Altai Mountains and surrounding regions that show a mid-Holocene cooling trend. Below see their Figure 37 (note panel d) from their synthesis of regional pollen records.




This is Figure 37 from Zhang and Feng, 2018 which was cited above.

Another example that does not support the conclusions drawn from the Chongce ice core is an alkenone-based 21 ka paleotemperature record from Lake Balikun (43.60-43.73ºN, 92.74- 92.84ºE, 1570 masl). As shown in the figure below (see panel d), this lake record shows that in this region the peak summer temperature occurred at 8 ka and was followed by general cooling throughout the Holocene.




This is Figure 8 is from Zhao *et al*. 2017 (Contrasting early Holocene temperature variations between monsoonal East Asia and westerly dominated Central Asia. *Quaternary Science Reviews* 178, 14-23).

Warmer conditions for the Early Holocene and cooler temperatures in the mid-Holocene are inferred by additional eastern TP records (see papers cited below). Many of these records are consistent with the Northern Hemisphere summer insolation curve (see panel a in the figure above from Zhang and Feng, 2018).

Shen, J., Liu, X., Wang, S., Ryo, M., 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. *Quaternary International* 136, 131–140.

Yu, X., Zhou, W., Franzen, L.G., Xian, F., Cheng, P., Jull, A.J.T., 2006. High-resolution peat records for Holocene monsoon history in the eastern Tibetan Plateau. *Science in China (Series D)* 49, 615–621.

Herzschuh, U., Kramer, A., Mischke, S., Zhang, C., 2009. Quantitative climate and vegetation trends since the late glacial on the northeastern Tibetan Plateau deduced from Koucha Lake pollen spectra. *Quaternary Research* 71, 162–171.

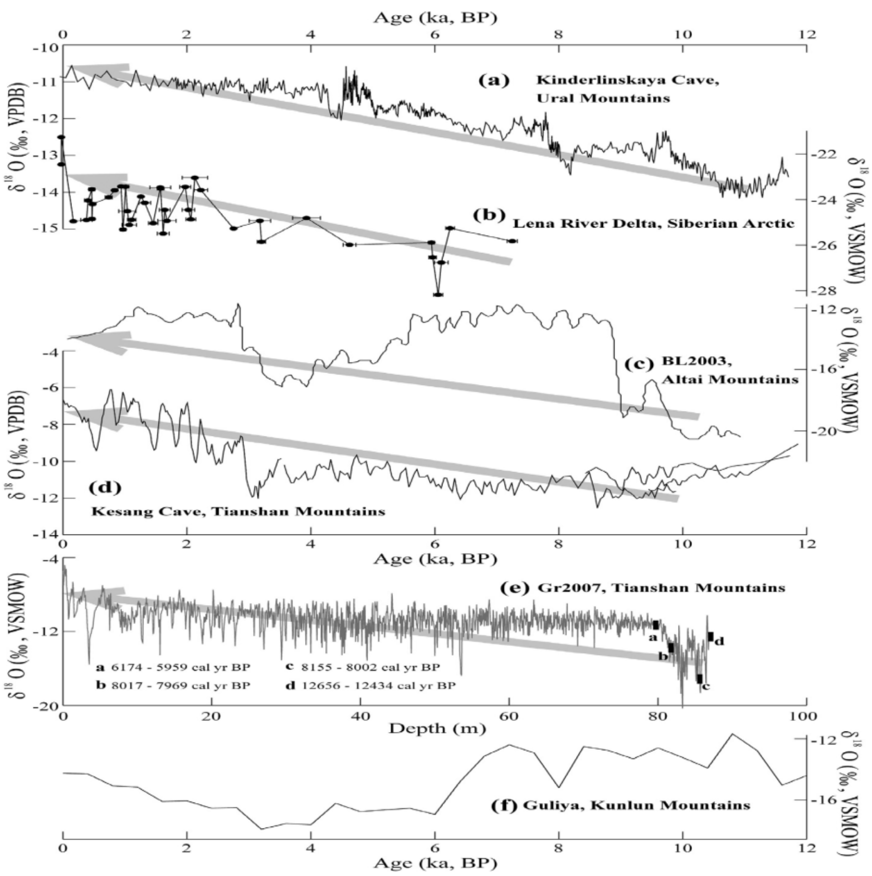
Zhang, C., Mischke, S., 2009. A Late Glacial and Holocene lake record from the Nianbaoyeze Mountains and inferences of lake, glacier and climate evolution on the eastern Tibetan Plateau. *Quaternary Science Reviews* 28, 1970–1983.

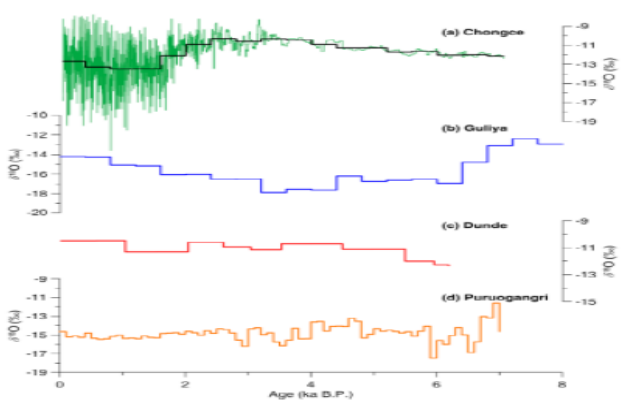
Kramer, A., Herzschuh, U., Mischke, S., Zhang, C., 2010. Holocene tree line shifts and monsoon variability in the Hengduan Mountains (southeastern Tibetan Plateau), implications from palynological investigations. *Palaeogeography, Palaeoclimatology, Palaeoecology* 286, 23–41

Response:

The reviewer listed a few studies in support of the Guliya record, which suggest warmer conditions for the Early Holocene and cooler temperatures in the mid-Holocene. However, there are many other studies that suggest otherwise. Most recently, Rao et al. (Earth-Science Reviews, 2019) compiled climatic reconstructions from lake sediments, loess, sand-dunes and peats in the Xinjiang and surrounding region of Norwest China, including northern parts of the Tibetan Plateau. The reconstructed records suggest a long-term warming trend during the Holocene. It is worth noting that the study area of Zhang et al. (2018) mentioned by the reviewer is in the Altai Mountains of the northern Xinjiang region, which is within the focus region of the Rao et al. (2019) study. Figure 5 of the Rao et al. paper (upper) is presented here with Figure 3 of our TCD paper (lower). The caption of Figure 5 (Rao et al., 2019) reads: "Fig. 5. Comparison of relevant Holocene $\delta^{18}O$ records from the Xinjiang region and its surroundings. (a) Stalagmite $\delta^{18}O$ record from the southern Ural Mountains (Baker et al., 2017); (b) ice wedge $\delta^{18}O$ record from the Lena River Delta in the Siberian Arctic (Meyer et al., 2015); (c) ice core $\delta^{18}O$ record from the Western Belukha Plateau in the Siberian Altai Mountains (Aizen et al., 2016); (d) stalagmite $\delta^{18}O$ record from Kesang Cave in the western Tianshan

Mountains (Cheng et al., 2012); (e) ice core $\delta^{18}O$ record from the Grigoriev Ice Cap in the western Tianshan Mountains (Takeuchi et al., 2014); (f) Guliya ice core $\delta^{18}O$ record from the western Kunlun Mountains (Thompson et al., 1997). All these $\delta^{18}O$ records exhibit an overall long-term positive trend, as indicated by the grey arrows. The sole exception is the Guliya ice core $\delta^{18}O$ record, which may be partially influenced by the Asian summer monsoon. Consequently, we speculate that the Holocene stalagmite $\delta^{18}O$ record from Kesang Cave in the western Tianshan Mountains is a record of changing temperature rather than moisture."



The possible reasons for such dramatic differences between Rao et al. (2019) and Zhang et al. (2018) reconstructions of the same region is beyond the scope of this document and our TCD paper. It is sufficient to say that further studies and data are necessary to reconcile the differences and narrow down the uncertainties in the Holocene climate history on the TP.

Although it is tempting to simply compile a list of studies supporting our conclusions in order to “settle the scores”, we also realize that to do so is missing the point of our paper. The purpose of our TCD paper is not to provide a definitive proof of a warming or cooling Holocene, but rather an attempt to reconcile the apparent discrepancy between the $\delta^{18}O$ records of two specific ice cores, i.e. Chongce and Guliya, which were retrieved at two sites only ~30 km apart. Both drilling sites are located in the western Kunlun Mountains on the northwestern Tibetan Plateau, where significantly positive correlation between air temperature and $\delta^{18}O$ in precipitation and ice cores is well established (Tian et al., 2006; Yao et al., 2013; An et al., 2016), and stays fairly stable throughout the Holocene (Risi et al., 2010). Therefore, the Chongce and the Guliya ice core $\delta^{18}O$ records reflect the temperature variation of the same region and should share very similar, if not exactly the same, characteristics given their close proximity to each other. Such similarity was not found between the two records based on the original Guliya chronology. Instead, they show divergent temperature trends for the Holocene, with a significant negative correlation between the two records during the common period ($r = -0.79$, $n = 16$, $p = 0.00$). However, if we compare the depth $\delta^{18}O$ profiles directly, we do see much similarity between the two ice cores. When the Chongce $\delta^{18}O$ values were averaged based on the same relative depth intervals of the Guliya profile (Fig. 5 in our TCD paper), the two records are highly correlated ($r = 0.57$, $n = 110$, $p = 0.00$). The chronology of the Chongce ice cores are well established by an array of newly developed as well as traditional dating methods such as the measurements of $^{14}C$ (22 samples for the Chongce Core 4 and 9 samples for the Chongce Core 2, respectively), $^{210}Pb$, tritium and $\beta$-activity (Hou et al., TC 2018). Such evidence has led to a reasonable doubt for the validity of Guliya’s original chronology, particularly in the light of the extraordinary length of the record, which is nearly two orders of magnitude longer than all other ice cores on the TP (Hou et al. 2018). We are pleased to see that new ice cores were recovered from the Guliya ice cap in 2015, and analyses of $^{14}C$, $^{36}Cl$, $^{10}Be$, $\delta^{18}O$ of air in bubbles and argon isotopic ratios ($^{40}Ar/^{38}Ar$) on deep sections of the new Guliya ice cores are under way (Thompson et al., 2018). We look forward to the new Guliya ice core results. As stated in our TCD paper, "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".

