Response to Referees and Revised Manuscript

We provide a detailed point-by-point response to all referee comments and we give the changes made in the revised manuscript. The response to the comments is constructed as: (1) comments from Referees, (2) author's response, and changes in manuscript. We include a marked-up manuscript version showing the changes made.

The reviewer's comments are in blue, our replies in black. The changes made to the manuscript are highlighted in red.

Response to reviewer #1

This paper titled "Significant recent warming over the northern Tibetan Plateau from ice core 18O records" presents the isotope variations from the top part of a new ice core drilled in the central Tibetan Plateau. The authors also compared with other available ice core 18O record relating the last past decades, and made a composite isotope record time series to compared with the temperature change in different spatial scale. The main finds in the paper are the rapid warming trend reflected from ice core isotope records and the diverged trend from the ice core from the observation temperature change in the past decade. The authors specifically discussed possible reason caused the diverged trends in the past decade. The sensitivity high elevation climate change is still a debated questions and ice core isotope records from high elevation probably bring some hints on the answer of the question. This paper provided new proof about a much higher warming trend from ice core record on the middle of the Tibetan Plateau, and comparison found this is not the unique phenomenon. The consistence between ice cores from different sites exclude the local temperature pattern. Therefore, the work from this paper is important, and the finding about the continuous warming trend from higher elevation ice core records is also an interesting phenomenon and need further research work from e.g. more ice core records. Although there are some uncertainties needing further discussion, the research from this paper should be considered for publication in the journal of Climate of the Past. Because the factors influencing precipitation isotopes in that region is not fully understood, the reasonable explanation of the Tibetan Plateau ice core record, especially for clear annual record, is still a tough work, and I think the authors should think over the following questions carefully.

Thank you for your insightful comments. We have incorporated your suggestions in the revised manuscript.

1. The difficulty in explaining the annual ice core 18O is that there is a very weak correlation with local meteorological temperature record, and there is a relative higher correlation in Spring (March–May), while the local precipitation is in summer.

Relative weak correlations between ice core $\delta^{18}O$ and instrumental temperature records are quite common for the Tibetan ice cores, such as in cases of Puruogangri and Geladaindong ice cores. This could be partly caused by the relatively large distance and elevation difference between meteorological stations and ice core drilling site. Weak correlations could also be a result of uncertainties in ice core dating. In order to reduce the impact of such dating uncertainties, we used 5 year running average instead of annual series to examine the relationships between ice core $\delta^{18}O$ and temperature. This significantly increased the correlation between the two time series (Table 1). In addition, we focused our discussion more on decadal temperature changes in the revised manuscript, as suggested in the following comment.

In the revised manuscript, we added possible explanations for higher correlation between Zangser Kangri (ZK) $\delta^{18}O$ and spring temperature, as following:

"The stronger spring temperature signal recorded in ZK $\delta^{18}O$ record may be attributed to the different seasonal moisture sources in this region. At Shiquanhe and Gêrzê, Yu et al. (2009) found that during the non-monsoon period (October–June) when local moisture recycling and the westerlies dominate the moisture sources, air temperature correlates more strongly with $\delta^{18}O$ in precipitation. On the other hand, precipitation $\delta^{18}O$ in monsoon season could be affected by a variety of factors other than temperature, including the convection intensity, distance from moisture sources and amount effect (Y. He et al., 2015; Tang et al., 2015). This could obscure the relationship between $\delta^{18}O$ and air temperatures (Joswiak et al., 2013). In addition, previous studies in the central Himalayas found that high elevation areas (> 3000ma.s.l.) can receive up to 40% of their annual precipitation during cold season because of terrain locked low pressure systems and orographically forced precipitation (Lang and Barros, 2004), a much higher

percentage than that of surrounding low altitude areas of the same region (Pang et al., 2014). Therefore, the ZK ice core (located at 6226 m a.s.l.) could have had more cold-season (non-monsoonal) precipitation than that indicated by nearby meteorological stations, located at much lower elevations. Both factors could result in a stronger signal of spring temperature in the ZK ice core $\delta^{18}O$ record."

2. Routinely, the annual signal from ice core in the central Tibetan Plateau might be not clear enough for dating the annual layer due to either the lack of winter precipitation or strong wind erosion on the glacier surface. This make the attempt of the accurate date in annul scale ice core difficult, at least from the isotope variation. From figure 2, if you account the seasonal cycle of isotope, there will be about only 20 years to the beta maximum. Therefore, please discuss in detail how the annual layer is determined in more clear way. In this case, I think the authors should more focus on the discussion of the ice core record in, for example, 5 years interval average.

In the revised manuscript, we discussed the Zangser Kangri (ZK) ice core dating in detail. The details are presented in the text as:

"*In the northern TP, the annual cycle in $\delta^{18}O$ along the ice core profile is primarily related to temperature variations (Araguás-Araguás et al., 1998; Yao et al., 2013). The $\delta^{18}O$ compositions in modern precipitation samples collected at northern TP show marked seasonal patterns with the highest values in summer and lowest in winter (Yu et al., 2009). In addition, the major ions (e.g., Mg^{2+} and $SO4^{2-}$) also show clear seasonal cycles with high concentrations in winter/spring and low concentrations in summer (Zheng et al., 2010), and have been used as complementary tools in ice core dating in the northern TP (Kang et al., 2007). Therefore, the ZK ice core was dated by using the seasonality of $\delta^{18}O$ in conjunction with the seasonal variations of major ions, including Mg^{2+}, Ca^{2+} and $SO4^{2-}$, with a reference layer of β activity peak in 1963 (Fig. 2). The core 1 was dated back to 1951 at 16.38 m depth with an uncertainty estimated within 1 year (Fig. 2, Zhang et al., 2016). The mean annual net accumulation rate calculated according to the dating result and density of the ice core profile is low for ZK glaciers (190 kg H_2O m^{-1} yr^{-1}). This study focused on the $\delta^{18}O$ records in the top 16.38 m of the ice core, corresponding to the time period 1951-2008.*"