*Returning to Lines 50-54,* The definition of “benchmark” is a point of reference from which measurements may be made. In none of the references cited above are the time series constructed to match that of Guliya. Those chronologies were independently developed. Therefore the suggestion that the Guliya record misled the development of the climate records in these or any other papers is false. This sentence should be rephrased as “The Guliya record has been compared with climate records from numerous studies…..”). The records in these and other references were broadly compared to the Guliya record. If the climate records from these independently dated records match the Guliya record then it is not because they *were matched to* Guliya in order to develop their chronologies, it is because their independent chronologies were coherent with the Guliya chronologies. Also, if the Holocene temperature records presented in these publications are similar to Guliya’s Holocene $\delta^{18}O$ (temperature) time series, which contradicts the Chongce $\delta^{18}O$ (temperature) record, it raises a serious challenge to the validity of the interpretation of the Chongce records, which the authors should address.

Response:

We revised the sentence as suggested. The Guliya record has been widely cited (999 times from Google Scholar on March 16, 2019), However, most of the time the record was used to provide a broad climate context, and very few studies made direct comparison, in part because the original data were not publically available. We would also like to point out when the Guliya record was compared with other reconstructions, not all of them were in agreement, such as the aforementioned Rao et al. (2019) study, which did bring to the attention the disagreement between the Guliya and other records. Cheng et al. (2012) also argued that the chronology of the Guliya ice core should be shortened by a factor of two in order to reconcile the difference in the $\delta^{18}O$ variations between the Guliya ice core and the Kesang stalagmite records. It is indeed very challenging to establish an accurate chronology for Tibetan ice cores, which has led to frequent inconsistencies among different records. We shall continue to test the validity of Chongce chronology and its temperature reconstruction through comparisons with other observation records as well as model simulations. We believe that all of us engaging in Tibetan ice core research should work together to reconcile existing inconsistencies among the Tibetan ice core records in order to enhance their credibility and increase people’s confidence in the climate history reconstructed from these important ice cores.

Hou *et al.* make statements that are inconsistent with existing evidence. For example they state (Line 179-181): "*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.*"

Guliya is not the solitary piece of evidence supporting asynchronous glaciation on the Tibetan Plateau. There are a number of exposure dates that also point to asynchronous glaciation. Owen *et al.* (2008, Quaternary glaciation of the Himalayan-Tibetan orogeny in *J. Quaternary Science* 23, 513-531) state in their abstract "Glaciers throughout monsoon-influenced Tibet, the Himalaya and the Transhimalaya are likely synchronous both with climate change resulting from oscillations in the South Asian monsoon and with Northern Hemisphere cooling cycles. In contrast, glaciers in Pamir in the far western regions of the Himalayan–Tibet orogen advanced asynchronously relative to the other regions that are monsoon-influenced regions and appear to be mainly in phase with the Northern Hemisphere cooling cycles."

Response:

The synchronicity of glaciation on the TP is a long standing issue of intellectual debate. There seems to be evidence on both sides. Evidence for synchronous glaciation on the TP is presented in many studies (e.g. Schäfer et al., 2002; Yi et al., 2008). Solomina et al. (2015), in an invited review to QSR, indicated that "Many glaciers worldwide record strong centennial scale climate signals. The accuracy and coverage of the records is still too low to assess the global or regional synchronicity of advances at the centennial scale with high confidence. At least some groups of glacier advances were clustered – for example, the advances at 11.0-11.4 ka documented in the NH and in the tropics, the events at 9.1-9.2 ka and 8.0-8.4 ka recorded in the NH and SH.". Our paper does not argue for or against synchronous glaciation on the TP, but rather we suggest that given our new understanding of the Tibetan ice core chronology, the Guliya record may not provide supporting evidence for asynchronous glaciation on the TP because of possible errors in its original chronology. We rephrased our sentence in the revised manuscript accordingly: "*This would also cast doubt on using the Guliya record as supporting evidence for asynchronous glaciation on the TP on Milankovitch timescales (Thompson et al., 2005), as it was based on record of its original chronology.*"

Lines 182-184: *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.* $^{81}$Kr ages on the margin of the Guliya ice cap tell us nothing about the age of the bottom ice of the

308m ice core at the Plateau “Site 2” drill site (where the 1992 core was drilled). Ice samples collected in 2015 for $^{81}Kr$ analyses were collected down the flowline and in close proximity to our 1992 Site 1 drill (see locations in Figure 1 of Thompson *et al.*, 1995, *Annals of Glaciology*). In 1992 the first Guliya core “Site 1” was drilled to 92.2 meters, at which point we terminated drilling because we found an unconformity in the ice layers 83 meters below the surface (see discussion on page 176 in the aforementioned Thompson *et al.* 1995 paper). Thus, there is no reason to believe there is a time stratigraphic linkage between the bottom ice along the margin (near the camp, see aforementioned map) and the ice at the bottom of our deep core drilled on the Plateau at Site 2 (see map).

Response:

In this study, they collected samples for $^{81}Kr$ measurement at three sites (red stars in the map below), and only one sampling site is near "site 1". The $^{81}Kr$ samples at different sites yielded remarkably consistent results, and all of the resulting ages are ~ one order of magnitude younger than the original chronology of the Guliya ice core (Tian Lide, Lu Zhengtian, personal communications). Such high consistency suggests that they indeed measure the same bottom age of the Guliya ice cap, and are unlikely to be affected by localized unconformities.

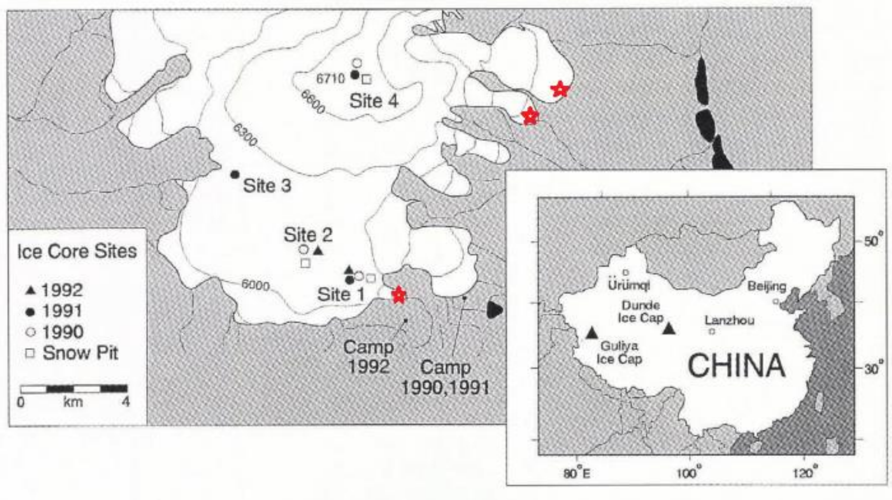



*Fig. 1. Locations of the Guliya and Dunde ice caps, and of snow-pit and ice-coring sites on Guliya.*

This is Figure 1 of Thompson et al., Annals of Glaciology, 1995. The three red stars indicate the sampling locations for the $^{81}Kr$ measurements.

Minor points

Some statements are erroneous or misleading and need to be checked and verified. For example, on *Lines 128-130 they state: “However, this high δ18O value is not observed around the depth of ~211 m* *in the Puruogangri depth δ18O profile (Fig. 2). Indeed, all δ18O values in the depth profile of the Puruogangri core are well below -12‰. Therefore, the high δ18O value around ~7 kaBP of the Puruogangri core (Fig. 3) needs further verification."* Those values exist in the raw data around 211 meters (the raw data below are ~ 6.9-7.0 ka), and this high δ18O value is a function of the time averaging (100 yr averages), whereas the authors are basing their observations on one meter averages, which incorporate ~30 data points).

| Depth (m) | $\delta^{18}O$ (‰) |
|---|---|
| 210.960 | -11.35 |
| 210.990 | -11.30 |
| 211.025 | -12.12 |

Response:

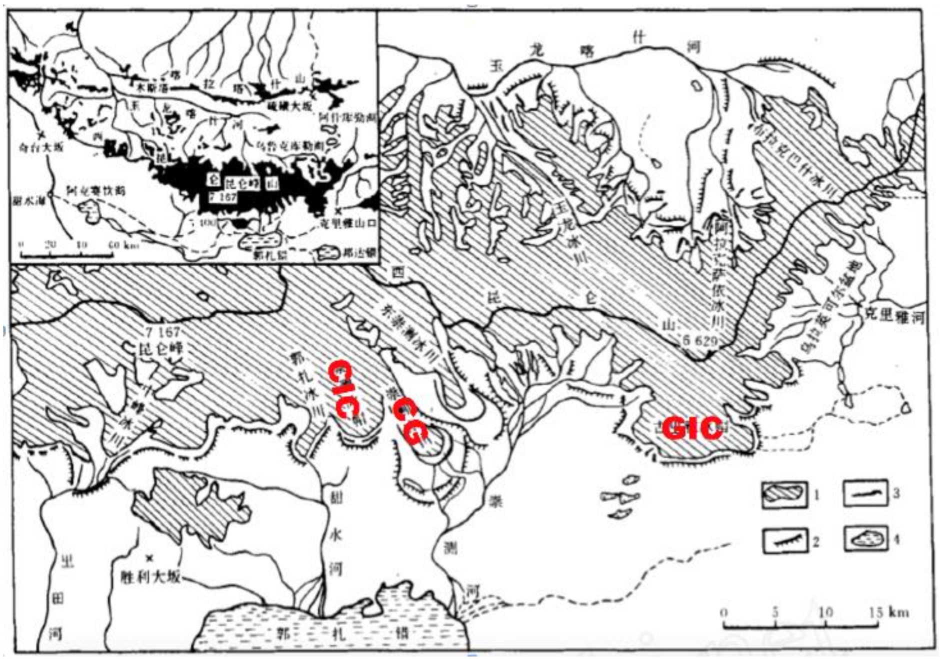
Many thanks for clarifying the Puruogangri profiles. We included this information in the revision. We'd like to point out that this kind of misunderstanding could have been avoided if the original raw data of the Puruogangri ice core were shared. We strongly believe that complete data sharing is extremely important for future scientific progress. As indicated in our TCD manuscript, we plan to provide the complete $\delta^{18}O$ data of the Chongce ice core upon the publication this paper.