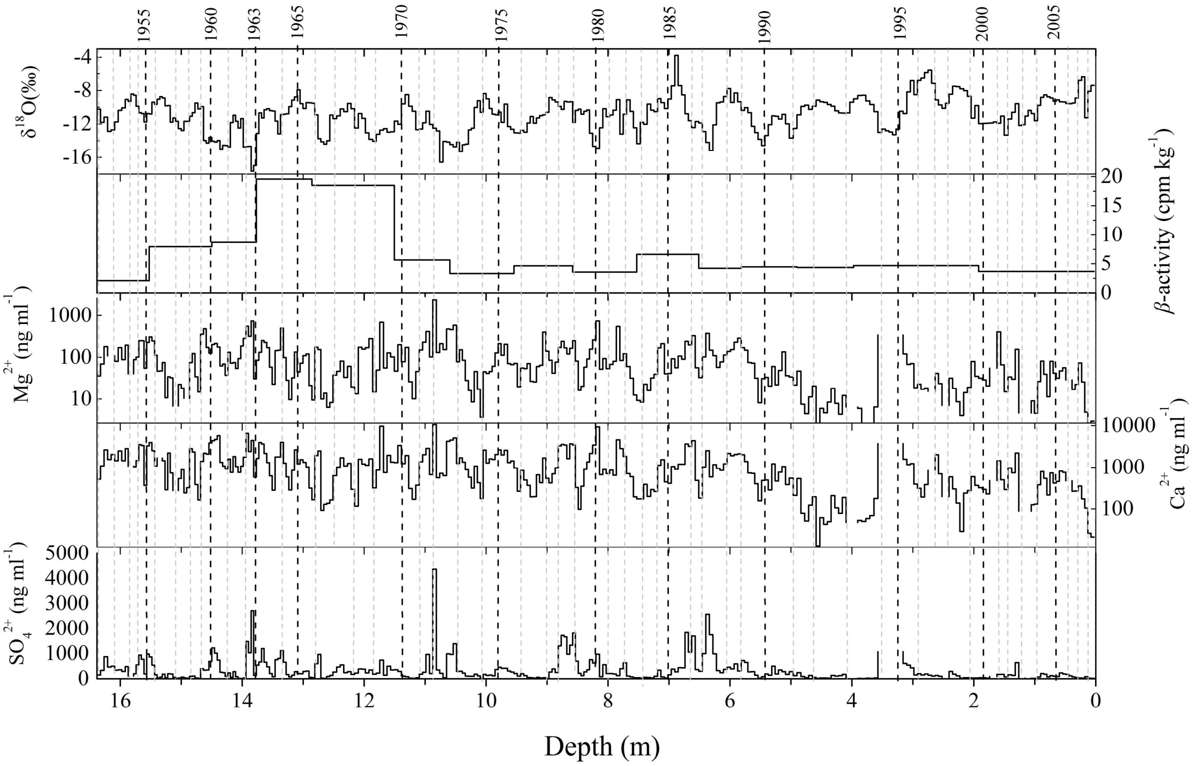
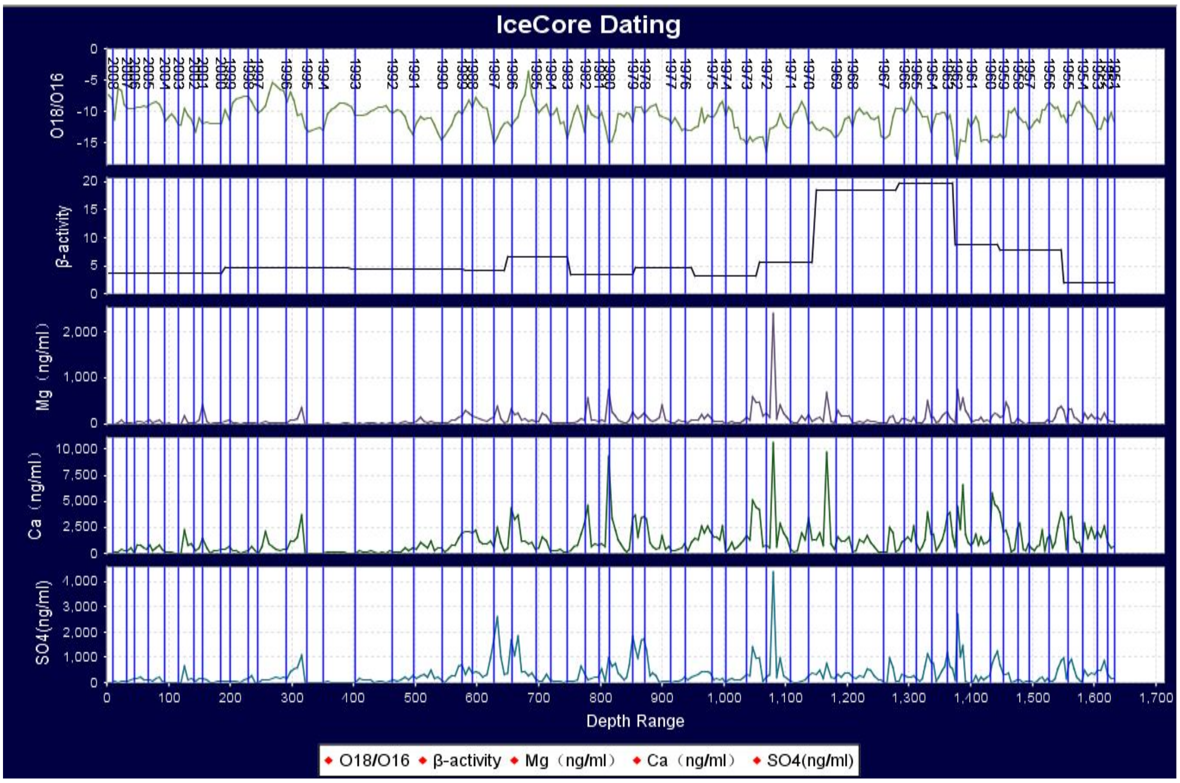


Figure 2. Variations of $\delta^{18}O$ in the ZK ice core and data used in dating: beta activity and major ion concentrations. We calculated the logarithm to the base 10 of the concentrations of the Ca^{2+} and Mg^{2+} to facilitate dating.

In addition, we used Ice Core Dating (ICD) software developed by Climate Change Institute at the University of Maine. The dating result, shown in the following figure, was in agreement with our previous results.



Variations of δ^{18}O in the ZK ice core and data used in dating: beta activity and major ion concentrations. We calculated the logarithm to the base 10 of the concentrations of the Ca^{2+} and Mg^{2+} to facilitate dating.

As suggested, we focus on the discussion of the ice core δ^{18}O record by 5-year running averages. The correlation coefficients between ZK ice core δ^{18}O and instrumental temperature records are listed in Table 1:

		Gêrzê		Xainza		Stations averaging		ITNTP
		March-May	Annual	March-May	Annual	March-May	Annual	Annual
Correlation coefficients	Annual	0.52^c	0.34^a	0.45^c	0.34^a	0.48^c	0.34^a	0.35^a
	5 year running average	0.63^c	0.53^c	0.73^c	0.60^c	0.73^c	0.60^c	0.61^c
Slope	Annual	0.93^b	0.67^a	0.93^b	0.98^a	1.00^c	0.88^a	0.87^a
	5 year running average	0.87^c	0.76^c	1.54^c	1.32^c	1.37^c	1.18^c	0.40^c

^{a} $p< 0.05$; ^{b} $p< 0.01$; ^{c} $p< 0.001$.

Table 1. Correlation coefficients and linear slopes between $\delta^{18}O$ values in the ZK ice core and instrumental spring (March–May) and annual temperature from closest Gêrzê (1973–2008) and Xainza stations (1961–2008), the averaging records of the two stations (1961–2008), and the ITNTP series (1961–2008).

3. The discussion about the reason of different warming trend in recent decade from both ice core and meteorological data is, somehow, not convincing. For instance, the addressing of "The increased vegetation density may also have contributed to the continuous warming by reducing albedo and heat loss." may not reasonable.

In the revised manuscript, we deleted the discussion about whether "[t]he increased vegetation density may also have contributed to the continuous warming by reducing albedo and heat loss." Instead, we focused on the possible influence of snow/ice albedo on temperature changes, as follows:

"*The persistent rapid warming in the northern TP could have been caused by the regional radiative and energy budget changes (K. Yang et al., 2014; Yan and Liu, 2014; Duan and Xiao, 2015). Many studies show that the snow/ice-albedo feedback is an important mechanism for enhanced warming at high elevation regions (Liu and Chen, 2000; Pepin and Lundquist, 2008; Rangwala and Miller, 2012). Ghatak et al. (2014) found that the surface albedo decreases more at higher elevations than lower elevations over the TP in recent years. Qu et al. (2013) observed a decreasing trend for the snow/ice albedo at the Nyainquentanglha glacier region, central TP, for the period 2000 to 2010. It has been found that the glacier albedo for the nine glaciers in western China has decreased during the period 2000-2011, especially for the central TP (J. Wang et al., 2014). For example, the glacial albedo of Dongkemadi and Puruogangri glaciers decreased at a rate of 0.0043-0.0059* yr^{-1} *and 0.001-0.004* yr^{-1} *respectively. Reduced surface albedo increases the surface absorption of solar radiation, and may have contributed to the continued warming over the high elevation regions of the northern TP. Further research is needed to identify and quantify the exact mechanisms accounting for the temperature variations over the Plateau.*"

Response to reviewer #2

Interactive comment on "Significant recent warming over the northern Tibetan Plateau from ice core $\delta^{18}O$ records" by W. An et al.

Anonymous Referee #2

Received and published: 29 September 2015

The authors first presented a new d18O records from an ice core located at Mt Zangser Kangri (ZK), which representing high elevation above 6 km. Then they reconstructed the regional temperate from 195-2008, by using ZK record and another three d18O records over northern Tibetan Plateau where two records are close to ZK and one is far at the northwestern part. The regional temperature reconstruction shows warming trend from 1970 without displaying any hiatus as observed in recent global mean temperature. This trend pattern from this regional reconstruction also differs from 14 meteorological station data over northern TP (ITNTP). The authors then discussed the possible reasons for this continuous warming trend from the regional reconstruction.

Due to the lack of meteorological stations in high and remote region such as western and northern part of TP, the reconstructions from ice core d18O can be useful to provide the climate information. However, the regional temperature reconstruction is not convincing. The authors may consider to carefully address my comments below.

We greatly appreciate your detailed and thoughtful input. In the revised manuscript, we have incorporated all your suggestions. A point-to-point response is provided as follows.

General comments:

1. The authors applied four d18O records to reconstruct the regional temperature in Fig5a, however, an visual comparison for the d18O value in Fig.4 raises doubt on the reconstruction. Global hiatus starts from late 1990s around 1999, to the end of data 2008. In four records only ZK extends to 2008 and there is an obvious drop pattern in this record from 1999 to 2005, one may consider this drop as a hiatus if just observing this individual data. Record from Puruogangri can

not contribution to the global hiatus period. Another two records, Muztagata extends to 2002 and Geladaindong extends to 2004, both show increasing trend and eventually compensate the drop shape in ZK record. Therefore at least the continuous warming trend from 1998 to 2004 is an artificial one resulting from combination record of a,b and d. Here I am not against there may be a continuous warming over the Tibetan Plateau, but the regional temperature reconstruction presented by the authors is not convincing.

In the revised manuscript, the regional reconstruction covered the years 1951-2002, the common period of the four ice core $\delta^{18}O$ records. At the same time, we further developed a temperature reconstruction only based on ZK ice core $\delta^{18}O$ record for 1951-2008 to investigate the temperature variations since the late 1990s.

The detailed trend analysis of the regional temperature reconstruction for the northern Tibetan Plateau (RTNTP) is documented in the revised text as follows:

"*The reconstruction captured the cooling period during 1960s, as well as the prominent warming since the 1970s to the end of the record, with the highest rate of increase in the late 1990s (Fig. 5). For the period from 1970 to 2002, the RTNTP showed more rapid warming trend at the rate of 0.51±0.07°C(10yr)$^{-1}$ than that of the global temperature (0.27±0.03°C(10yr)$^{-1}$). The RTNTP rate was also higher than the ITNTP rate of increase at 0.43±0.08°C(10yr)$^{-1}$ for the same time period. From 1990 to 2002, the warming accelerated on the northern TP with rates of temperature increase at 0.95±0.21°C(10yr)$^{-1}$ for the RTNTP and 0.90±0.29°C(10yr)$^{-1}$ for the ITNTP, much higher than the warming rate of the global temperature (0.37±0.13°C(10yr)$^{-1}$). These results seemed to indicate enhanced warming at the high elevation regions on the northern TP.*"

The temperature reconstruction for the Zangser Kangri region (ZK) showed a brief pause during the early 2000s before warming picked up again. Despite the short pause, the mean decadal annual temperature change based on LOESS regression model is the highest for the decade since 1999, higher than any other decade on the record, suggesting an enhanced warming since the late 1990s. The detailed trend analysis of the temperature reconstruction for the Zangser Kangri region (ZK) is documented in the revised text as follows:

"*However, the ZK series revealed a continued warming trend in recent years after a brief pause during the early 2000s (Fig. 5b). We calculated mean decadal annual temperature change based on the LOESS regression model for all three time series (Fig. 7). For both the global temperature and ITNTP series, the highest average warming rates occurred during 1990s, and then decreased significantly since 1999 (Fig. 7c and d). The reduction of warming rate in the ITNTP series was consistent with results by Duan and Xiao (2015), who found weaker warming trend during the period 1998-2013 in the northern TP based on the instrumental temperature records. However, the rates of increase remained high for the temperature records in the ZK series since 1999 (Fig. 7b), in contrast to the slowdown of climate warming observed for the global mean and ITNTP temperature records since 1999 (Fig. 7d). The persistent high warming rates derived from our regional reconstructions seem to suggest that the elevation-dependent warming is still evident over the high elevations of the northern TP despite the reduced warming rates observed at lower stations in ITNTP (Fig. S5).*"