Finally, the authors' failed to mention that evidence exists suggesting that Chongce may be a surging glacier. In 1991 Chinese scientists published a Quaternary Glacial Distribution Map of the Tibetan Plateau. According to this map, the terminal moraines around the Guliya ice cap are very close to their maximum position during the last two glaciations. However, this is not the case for the Chongce ice cap which shows the greatest variations in ice extent of any of the ice caps in this region. In addition, the Chongce glacier, which flows from the Chongce ice cap, surged between 1992 and 2014 while the Guliya ice cap remained static (Yasuda and Furuya, 2015; Fig. 3). Therefore, it might be inaccurate to assume that the timescale developed for the Chongce cores should reflect that of Guliya. In light of the geophysical considerations discussed above it is premature to conclude that the Chongce results invalidate the much longer Guliya timescale.

Yasuda, T. and Furuya, M. 2015. Dynamics of surge-type glaciers in West Kunlun Shan, Northwestern Tibet. *Journal of Geophysical Research - Earth Surface*, https://doi.org/10.1002/2015JF003511.

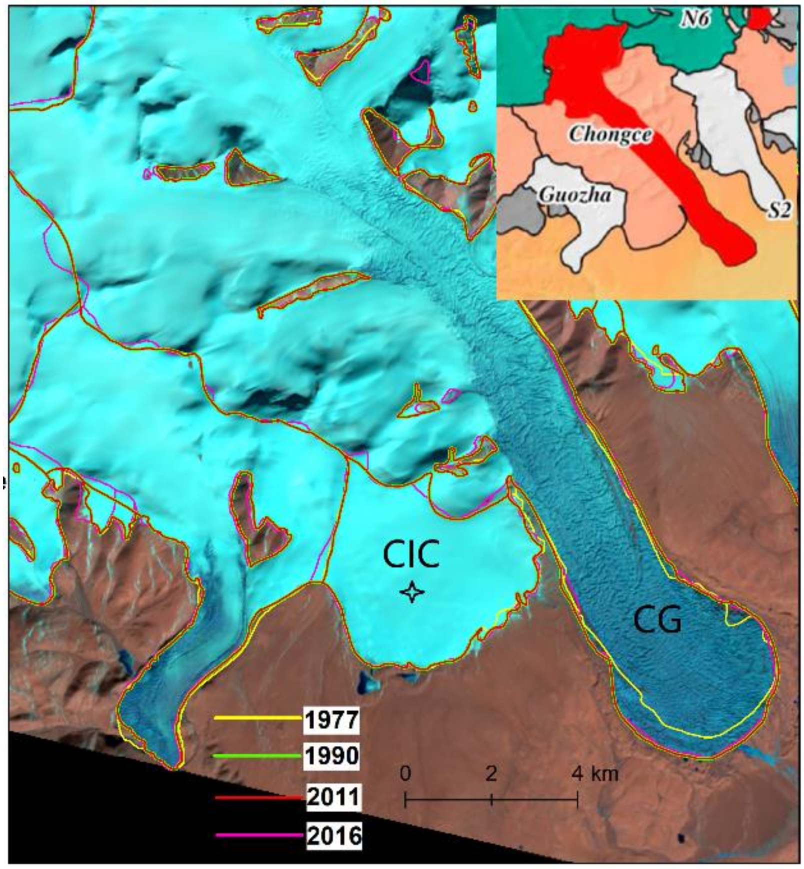
Response:

Although the 1991 Quaternary Glacial Distribution Map of the TP (Li and Li, 1991) can provide valuable information about the quaternary glacier variation on the TP, its spatial resolution (1:3,000,000) is often insufficient to delineate the variation of a specific glacier or ice cap. Later, Jiao et al. (2000) studied the evolution of glaciers in the West Kunlun Mountains during the past 32 ka (map below). It is clear that, although the Chongce glacier advanced considerably during the LGM, the present terminus of the Chongce ice cap is very close to their maximum position during the LGM, similar to the Guliya ice cap. This confirms the stability of the Chongce ice cap since the LGM.

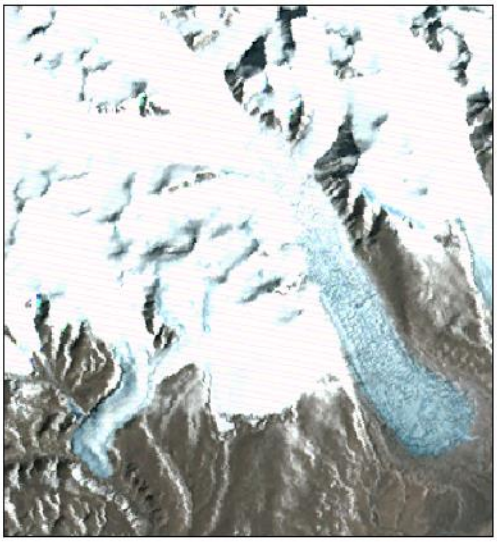



Map showing the glacier distribution and the lower limit of the LGM in the West Kunlun Mountains (Jiao et al., 2000). CIC: Chongce Ice Cap, CG: Chongce Glacier, GIC: Guliya Ice Cap. 1: present glacier, 2: terminal moraine during the LGM, 3: terminal moraine during the Neoglaciation, 4. lakes

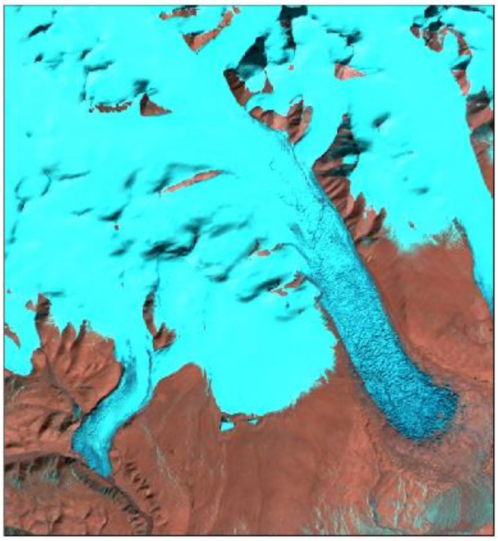
From Fig. 3 of Yasuda and Furuya's paper, it is clear that the surged area is confined within the Chongce glacier (map below). Using topographical maps, Shuttle Radar Topography Mission (SRTM) and Landsat data, Wang et al. (2018) examined the area changes of glaciers on the Western Kunlun Mountain (including the Chongce and Guliya ice caps) since the 1970s. For the whole area, change of the glacier area reveals insignificant shrinkage by 0.07 ± 0.1% $yr^{-1}$ from the 1970s to 2016. The Chongce glacier retreated between 1977 and 1990, and advanced from 1990 to 2011 (period of surge), then remained stable until 2016. In contrast, the Chongce ice cap remained static from the 1977 to 2016, confirming the stability of the Chongce ice cap, where our ice cores were recovered. In addition, we observed similar mass changes for surge-type and non-surge-type glaciers over the Western Kunlun Mountains (Wang et al., 2018), suggesting that the flow instabilities seem to have little effect on the glacier-wide mass balance. Similar results are also reported for the Pamirs and Karakoram (Gardelle et al., 2013). Therefore, the impact of glacial surge on the stratigraphy of the Chongce ice cap is minimal, especially in its accumulation zone where our Chongce ice cores were drilled. This can be further confirmed by studies of by Lin et al. (2017) and Zhou et al. (2018), who estimated of elevation changes over the West Kunlun Mountain between 1973 and 2014 (Figures below), which shows minimal change for the Chongce ice cap. It is therefore reasonable to assume that Chongce ice cap is in balance over this period of time.



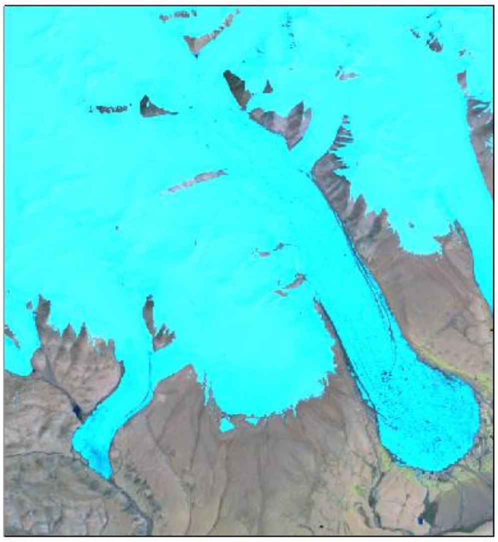

Map showing the Chongce Ice Cap (CIC) and the Chongce Glacier (CG), with the terminus positions at different time (Wang et al., 2018). The star shows the drilling site of the Chongce Cores 2 and 3, which we deem to be an optimal location for retrieving an undisturbed paleoclimate record. The inset is from Fig. 3 of Yasuda and Furuya (2015) with red showing the surged area, which is confined within the Chongce glacier. Terminus positions are determined from Landsat images as shown below.



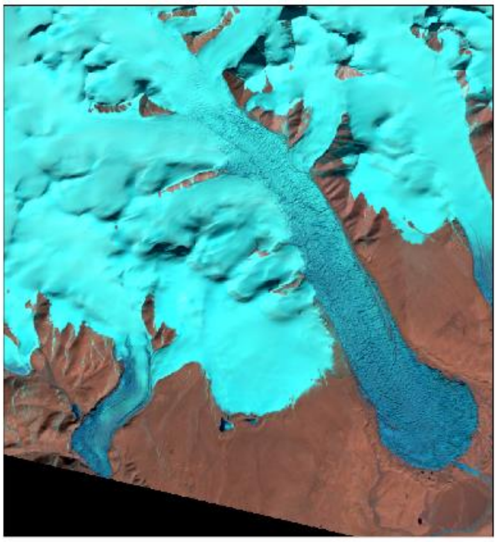
Landsat MSS (17, Feb, 1977)



Landsat TM ( 15, Nov. 1990)