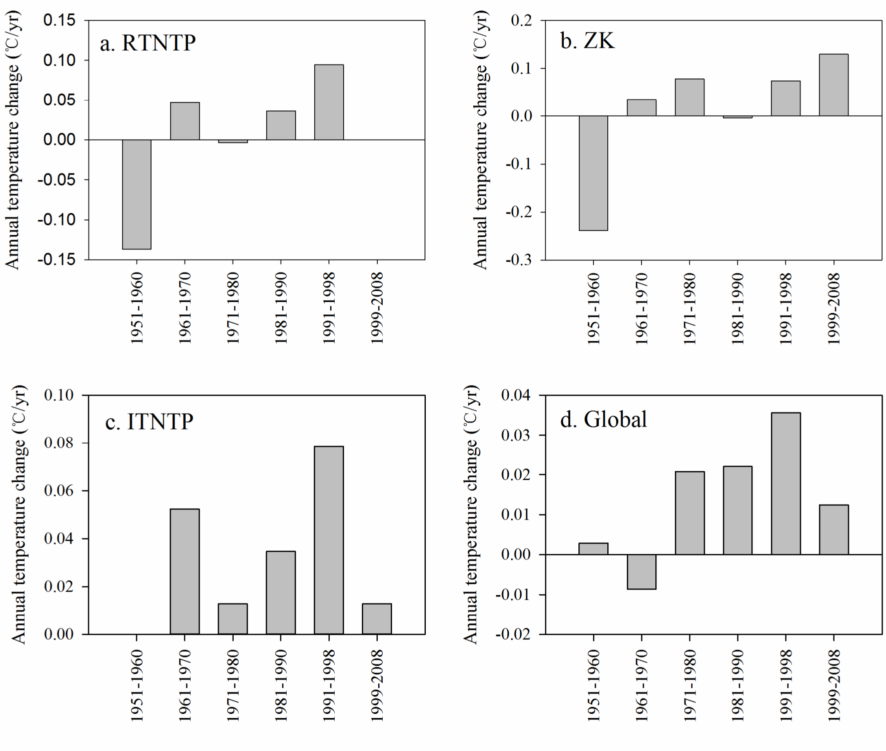


Figure 7. Decadal mean annual change rates for the regional temperature reconstruction series for northern TP (RTNTP) from ZK, Muztagata, Puruogangri and Geladaindong ice core $\delta^{18}O$ records (a), the temperature reconstruction only from ZK ice core $\delta^{18}O$ record (b, ZK), the instrumental temperature record of the northern

TP (ITNTP) (c), and global average temperature (d). The decadal mean annual change rates were estimated using the non-parametric LOESS regression model with a span of 0.4.

2. P2710 line 10, the authors state that "The continuous warming trend was also recorded in the ITNTP (Fig. 5b)", but what I observed from Fig. 5b is a similar hiatus roughly after 2000 as seen on global mean in Fig. 5c. I am wondering if the authors put the wrong figure for Fig.5b. Because when authors introduce the ITNTP data in P2705 line 16-17 they state that "Most of the stations used in ITNTP time series were located on the eastern part of the northern TP: : :". According to a recent report by Duan and Xiao (2015), there is an warming trend from 1980 to 2013 and especially an accelerated warming trend over the TP from 2008 to 2013. The station data they used covering mostly eastern TP, which may include the 14 stations that used for representing ITNTP. Therefore I suspect that ITNTP should show a continuous warming trend but Fig. 5b really did not tell this.

In the revised manuscript, we calculated the warming trend of ITNTP, and did find a reduction of warming rate since late 1990s (Figure 7). We changed the "The continuous warming trend was also recorded in the ITNTP (Fig. 5b)" to "a reduction in warming rate since 1999 for the ITNTP series (Fig. 7c)".

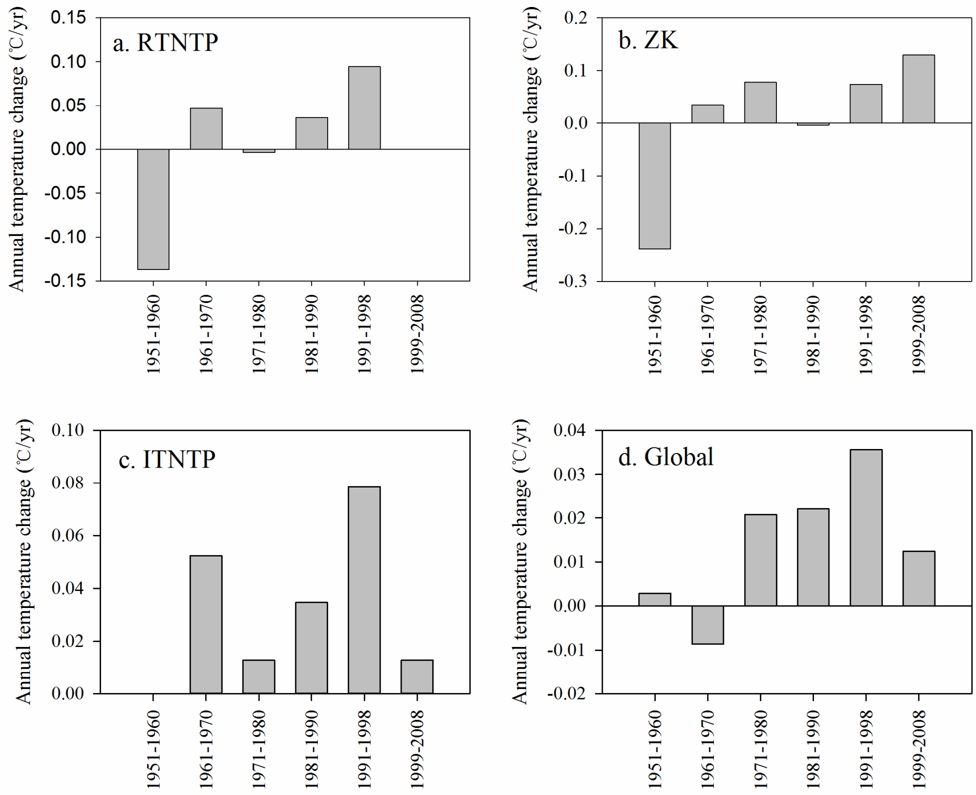


Figure 7. Decadal mean annual change rates for the regional temperature reconstruction series for northern TP (RTNTP) from ZK, Muztagata, Puruogangri and Geladaindong ice core $\delta^{18}O$ records (a), the temperature reconstruction only from ZK ice core $\delta^{18}O$ record (b, ZK), the instrumental temperature record of the northern TP (ITNTP) (c), and global average temperature (d). The decadal mean annual change rates were estimated using the non-parametric LOESS regression model with a span of 0.4.

It is true that the 14 stations over the northern Tibetan Plateau (TP) in this study were included in the data used by Duan and Xiao (2015). However, they used 73 stations on the TP, and the majority of the stations were located in southern TP. From Figure 3 in Duan and Xiao (2015), it could be seen that the stations with accelerating warming trend from 1998 to 2013 were mostly located in southern TP. For stations in the northern TP, the warming rates during period 1998-2013 were much lower, and some stations even show negative trends. We calculated the decadal temperature change for just the 14 stations in the northern TP during the period 1998-2013, using simple linear regression equation (the same method used by Duan and Xiao, 2015). The results are shown in the following table. Therefore, our result was not in contradiction to the results of Duan and Xiao (2015).

Decadal temperature Trend (℃$(10yr)^{-1}$)	-0.22	0.38	0.19	-0.51	0.13	0.18	0.17	-0.12	0.34	-0.03	0.16	-0.08	-0.1	-0.14
R^2	0.09	0.17	0.06	0.27	0.03	0.06	0.04	0.01	0.13	0.001	0.06	0.01	0.02	0.03

Table. The decadal temperature trends for the 14 stations from the northern TP for the period 1998–2013.

In the revised manuscript, we discussed the possible hiatus recorded in ITNTP as follows:

"*The reduction of warming rate in the ITNTP series was consistent with results by Duan and Xiao (2015), who found weaker warming trend during the period 1998-2013 in the northern TP based on the instrumental temperature records. However, the rates of increase remained high for the temperature records in the ZK series since 1999 (Fig. 7b), in contrast to the slowdown of climate warming observed for the global mean and ITNTP temperature records since 1999 (Fig. 7d). The persistent high warming rates derived from our regional reconstructions seem to suggest that the elevation-dependent warming is still evident over the high elevations of the northern TP despite the reduced warming rates observed at lower stations in ITNTP (Fig. S5).*"

3. I am not convinced to select isotope sensitivity in section 3.2 as 0.6 and 0.7 as for a far away site Muztagata, why do not the authors refer to more nearby stations such as Gerze and Shiquanhe, at least they are latitudinally close, have similar temperature and following the same wind flow to receive the similar water vapour. I think the choice made here dominates the reconstructed temperature. Will be results quite different if one choose isotope sensitivity as 0.33 rather than 0.6?

We did not use the $\delta^{18}O$-temperature relationships derived from precipitation $\delta^{18}O$ and the monthly mean temperatures at Gêrzê and Shiquanhe stations for several reasons. First, even though Gêrzê and Shiquanhe stations are relatively close latitudinally to the Zangser Kangri (ZK) drilling site, they are far way from the other three ice core sites (Fig. 1). Therefore, it maybe not appropriate to use the isotope sensitivity derived from these stations to reconstruct the regional temperature at such an extensive area over the northern Tibetan Plateau (northern TP). Second, the $\delta^{18}O$-temperature relationship (isotope sensitivity) usually increases with elevation as indicated by Rayleigh-type equilibrium fractionation model (Rowley et al., 2001). The elevation of the two stations (Gêrzê, 4414.9m a.s.l.; Shiquanhe 4278m a.s.l.) are 1000-2000 m lower than the ZK as well as the other three ice core sites (i.e. Muztagata, Puruogangri and Geladaindong). It has been found that the isotope sensitivity is substantially higher at high latitudes than that found at low latitudes (Dansgaard, 1964).

In the revised manuscript, the isotopic sensitivity was established for the regional temperature reconstruction based on the linear regression of 5-year running average between the regional $\delta^{18}O$ records and ITNTP temperature records, and it was derived for the ZK temperature reconstruction based on the linear regression of 5-year running average between the ZK $\delta^{18}O$ records and the average temperature records of the two nearby stations (Figure S3).

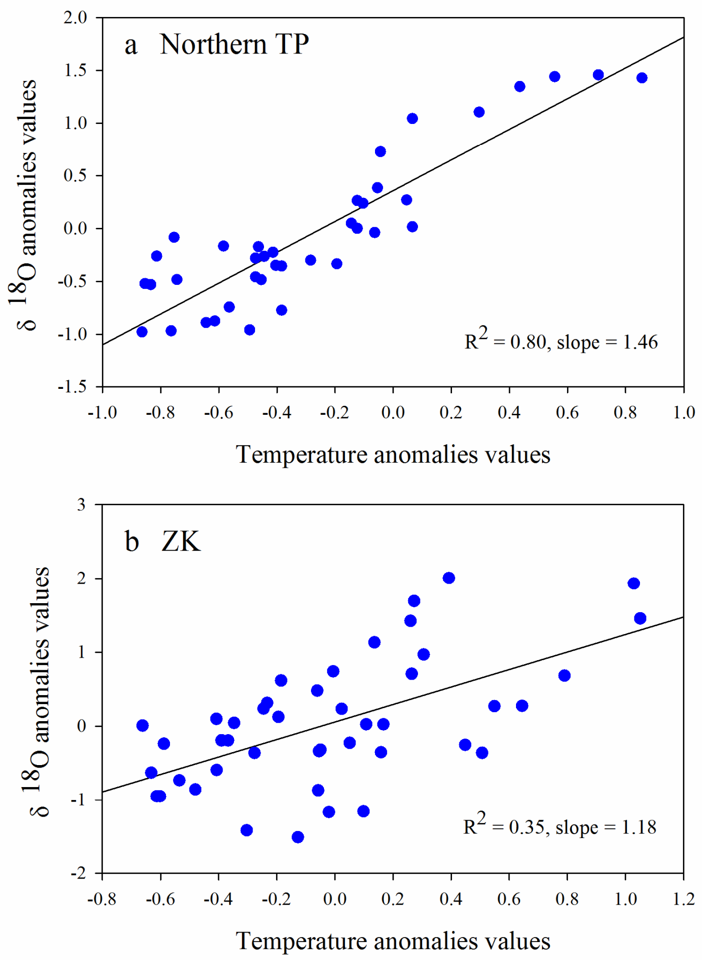


Figure S3. Scatter plots between regional $\delta^{18}O$ and regional instrumental temperature of the northern TP (RTNTP) (5 year running averages) (a), and scatter plots between ZK $\delta^{18}O$ and regional instrumental temperature (averaged from Gêrzê and Xainza) (5 year running averages) (b).

In addition, we examined the sensitivity of decadal warming rates to different values of isotope sensitivity. We calculated the decadal warming rates based on a range of isotope sensitivity commonly used to convert $\delta^{18}O$ to temperature for ice cores on the TP (0.3 to 1.5) for two time periods: 1970-2002 and 1990-2002. The results indicate that as the value of isotope sensitivity increases, the response of decadal warming rate to the isotope sensitivity decreases, especially when the value of isotope sensitivity gets higher than 1.0 (Fig. S4). This pattern is relatively consistent temporally, as indicated by the similar response for the two different time periods.