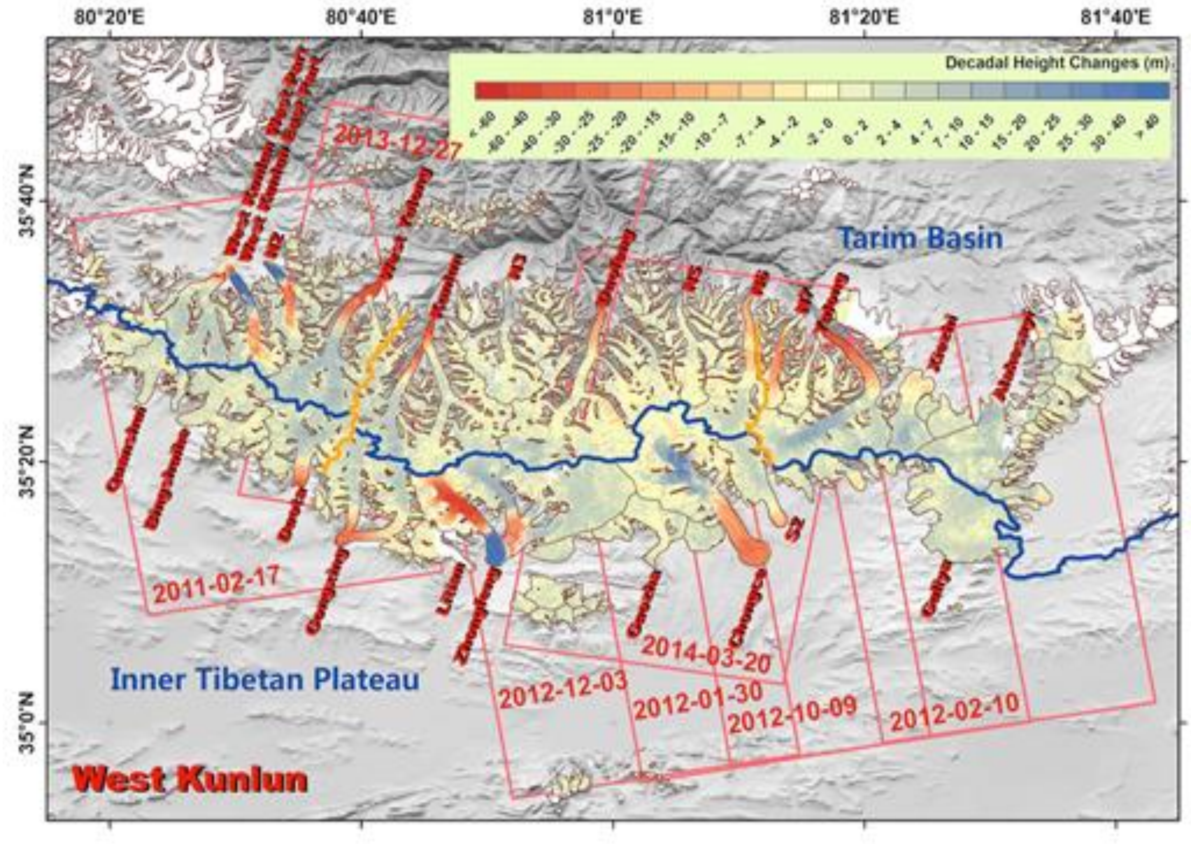


Landsat TM ( 5, Aug. 2011)

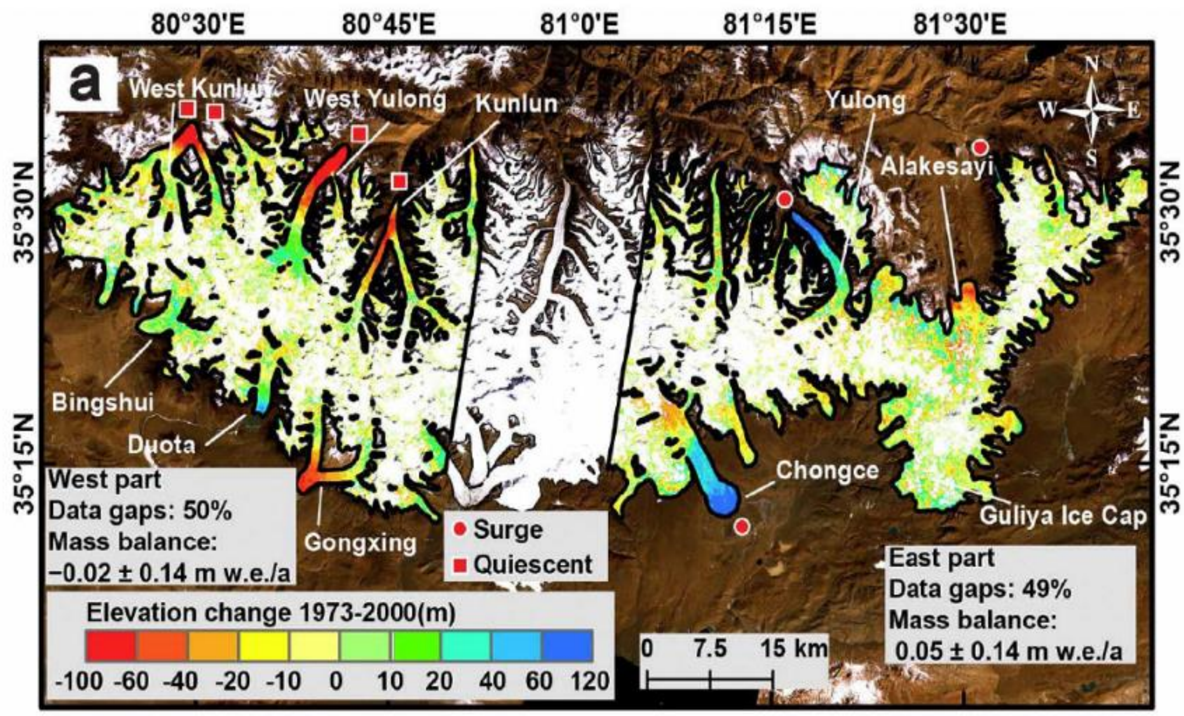


Landsat 8 ( 5,Oct. 2016)

LandSat images for the Chongce glacier and ice cap terminus position assessment. They are co-registered to the topographical maps and the accuracy of co-registration is about 20 m (slightly more than half of one pixel of Landsat images) (Wang et al., 2018).




Glacier height changes from 2000 to the 2010s from Lin et al. (2017)




Glacier elevation change from 1973 to 2010 from Zhou et al. (2018)

Note to readers of this review:

When asked by Editor Carlos Martin to serve as a referee for this paper, I inquired whether this would constitute a conflict of interest as our Guliya record is a major subject of the paper. I was told "My view is that there is no conflict of interest". Therefore, I opted to serve as a referee.

Response:

We certainly welcome and appreciate the opportunity to discuss our study directly with Dr. Lonnie Thompson.

References cited:


An, W., Hou, S., Zhang, W., Wu, S., Xu, H., Pang, H., Wang, Y., and Liu, Y.: Possible recent warming hiatus on the northwestern Tibetan Plateau derived from ice core records, Sci. Rep., 6, 32813, doi: 10.1038/srep32813, 2016.

Cheng, H., Zhang, P., Spötl, C., Edwards, R., Cai, Y., Zhang, D., Sang, W., Tan, M., and An, Z.: The climatic cyclicity in semiarid-arid central Asia over the past 500,000 years, Geophys. Res. Lett. 39, L01705, doi: 10.1029/2011gl050202, 2012.

Gardelle, J., Berthier, E., Arnaud, Y., and Kääb A.: Region-wide glacier mass balances over the Pamir–Karakoram–Himalaya during 1999–2011, The Cryosphere, 7, 1263–1286, doi: 10.5194/tc-7-1263-2013, 2013.

Hou, S., Jenk, T., Zhang, W., Wang, C., Wu, S., Wang, Y., Pang, H., Schwikowski, M.: Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains, The Cryosphere 12, 2341 – 2348, doi: 10.5194/tc-12-2341-2018, 2018.

Jiao, K., Yao, T., and Li, S.: Evolution of glaciers and environment in the West Kunlun Mountains during the past 32 ka, J. Glacio. Geocryo., 22, 250-256, 2000 (in Chinese with English abstract).

Li, B., and Li, J.: Quaternary glacial distribution map of Qinghai-Xizang (Tibet) Plateau. Science Press, Beijing, 1991.

Lin, H., Li, G., Cuo, L., Hooper, A., and Ye, Q.: A decreasing glacier mass balance gradient from the edge of the Upper Tarim Basin to the Karakoram during 2000–2014, Sci. Rep., 7, 612, doi:10.1038/s41598-017-07133-8, 2017.

Rao, Z., Wu, D., Shi, F., Guo, H., Cao, J., and Chen, F.: Reconciling the 'westerlies' and 'monsoon' models: A new hypothesis for the Holocene moisture evolution of the Xinjiang region, NW China, Earth-Sci. Rev., 191, 263-272, doi: 10.1016/j.earscirev.2019.03.002, 2019.

Risi, C., Bony, S., Vimeux, F., and Jouzel, J.: Water stable isotopes in the LMDZ4 General Circulation Model: Model evaluation for present day and past climates and applications to climatic interpretation of tropical isotopic records, J. Geophys. Res., 115, D12118, doi:10.1029/2009jd013255, 2010.

Schäfer, J. M., Tschudi, S., Zhao, Z., Wu, X., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P. W., Schlüchter, C.: The limited influence of glaciations in Tibet on global climate over the past 170 000 yr, Earth Planet. Sci. Lett., 194, 287-297, 2002.

Solomina, O., Bradley, R., Hodgson, D., Ivy-Ochs, S., Jomelli, V., Mackintosh, A., Nesje, A., Owen, L., Wanner, H., Wiles, G., and Young, N.: Holocene glacier fluctuations, Quat. Sci. Rev., 111, 9-34, doi:10.1016/j.quascirev.2014.11.018, 2015.

Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J. F.: Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821-1825, doi: 10.1126/science.276.5320.1821, 1997.

Thompson, L., Yao, T., Davis, M., Mosley-Thompson, E., Wu, G., Porter, S., Xu, B., Lin, P., Wang, N., Beaudon, E., Duan, K., Sierra-Hernández, M., and Kenny, D.: Ice core records of climate variability on the Third Pole with emphasis on the Guliya ice cap, western Kunlun Mountains, Quat. Sci. Rev., 188, 1-14, doi: 10.1016/j.quascirev.2018.03.003, 2018.

Tian, L., Yao, T., Li, Z., MacClune, K., Wu, G., Xu, B., Li, Y., Lu, A., and Shen, Y.: Recent rapid warming trend revealed from the isotopic record in Muztagata ice core, eastern Pamirs, J. Geophys. Res., 111, D13103, doi: 10.1029/2005JD006249, 2006.

Wang, Y., Hou, S., Huai, B., An, W., Pang, H., and Liu, Y.: Glacier anomaly over the Western Kunlun Mountains, northwestern Tibetan Plateau, since the 1970s, J. Glacio., 64, 624–636, doi: 10.1017/jog.2018.53, 2018.

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., Sturm, C., Werner, M., Zhao, H., He, Y., Ren, W., Tian, L., Shi, C., and Hou, S.: A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations, Rev. Geophys., 51, 525-51548, doi: 10.1002/rog.20023, 2013.

Yasuda, T. and Furuya, M.: Dynamics of surge-type glaciers in West Kunlun Shan, Northwestern Tibet, J. Geophys. Res. Earth Surf., 120, 2393–2405, doi: 10.1002/2015JF003511, 2015.

Yi, C., Chen, H., Yang, J., Liu, B., Fu, P., Liu, K., and Li, S.: Review of Holocene glacial chronologies based on radiocarbon dating in Tibet and its surrounding mountains, J. Quat. Sci., 23, 533-558, 2008.

Zhang, Y., Yang, P., Tong, C., Liu, X., Zhang, Z., Wang, G., and Meyers, P. A.: Palynological record of Holocene vegetation and climate changes in a high-resolution peat profile from the Xinjiang Altai Mountains, northwestern China, Quat. Sci. Rev., 201, 111-123, doi: 10.1016/j.quascirev.2018.10.021, 2018.

Zhou, Y., Li, Z., Li, J., Zhao, R., and Ding, X.: Glacier mass balance in the Qinghai–Tibet Plateau and its surroundings from the mid-1970s to 2000 based on Hexagon KH-9 and SRTM DEMs, Remote Sens. Environ., 210, 96-112, doi: 10.1016/j.rse.2018.03, 2018.

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

Shugui Hou[1], Wangbin Zhang[1], Hongxi Pang[1], Shuang~~-y~~Ye Wu[2], Theo M. Jenk[3,4], ~~and~~ Margit Schwikowski[3,4], Yetang Wang[5]

[1] School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, 210023, China.

[2] Department of Geology, University of Dayton, Dayton, OH 45469, USA.

[3] Laboratory of Environmental Chemistry, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland.

[4] Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

[5] College of Geography and Environment, Shandong Normal University, Jinan, China.

Correspondence to: Shugui Hou (shugui@nju.edu.cn)

**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.

## 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, present = 1950AD), 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 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 to provide a climate context for numerous studies~~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),~~.~~ but its data from the NOAA online repository have an average resolution of ~1 m for the depth of 0-120 m, and ~0.5 m below 120 m.~~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**

The Chongce ice cap has been stable throughout the Holocene, hence provides an ideal location for retrieving ice cores used to reconstruct past climate. The ice flows from the Chongce ice cap into the Chongce glacier (Fig. 1). Although the Chongce glacier was suggested to surge between 1992 and 2014 (Yasuda and Furuya, 2015), it is clear that the surged area is confined within the Chongce glacier and did not affect the Chongce ice cap (Fig. 3 of Yasuda and Furuya, 2015). Several other studies have also confirmed the recent stability of the Chongce ice cap (Lin et al., 2017; Wang et al., 2018; Zhou et al., 2018). In addition, Wang et al. (2018) found similar mass changes for surge-type and non-surge-type glaciers over the western Kunlun Mountains, suggesting that the flow instabilities seem to have little effect on the glacier-wide mass balance. Therefore, the impact of glacial surge on the stratigraphy of the Chongce ice cap is minimal, especially in its accumulation zone where our Chongce ice cores were drilled. Over the longer time scale, Jiao et al. (2000) studied the evolution of glaciers in the west Kunlun Mountains during the past 32 kaBP. They found that the present terminus of the Chongce ice cap was very close to its maximum position during the last glacial maximum (LGM), similar to the Guliya ice cap. This confirms the stability of the Chongce ice cap since the LGM.

Many studies have shown a significant positive correlation between local temperature and isotopic composition in precipitation in the northern Tibetan Plateau (e.g., Yao et al., 1996; Tian et al., 2003). This positive correlation is also observed between local temperature from instrumental records and isotopic composition in ice cores from Tibetan Plateau (e.g., Tian et al., 2006; Kang et al., 2007; An et al., 2016). Specifically, An et al (2016) established a statistically significant correlation between annual ~~(not seasonal)~~ $\delta^{18}O$ of Chongce ice core and annual temperature record at Shiquanhe (the nearest climate station). In addition, simulations by the LMDZ4 general circulation model indicate that this positive correlation between local temperature and precipitation isotope has persisted during the Holocene (Risi et al., 2010).

Although changes in moisture source (e.g., Liu et al., 2015) or large-scale atmospheric circulation (e.g., Shao et al., 2017) could influence precipitation isotopic composition in the Tibetan Plateau, such changes often lead to concurrent temperature change with the same effect on the precipitation isotopes. Therefore, we believe that the isotopic variations~~bility~~ of Chongce ice core ~~can~~ primarily reflect local temperature signals.

Large amplitudes of $\delta^{18}O$ variations are often observed in the Tibetan core cores during the Holocene, such as ~8 ‰ for the Guliya ice core (Fig. 5) (or ~6‰ based on its original chronology, Fig. 3), ~6.5 ‰ for the Chongce ice core (Fig. 5), and ~6 ‰ for the Puruogangri ice core (Fig. 3). This is largely attributed to the elevation dependency of temperature change observed in many studies, i.e. high altitude regions experience larger temperature changes than low elevation regions (Beniston et al. 1997; Liu and

Chen, 2000; Mountain Research Initiative EDW Working Group, 2015). In addition, prominent changes in water vapor sources associated with northward and southward shifts of the westerly circulation from multi-millennial to orbital timescales (Cheng et al., 2016) may also contribute to the large amplitude of $\delta^{18}O$ variation in core cores on TP.

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 temporal $\delta^{18}O$ profiles ~~for~~ of 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 δ$^{18}$O value is not observed around the depth of ~211 m in the Puruogangri depth δ$^{18}$O profile (Fig. 2). Indeed, all δ$^{18}$O values in the depth profile of the Puruogangri core are well below -12‰. Therefore, the high δ$^{18}$O value around ~7 kaBP of the Puruogangri core (Fig. 3) needs further verification. From ~6.5 kaBP to ~4 kaBP,~~ T~~t~~he δ$^{18}$O profile of the Puruogangri core shows an increasing trend from ~6.5 kaBP to ~4 kaBP~~,~~, 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 δ$^{18}$O since ~8 kaBP (Takeuchi et al., 2014). Most recently, Rao et al. (2019) compiled climatic reconstructions from lake sediments, loess, sand-dunes and peats in the Xinjiang and surrounding region of Norwest China, including northern parts of TP, and brought to the attention the disagreement between the Guliya ice core and other records. Their reconstructed records suggest a long-term warming trend during the Holocene. ~~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 δ$^{18}$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~~, ~~ in 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 in Fig. 2~~, 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). Although a more definitive conclusion would require detailed comparison ~~would be necessary when more evidence and~~ with the original Guliya dataset (unavailable at the moment) and addition evidence from other~~s of the~~ Tibetan ice cores ~~become available in order to confirm the Guliya New chronology (Fig. 4)~~, t~~T~~he 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 using the Guliya record based on its original chronology as supporting evidence for asynchronous glaciation on the TP on Milankovitch timescales (Thompson et al., 2005)~~, as it was based on record of its original 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 In fact, the exact age is likely to be even younger than 50 kaBP because this age lies at the low limit of the ATTA method and serves as an upper constraint for the actual age. The $^{81}$Kr samples collected at three different sites yielded remarkably consistent results (Tian Lide, Lu Zhengtian, personal communications), and all t~~T~~he $^{81}$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 (35°17′ N, 81°29′ 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 $\delta^{18}O$ 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 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. YW and WZ drilled the Chongce ice cores. 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.

**Acknowledgments.** Thanks are due to many scientists, technicians, graduate students and porters, especially to Yongliang Zhang, ~~Yetang Wang~~, Hao Xu and Yaping Liu, for their great efforts in the high elevations, ~~and~~ to Guocai Zhu for providing the ground penetrating radar results of the Chongce ice cap, and to Lonnie Thompson and Ellen Mosley-Thompson for sharing the Dunde ice core data. This work was supported by the National Natural Science Foundation of China (91837102, 41830644, 41711530148, 41330526).

## References

An, W., Hou, S., Zhang, W., Wu, S., Xu, H., Pang, H., Wang, Y., and Liu, Y.: Possible recent warming hiatus on the northwestern Tibetan Plateau derived from ice core records, Sci. Rep., 6, 32813, https://doi.org/10.1038/srep32813, 2016.

Beniston, M., Diaz, H. F., and Bradley, R. S.: Climatic change at high elevation sites: an overview, Clim. Change, 36, 233-251, https://doi.org/10.1023/A:1005380714349, 1997.

Bolzan, J.: Ice flow at the Dome C ice divide based on a deep temperature profile, J. Geophys. Res., 90, 8111–8124, 1985.

Cheng, H., Zhang, P., Spötl, C., Edwards, R., Cai, Y., Zhang, D., Sang, W., Tan, M., and An, Z.: The climatic cyclicity in semiarid-arid central Asia over the past 500,000 years, Geophys. Res. Lett. 39, L01705, https://doi.org/10.1029/2011gl050202, 2012.

Cheng, H., Spötl, C., Breitenbach, S. F. M., Sinha, A., Wassenburg, J. A., Jochum, K. P., Scholz, D., Li, X., Yi, L., Peng, Y., Lv, Y., Zhang, P., Votintseva, A., Loginov, V., Ning, Y., Kathayat, G., and Edwards, R. L.: Climate variations of central Asia on orbital to millennial timescales, Sci. Rep., 6, 36975, https://doi.org/10.1038/srep36975, 2016.

Fang, X., Li, J., and van der Voo, R.: Rock magnetic and grain size evidence for intensified Asian atmospheric circulation since 800,000 years BP related to Tibetan uplift, Earth Planet. Sci. Lett., 165, 129-144, https://doi.org/10.1016/S0012-821X(98)00259-3, 1999.

Hou, J., Huang, Y., Zhao, J., Liu, Z., Colman, S., and An, Z.: Large Holocene summer temperature oscillations and impact on the peopling of the northeastern Tibetan Plateau, Geophys. Res. Lett., 43, 1323-1330, https://doi.org/10.1002/2015GL067317, 2016.

Hou, S., Jenk, T., Zhang, W., Wang, C., Wu, S., Wang, Y., Pang, H., Schwikowski, M.: Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains, The Cryosphere 12, 2341–2348, https://doi.org/10.5194/tc-12-2341-2018, 2018.