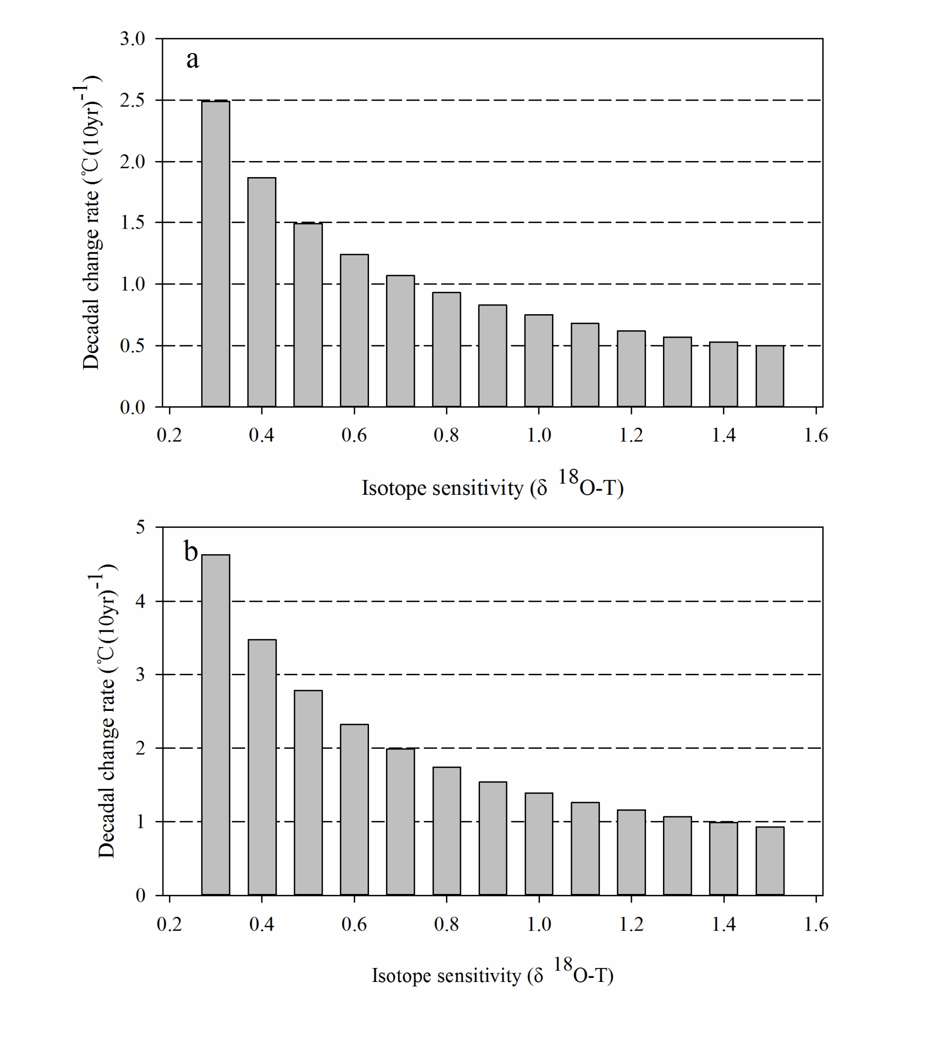


Figure S4. The variations of decadal warming rate with isotope sensitivity values range from 0.3 to 1.5 during 1970-2002 (a) and 1990-2002 (b), respectively. The decadal warming rates were calculated from the RTNTP.

The related contents were presented in the revised text as follows:

"*In our study, the strongest correlation was found between the 5 year running average of the regional $\delta^{18}O$ record and ITNTP (r = 0.89, p < 0.001) (Fig. S3). The ZK $\delta^{18}O$ correlates most strongly with the 5 year running average of the mean temperature from two nearby stations (Gêrzê and Xainza, r = 0.60, p < 0.001) (Table 1). Based on these significant relationships, the isotope sensitivities were determined as 1.46‰ °C^{1} for the regional $\delta^{18}O$ series and 1.18‰ °C^{1} for ZK $\delta^{18}O$ series, and were used to reconstruct regional temperature series for the northern TP (RTNTP) and the ZK temperature series respectively. Additional analysis showed that as isotope sensitivity value increases, the response of decadal warming rate decreases, especially for the isotope* *sensitivity values greater than 1.0 (Fig. S4).* "

Specific comments:

1. Last sentence in Abstract, too general conclusion that can be drawn by any studies for TP temperature trend, I suggest the authors present a more concrete conclusion if you regard this work is a valuable contribution to the community.

We revised the abstract to include more concrete conclusions from our study, specifically the following:

"*The RTNTP showed significant warming at 0.51±0.07°C per decade since 1970, a higher rate than the trend of instrumental records of the northern TP (0.43±0.08°C per decade) and the global temperature trend (0.27±0.03°C per decade) at the same time. In addition, the ZK temperature record, with extra length until 2008, seems to suggest that the rapid elevation-dependent warming continued for this region during the last decade, when the mean global temperature showed very little change. This could provide insights into the behavior of the recent warming hiatus at higher elevations, where instrumental climate records are lacking.*"

2. In section 2 for methodology and data the authors do not mention if the d18O record has annual resolution or monthly resolution, but they claim in section 3.1 that the record "showed distinctive seasonal variations". Do all the d18O records used in this study have monthly resolution? If not, how do they show seasonal variations? Because I am also confused by the correlations in Table 1, are they simultaneous correlations between the d18O and temperature?

In this study, all the $\delta^{18}O$ records only have annual resolution. However, there could be several samples per year, showing the seasonal variations of the $\delta^{18}O$ values. Such seasonal variations of $\delta^{18}O$ in the northern TP are dominated by the 'temperature effect', with relatively high $\delta^{18}O$ in the summer (peak) and low $\delta^{18}O$ (valley) during the winter and spring, which can be used to date the ice core. The annual value of $\delta^{18}O$ values is calculated as the mean value of the several samples from each year, i.e. the section between two consecutive valleys.

The correlation coefficients in Table 1 were calculated between the annual $\delta^{18}O$ values and the instrumental annual temperature records at nearby stations and the regional records (ITNTP).

3. P2706 line 12 "suggesting more influence of spring temperature on the ZK d18O values", can you explain why? Do not tell me because the correlation is high.

In the revised manuscript, the influence of spring temperature on ZK $\delta^{18}O$ values was explained in the following text:

"*The stronger spring temperature signal recorded in ZK $\delta^{18}O$ record may be attributed to the different seasonal moisture sources in this region. At Shiquanhe and Gêrzê, Yu et al. (2009) found that during the non-monsoon period (October–June) when local moisture recycling and the westerlies dominate the moisture sources, air temperature correlates more strongly with $\delta^{18}O$ in precipitation. On the other hand, precipitation $\delta^{18}O$ in monsoon season could be affected by a variety of factors other than temperature, including the convection intensity, distance from moisture sources and amount effect (Y. He et al., 2015; Tang et al., 2015). This could obscure the relationship between $\delta^{18}O$ and air temperatures (Joswiak et al., 2013). In addition, previous studies in the central Himalayas found that high elevation areas (> 3000ma.s.l.) can receive up to 40% of their annual precipitation during cold season because of terrain locked low pressure systems and orographically forced precipitation (Lang and Barros, 2004), a much higher percentage than that of surrounding low altitude areas of the same region (Pang et al., 2014). Therefore, the ZK ice core (located at 6226 m a.s.l.) could have had more cold-season (non-monsoonal) precipitation than that indicated by nearby meteorological stations, located at much lower elevations. Both factors could result in a stronger signal of spring temperature in the ZK ice core $\delta^{18}O$ record.*"

4. P2707 line 13 ": : : reflect its unique local climate conditions", what kind of unique climate conditions does Geladaindong have? If the climate condition of this site is so different from the other three, why do you include it to reconstruct the regional temperature? And eventually it seems the contribution from this site compensates the decreasing trend around 2000 and lead to the major conclusion, refer to my general comment 1.

The lack of correlation between Geladaindong and the other three ice cores could reflect its local climate conditions (Table 3), such as the influence of local convective vapor due to its more northern location (Kang et al., 2007). Despite this lack of correlation, Geladaindong ice core $\delta^{18}O$ series showed similar general climate patterns as other ice cores. For example, it captured the significant increasing trend from 1970 to 2004. In order to assess its impact on the regional composite, we calculated two regional average ice core $\delta^{18}O$ series, one with and one without Geladaindong (Fig. S2). The two series showed high degree of correlation ($r = 0.95$, 1951-2002, $p < 0.0001$), and there was little difference in trends and magnitude variations calculated from the two series (Fig. S2). Moreover, the correlation between Geladaindong ice core $\delta^{18}O$ series and the regional composite was also significant ($r = 0.38$, $p < 0.001$, Table 3). Therefore, we decided to include the Geladaindong ice core $\delta^{18}O$ so that the final regional reconstruction could have larger spatial coverage to better represent the regional climate of the northern TP.