Jiao, K., Yao, T., and Li, S.: Evolution of glaciers and environment in the West Kunlun

Mountains during the past 32 ka, J. Glacio. Geocryo., 22, 250-256, 2000 (in Chinese with English abstract).

Kang, S., Zhang, Y., Qin, D., Ren, J., Zhang, Q., Grigholm, B., and Mayewski, P.: Recent temperature increase recorded in an ice core in the source region of Yangtze River. Chin. Sci. Bull., 52, 825–831, https://doi.org/10.1007/s11434-007-0140-1, 2007.

Kutuzov, S., Thompson, L. G., Lavrentiev, I., and Tian, L. D.: Ice thickness measurements of Guliya ice cap, western Kunlun Mountains (Tibetan Plateau), China, J. Glaciol., 64(248), 977-989, https://doi.org/10.1017/jog.2018.91, 2018.

Li, X., Wang, M., Zhang, Y., Li, L., and Hou, J.: Holocene climatic and environmental change on the western Tibetan Plateau revealed by glycerol dialkyl glycerol tetraethers and leaf wax deuterium-to-hydrogen ratios at Aweng Co, Quat. Res., 87, 455-467, https://doi.org/10.1017/qua.2017.9, 2017.

Lin, H., Li, G., Cuo, L., Hooper, A., and Ye, Q.: A decreasing glacier mass balance gradient from the edge of the Upper Tarim Basin to the Karakoram during 2000–2014, Sci. Rep., 7, 612, https://doi.org/10.1038/s41598-017-07133-

8, 2017.

Liu, X. and Chen, B.: Climatic warming in the Tibetan Plateau during recent decades, Int. J. Climol. 20, 1729–1742, 2000.

Liu, X., Rao, Z., Zhang, X., Huang, W., Chen, J., and Chen, F.: Variations in the oxygen isotopic composition of precipitation in the Tianshan Mountains region and their significance for the Westerly circulation. J. Geography Sci. 25, 801–816, https://doi.org/10.1007/s11442-015-1203-x, 2015.

Liu, Z., Zhu, J., Rosenthal, Y., Zhang, X., Otto-Bliesner, B., Timmermann, A., Smith, R., Lohmann, G., Zheng, W., and Timm, O.: The Holocene temperature conundrum, Proc. Natl Acad. Sci. USA, 111, E3501-E3505, https://doi.org/10.1073/pnas.1407229111, 2014.

Mountain Research Initiative EDW Working Group.: Elevation-dependent warming in mountain regions of the world, Nat. Clim. Change, 5, 424-430, https://doi.org/10.1038/nclimate2563, 2015.

Marcott, S., Shakun, J., Clark, P., and Mix, A.: A reconstruction of regional and global temperature for the past 11,300 years, Science, 339, 1198–1201, https://doi.org/10.1126/science.1228026, 2013.

Marsicek, J., Shuman, B., Bartlein, P., Shafer, S., and Brewer, S.: Reconciling divergent trends and millennial variations in Holocene temperatures, Nature, 554, 92-96, https://doi.org/10.1038/nature25464, 2018.

North Greenland Ice Core Project members: High-resolution record of northern Hemisphere climate extending into the last interglacial period, Nature, 431, 147-151, https://doi.org/10.1038/nature02805, 2004.

Rahaman, W., Singh, S., Sinha, R., and Tandon, S.: Climate control on erosion distribution over the Himalaya during the past ~100 ka, Geology, 37, 559-562, https://doi.org/10.1130/G25425A.1, 2009.

Rao, Z., Wu, D., Shi, F., Guo, H., Cao, J., and Chen, F.: Reconciling the 'westerlies' and 'monsoon' models: A new hypothesis for the Holocene moisture evolution of the Xinjiang region, NW China, Earth-Sci. Rev., 191, 263-272, https://doi.org/10.1016/j.earscirev.2019.03.002, 2019.

Risi, C., Bony, S., Vimeux, F., and Jouzel, J.: Water stable isotopes in the LMDZ4 General Circulation Model: Model evaluation for present day and past climates and applications to climatic interpretation of tropical isotopic records, J. Geophys. Res., 115, D12118, https://doi.org/10.1029/2009jd013255, 2010.

Ritterbusch, F., Chu, Y., Dong, X., Gu, J., Hu, S., Jiang, W., Landais, A., Lipenkov, V., Lu, Z., Shi, G., Stenni, B., Taldice team, Tian, L., Tong, A., Yang, G., and Zha, L.: Revealing old ice with $^{81}$Kr, Geophysical Research Abstracts. 20, EGU2018-2350-5, 2018.

Saini, J., Günther, F., Aichner, B., Mischke, S., Herzschuh, U., Zhang, C., Mäusbacher, R., and Gleixner, G.: Climate variability in the past ~19,000 yr in NE Tibetan Plateau inferred from biomarker and stable isotope records of Lake Donggi Cona, Quat. Sci. Rev., 157, 129-140, https://doi.org/10.1016/j.quascirev.2016.12.023, 2017.

~~Samartin, S., Heiri, O., Joos, F., Renssen, H., Franke, J., Brönnimann, S., and Tinner, W.: Warm Mediterranean mid-Holocene summers inferred from fossil midge~~

~~assemblages, Nat. Geosci., 10, 207-212, https://doi.org/10.1038/ngeo2891, 2017.~~

Sanwal, J., Rajendran, C. P., and Sheshshayee, M. S.: Reconstruction of late quaternary climate from a paleo-lacustrine profile in the central (Kumaun) Himalaya: viewing the results in a regional context, Front. Earth Sci., 7. https://doi.org/10.3389/feart.2019.00002, 2019.

Shao, L., Tian, L., Cai, Z., Cui, J., Zhu, D., Chen, Y., and Palcsu, L.: Driver of the interannual variations of isotope in ice core from the middle of Tibetan Plateau, Atmos. Res., 188, 48–54, https://doi.org/10.1016/j.atmosres.2017.01.006, 2017.

Sun, Y., Clemens, S., Morrill, C., Lin, X., Wang, X., and An, Z.: Influence of Atlantic meridional overturning circulation on the East Asian winter monsoon, Nat. Geosci. 5, 46-49, https://doi.org/10.1038/ngeo1326, 2012.

Takeuchi, N., Fujita, K., Aizen, V., Narama, C., Yokoyama, Y., Okamoto, S., Naoki, K., and Kubota, J.: The disappearance of glaciers in the Tien Shan Mountains in Central Asia at the end of Pleistocene, Quat. Sci. Rev., 103, 26-33, https://doi.org/10.1016/j.quascirev.2014.09.006, 2014.

Tang, Y., Pang, H., Zhang, W., Li, Y., Wu, S., and Hou, S.: Effects of changes in moisture source and the upstream rainout on stable isotopes in precipitation – a case study in Nanjing, eastern China, Hydrol Earth Syst. Sc. 19, 4293-4306, https://doi.org/10.5194/hess-19-1-2015, 2015.

Thompson, L. G., Mosley-Thompson, E., Davis, M., Bolzan, J., Dai, J., Klein, L., Yao, T., Wu, X., Xie, Z., and Gundestrup, N.: Holocene-late pleistocene climatic ice core records from Qinghai-Tibetan Plateau, Science, 246, 474-477, https://doi.org/10.1126/science.246.4929.474, 1989.

Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J. F.: Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821-1825, https://doi.org/10.1126/science.276.5320.1821, 1997.

Thompson, L. G., Davis, M., Mosley-Thompson, E., Lin, P., Henderson, K., and Mashiotta, T.: Tropical ice core records: evidence for asynchronous glaciation on Milankovitch timescales, J. Quat. Sci., 20, 723-733, https://doi.org/10.1002/jqs.972, 2005.

Thompson, L. G., Yao, T., Davis, M., Mosley-Thompson, E., Mashiotta, T., Lin, P., Mikhalenko, V., and Zagorodnov, V.: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau, Ann. Glaciol., 43, 61-69, https://doi.org/10.3189/172756406781812357, 2006.

Thompson, L.: Past, present, and future of glacier archives from the world's highest mountains, Proc. Am. Philos. Soc., 161, 226-243, 2017.

Thompson, L., Yao, T., Davis, M., Mosley-Thompson, E., Wu, G., Porter, S., Xu, B., Lin, P., Wang, N., Beaudon, E., Duan, K., Sierra-Hernández, M., and Kenny, D.: Ice core records of climate variability on the Third Pole with emphasis on the Guliya ice cap, western Kunlun Mountains, Quat. Sci. Rev., 188, 1–14, https://doi.org/10.1016/j.quascirev.2018.03.003, 2018.

Tian, L., Yao, T., Schuster, P. F., White, J. W. C., Ichiyanagi, K., Pendall, E., Pu, J., and Yu, W.: Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau, J. Geophys. Res., 108(D9), 4293, https://doi.org/10.1029/2002JD002173, 2003.

Tian, L., Yao, T., Li, Z., MacClune, K., Wu, G., Xu, B., Li, Y., Lu, A., and Shen, Y.: Recent rapid warming trend revealed from the isotopic record in Muztagata ice core, eastern Pamirs, J. Geophys. Res., 111, D13103, https://doi.org/10.1029/2005JD006249, 2006.

Wang, Y., Hou, S., Huai, B., An, W., Pang, H., and Liu, Y.: Glacier anomaly over the Western Kunlun Mountains, northwestern Tibetan Plateau, since the 1970s, J. Glaciol. 64, 624-636, https://doi.org/10.1017/jog.2018.53, 2018.

Yao, T., Thompson, L. G., Mosley-Thompson, E., Yang, Z., Zhang, X., and Lin, P.: Climatological significance of $\delta^{18}O$ in north Tibetan ice cores, J. Geophys. Res., 101(D23), 29531-29537, https://doi.org/10.1029/96JD02683, 1996.

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., Sturm, C., Werner, M., Zhao, H., He, Y., Ren, W., Tian, L., Shi, C., and Hou, S.: A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations, Rev. Geophys., 51, 525-51548, https://doi.org/10.1002/rog.20023, 2013.

Yasuda, T. and Furuya, M.: Dynamics of surge-type glaciers in West Kunlun Shan, Northwestern Tibet, J. Geophys. Res., 120, 2393–2405, https://doi.org/10.1002/2015JF003511, 2015.

Zhang, Z., Hou, S., and Yi, S.: The first luminescence dating of Tibetan glacier basal sediment, The Cryosphere, 12, 1-6, https://doi.org/10.5194/tc-12-1-2018, 2018.

Zhong, Z. P., Solonenko, N.E., Gazitúa, M. C., Kenny, D. V., Mosley-Thompson, E., Rich, V. I., Van Etten, J. L., Thompson, L. G., and Sullivan, M. B.: Clean low-biomass procedures and their application to ancient ice core microorganisms, Front. Microbiol., 9, 1-15, https://doi.org/10.3389/fmicb.2018.01094, 2018.

Zhou, Y., Li, Z., Li, J., Zhao, R., and Ding, X.: Glacier mass balance in the Qinghai–Tibet Plateau and its surroundings from the mid-1970s to 2000 based on Hexagon KH-9 and SRTM DEMs, Remote Sens. Environ., 210, 96-112, https://doi.org/10.1016/j.rse.2018.03, 2018.

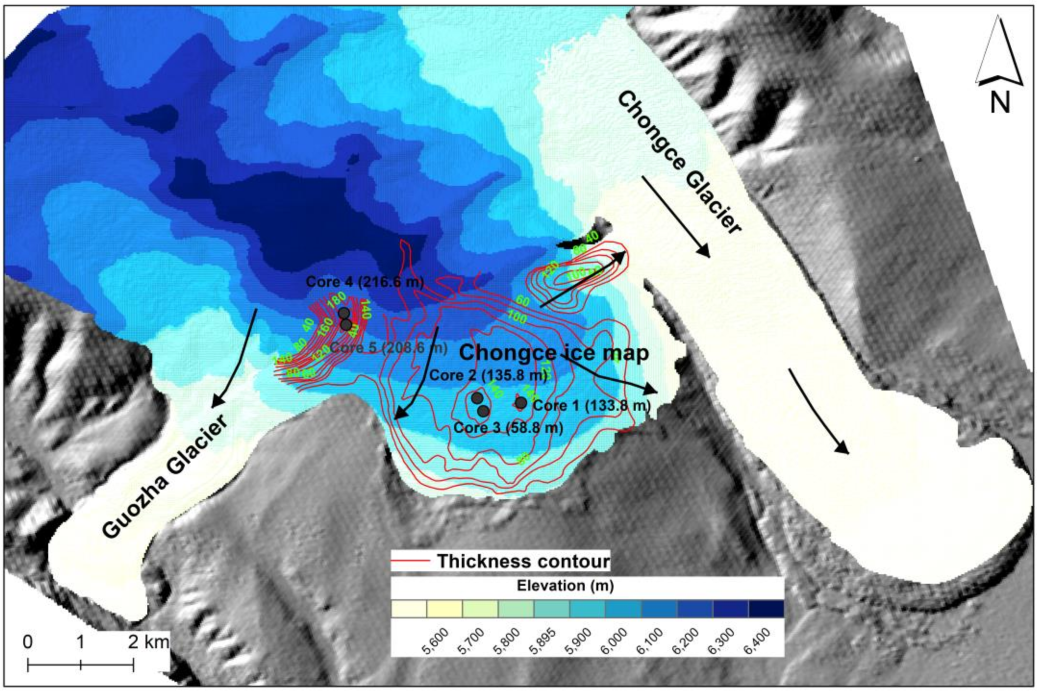
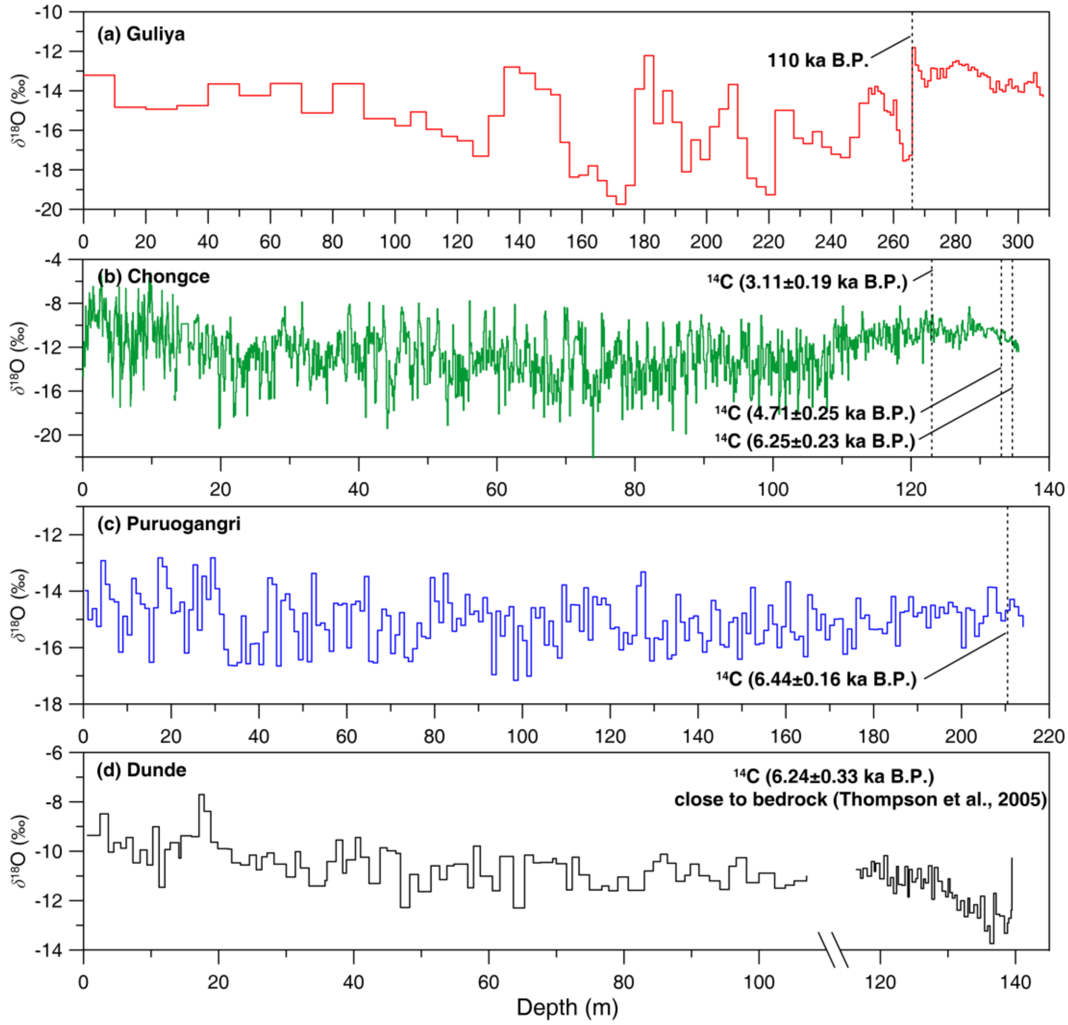



Figure 1. Map showing the topography (red contour lines) and ice thickness (blue color ramp) of the Chongce ice cap with the drilling sites (black dots). The black arrows show the ice flow direction. The effects of the Chongce Glacier surging on the mass balance of the Chongce ice cap is limited, if 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).


(a) Guliya
110 ka B.P.
δ18O (‰)
(b) Chongce
14C (3.11±0.19 ka B.P.)
14C (4.71±0.25 ka B.P.)
14C (6.25±0.23 ka B.P.)
δ18O (‰)
(c) Puruogangri
14C (6.44±0.16 ka B.P.)
δ18O (‰)
(d) Dunde
14C (6.24±0.33 ka B.P.)
close to bedrock (Thompson et al., 2005)
δ18O (‰)
Depth (m)

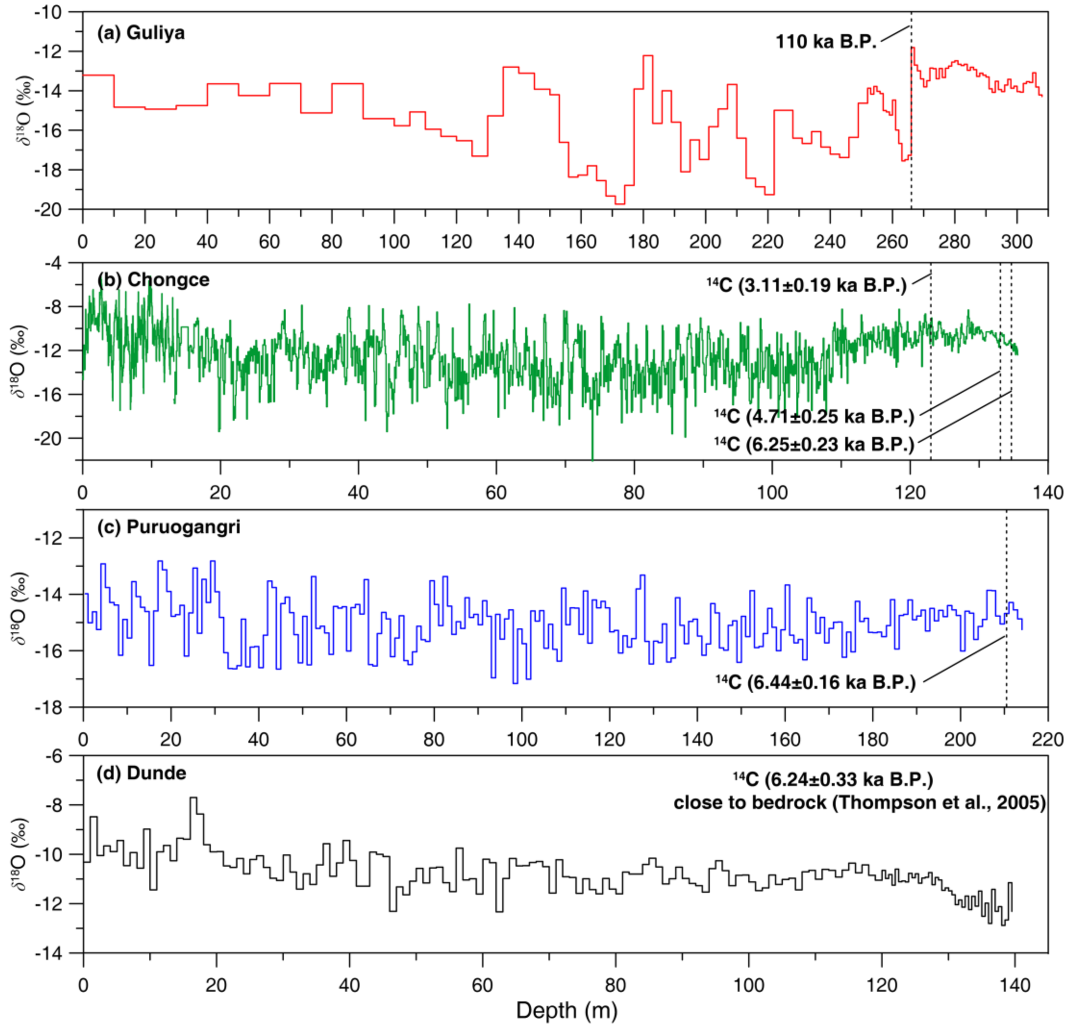



Figure 2. The $\delta^{18}O$ profiles of the ice cores against each respective depth. The age of 110 kaBP at the depth 266 m of the Guliya ice core is from Thompson et al. (1997). The top 13.2 m of Chongce Core 3 profile (An et al., 2016) is combined with Core 2 to form a single profile because the distance 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.