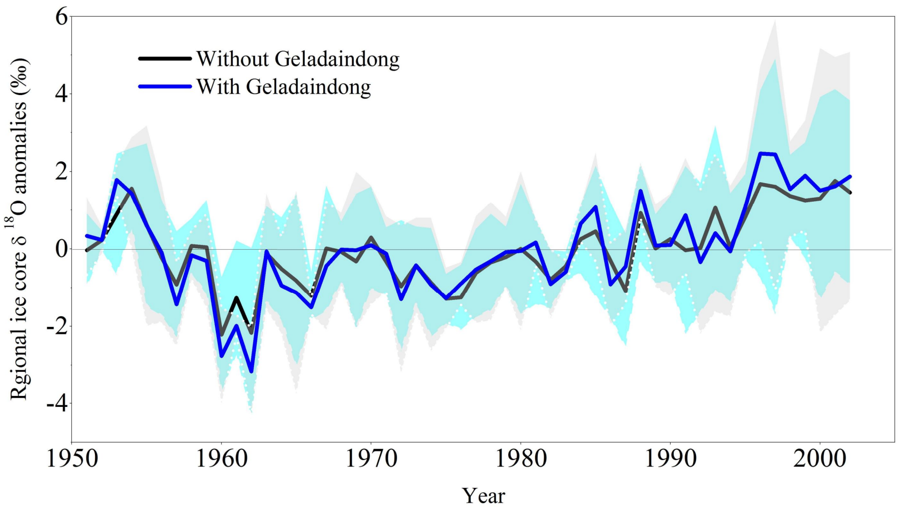


Figure S2. The regional ice core $\delta^{18}O$ time series (from 1951 to 2002) averaged from three ice cores (including ZK, Muztagata and Puruogangri, without Geladaindong), and from four ice cores (with Geladaidong). The shadowed area indicates the range of one standard deviation from the mean.

5. P2727, Fig6, 1) better to indicate the ITNTP as well in this figure; 2) colour scale should be

adjusted to show more positive correlation since there are no negative correlations and those blue scales are useless. 3) Fig6a and Fig6b are not comparable because they do not have the same sample size. Either use the same sample size or add another correlation map for regional reconstruction for the period 1961-2007.

As suggested, we added the blue rectangle to indicate the ITNTP in figure 6, and changed the color scale to show more positive correlations. In the revised manuscript, the regional temperature reconstruction was from 1951 to 2002, the correlation maps are redraw for the period 1961-2002.

Technical corrections

1. P2704 line 5, "(2005 data)", please provide a reference.

The reference is added to the text:

Shi, Y. F.: Concise Glacier Inventory of China, Shanghai Science Press, 2008.

2. P2722, Fig1, "Geladaigong" in figure caption and "Geladaindong" marked in the figure, which one is the right spelling? It would be good to have another rectangle to indicate the ITNTP region.

The correct spelling is 'Geladaindong', and we have corrected the spelling in the figure caption.

3. P2723, in all the other time evolution figures, year number increases from left to right, but in Fig2 time axis is opposite to the others, better to be consistent.

Changed as suggested.

4. P2724, in Fig 3d, should be "Spring minimum temperature".

Changed as suggested.

5. P2725, Fig4, would be better if indicate " standard values of d18O".

In the revised manuscript, we used '$\delta^{18}O$ anomalies values'.

6. P2726, Fig5, did not explain what do those dots mean.

In the revised manuscript, we added the following in the figure caption: 'the dots indicate the raw values of corresponding temperature series'.

7. P2728, Y-axis scale should fit for the data range, otherwise one has to guess the value for 1951-1960 in Fig7a. In Fig7a, all the decades show two values for 0.6 and 0.7 but not for the decade 1951-1960, why?

In the revised manuscript, we changed the Y-axis scale as suggested. In the previous version, we missed two values for the decade 1951-1960. In the revised manuscript, this became irrelevant, since we used 1.46‰ $°C^{-1}$ $\delta^{18}O$-temperature relationship (please see answer to the General comments 3). Please see the revised figure 7.

Reference:

Duan, A., and Z. Xiao, 2015: Does the climate warming hiatus exist over the Tibetan lateau? Scientific Reports, 5, 13711.

Many thanks for providing this information. This paper was added to the references.

Response to reviewer #3

Interactive comment on "Significant recent warming over the northern Tibetan Plateau from ice core $\delta^{18}O$ records" by W. An et al.

Anonymous Referee #3

Received and published: 29 September 2015

GENERAL COMMENTS In 'Significant recent warming over the northern Tibetan Plateau from ice core d18O records', An et al. introduce a new delta-18-oxygen isotope record from the northern Tibetan Plateau glacier, the Mt Zangser Kangri. They correlate their isotope record with nearby ice core records of the northern Tibetan Plateau, and then use the delta-18-oxygen records of the northern Tibetan Plateau to reconstruction regional temperature history for 1951-2008. In doing so, they find pronounced decadal regional warming trends over the northern Tibetan Plateau, rates of 1.12-1.31 degrees per decade since 1970. These decadal warming rates are compared with the much lower values for both the instrumental record from the northern Tibetan Plateau and the global mean (0.45 and 0.28 degrees per decade). This is an outstanding contribution of a new proxy record from a remote Tibetan Plateau location. The authors rightly attempt to reconcile the new isotope records with others from the region and to place the record in a global and warming context which is appropriate. The temperature reconstructions from the delta-18-oxygen isotope record would benefit from a more quantitative selection of the isotope sensitivity and assessment of results to choice of this isotope sensitivity. I would recommend publication of the manuscript following revision based on the provided comments.

SPECIFIC COMMENTS It would be great to see a figure that presents the sensitivity of their results for decadal rates of warming to choice of isotope sensitivity (delta value per mil per degrees Celsius). The first paragraph of page 2708 outlines some bases for their choice of isotope sensitivity but it would be great to see a more quantitive reason for the selection of 0.6-0.7 per mil per degrees Celsius. The outcome of this paper as it is presented depends largely on this selection and so this is a critical part of the paper and I would like to see more about it. Since the use of

0.6-0.7 represents a ’low end of the range’ of estimate (p. 2708, line 18), what would use of lower and higher values of isotope sensitivity indicate about decadal warming rates for the northern Tibetan Plateau? What does a figure of warming rate (degrees per decade for 1970s-2008) versus isotope sensitivity (delta-per mil per degrees Celsius) look like? Then, how does the uncertainty associated with the delta-18-oxygen values influence that figure? Finally, what if isotope sensitivity is time-variable?

Thank you for the helpful suggestion. We have made several changes accordingly. First, in the revised manuscript, we no longer used the range of 0.6 to 0.7‰ $°C^{-1}$ $\delta^{18}O$-temperature relationship, which was used to convert the $\delta^{18}O$ of the Muztagata ice core to temperature (Tian et al, 2006). Instead, the isotopic sensitivity was established for the regional temperature reconstruction based on the linear regression of 5-year running average between the regional $\delta^{18}O$ records and ITNTP temperature records, and it was derived for the ZK temperature reconstruction based on the linear regression of 5-year running average between the ZK $\delta^{18}O$ records and the average temperature records of the two nearby stations (Figure S3).