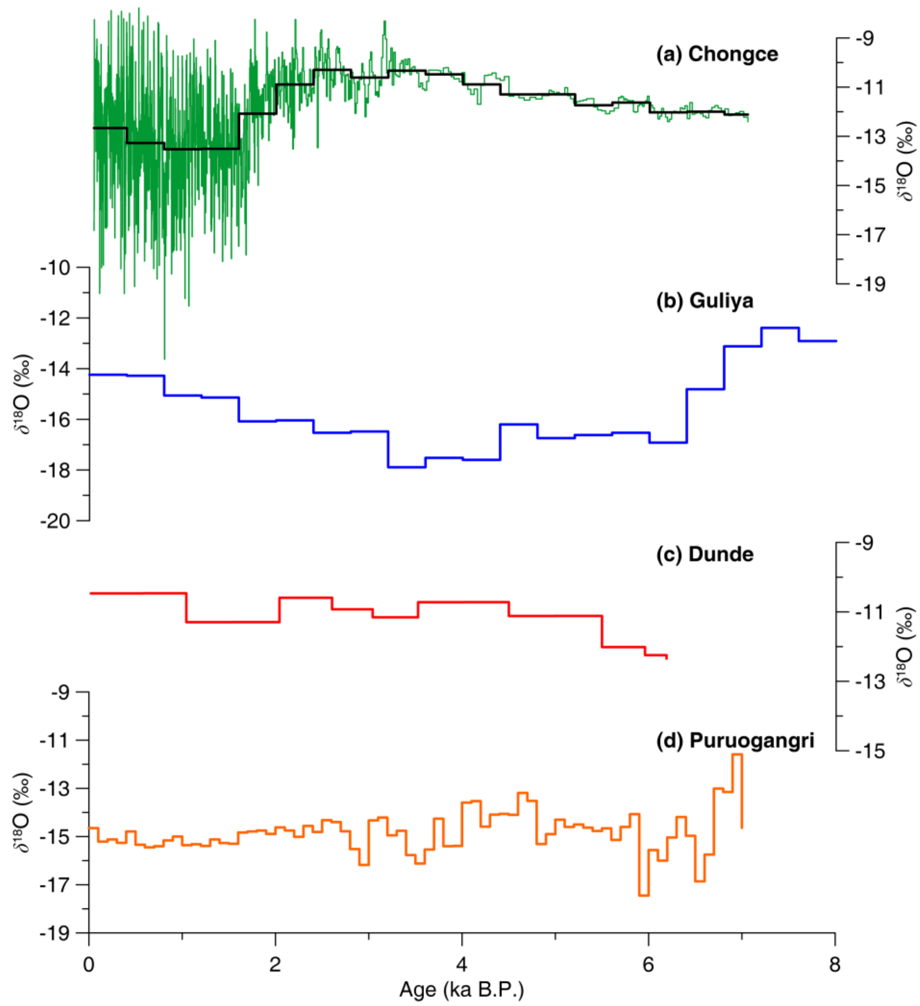



Figure 3. The $\delta^{18}O$ profiles of the Chongce (a), Guliya (b), Dunde (c) and Puruogangri (d) ice cores by age. We combined the $\delta^{18}O$ profiles of Core 2 and Core 3 into a single time series. The black line of the Chongce $\delta^{18}O$ profile represents 400-year averages to match the 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).

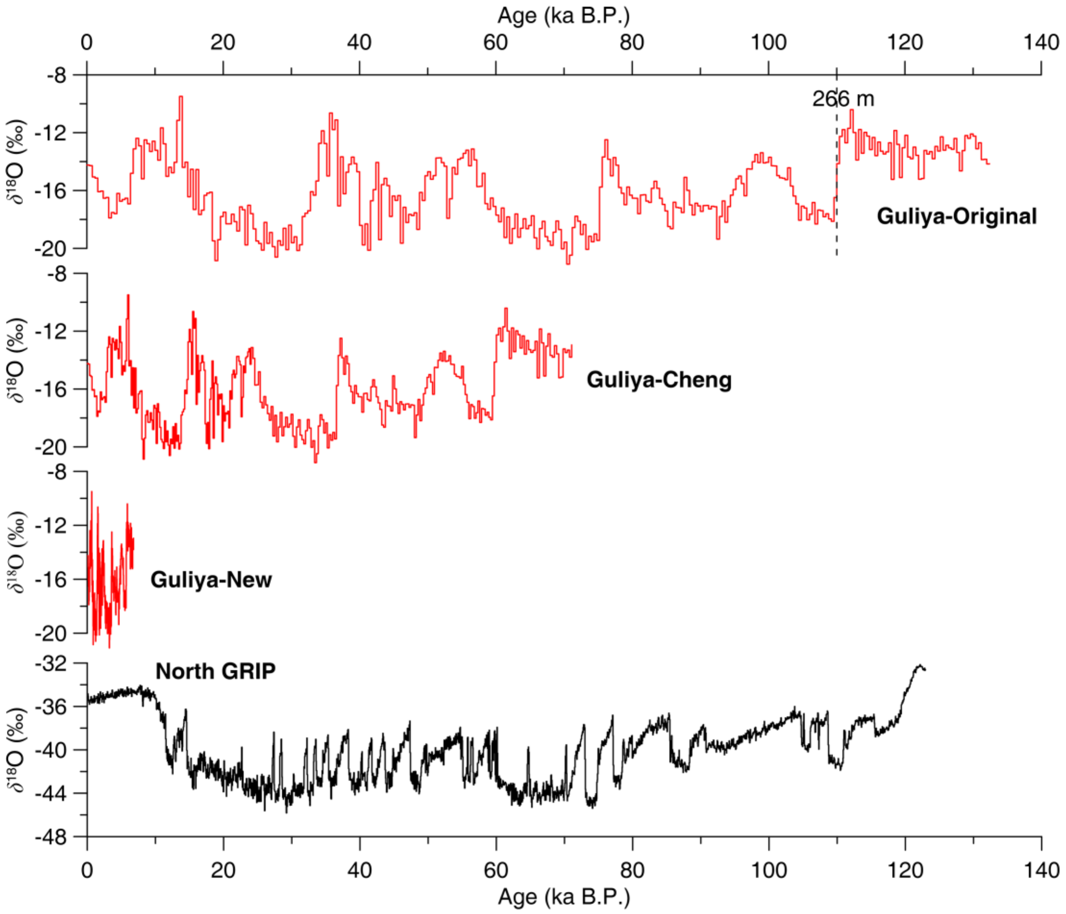



Figure 4. The $\delta^{18}O$ profiles of the Guliya and North GRIP ice cores. The Guliya-Original is plotted on its original chronology (Thompson et al., 1997). The Guliya-Cheng profile is the original Guliya record linearly compressed by a factor of two, as suggested in Cheng et al. (2012). The Guliya-New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

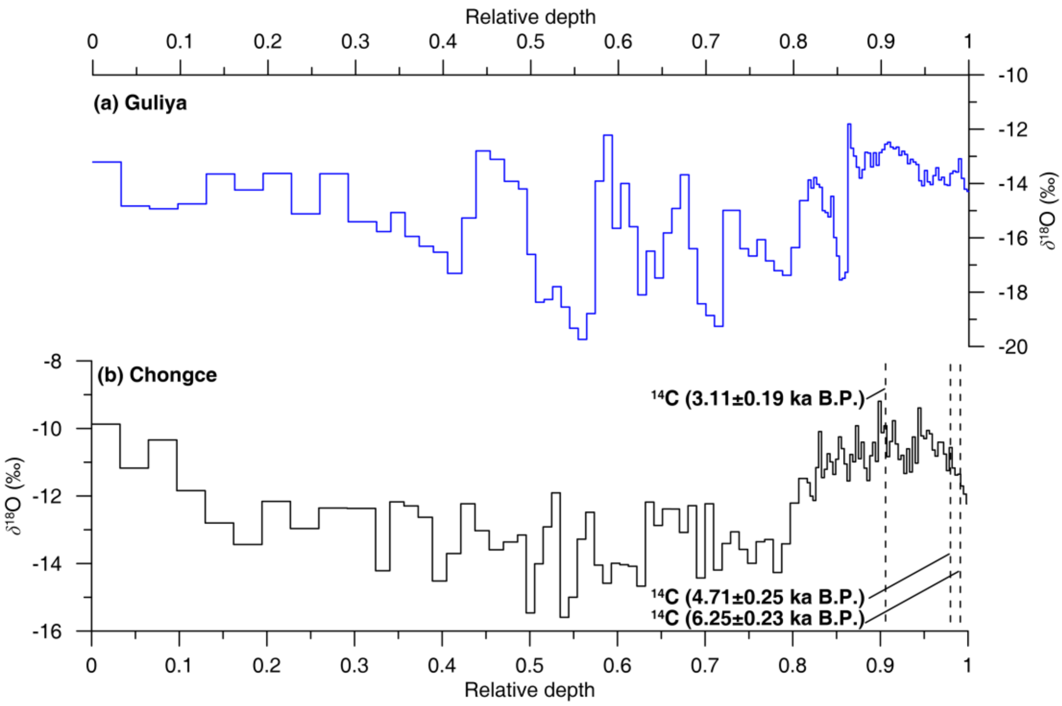



Figure 5. The $\delta^{18}O$ profiles of the Guliya (a) and Chongce (b) ice cores, plotted against their relative depth. The Chongce profile was averaged to match the temporal resolution of the published Guliya record as shown in Fig. 2a (Thompson et al., 1997).

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] $p < 0.001$