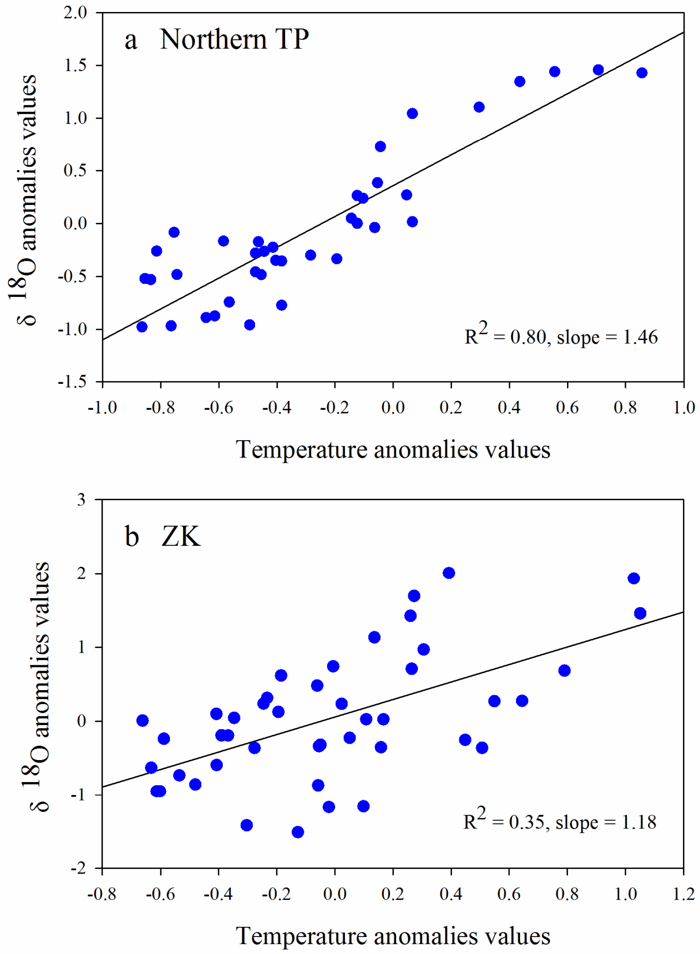


Figure S3. Scatter plots between regional $\delta^{18}O$ and regional instrumental temperature of the northern TP (RTNTP) (5 year running averages) (a), and scatter plots between ZK $\delta^{18}O$ and regional instrumental temperature (averaged from Gêrzê and Xainza) (5 year running averages) (b).

In addition, we examined the sensitivity of decadal warming rates to different values of isotope sensitivity. We calculated the decadal warming rates based on a range of isotope sensitivity commonly used to convert $\delta^{18}O$ to temperature for ice cores on the TP (0.3 to 1.5) for two time periods: 1970-2002 and 1990-2002. The results indicate that as the value of isotope sensitivity increases, the response of decadal warming rate to the isotope sensitivity decreases, especially when the value of isotope sensitivity gets higher than 1.0 (Fig. S4). This pattern is relatively consistent temporally, as indicated by the similar response for the two different time periods.

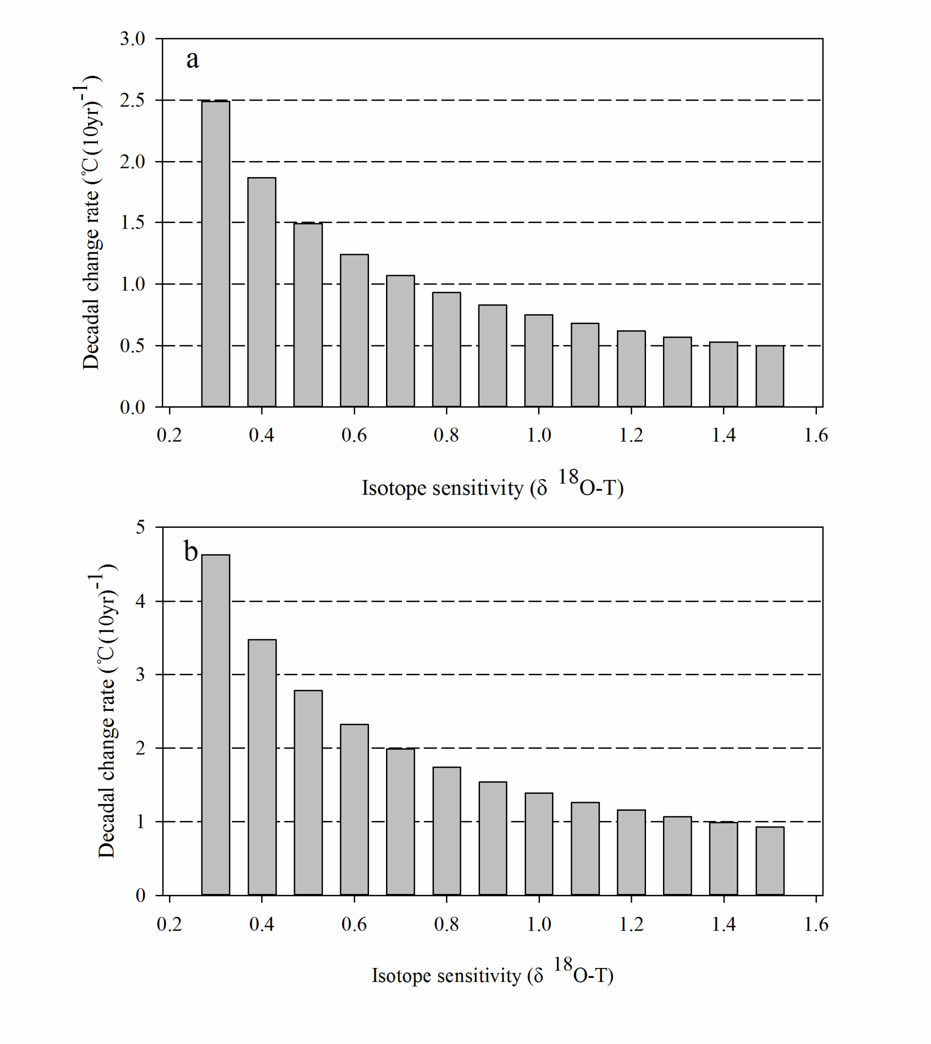


Figure S4. The variations of decadal warming rate with isotope sensitivity values range from 0.3 to 1.5 during 1970-2002 (a) and 1990-2002 (b), respectively. The decadal warming rates were calculated from the regional temperature reconstruction for the northern TP (RTNTP).

TECHNICAL COMMENTS p. 2703, line 16: ice core d18O is not ’unique’ to the TP, nor is ice core d18O the only paleoclimate proxy of the TP, remove ’unique’

Changed as suggested. We deleted this word and rephrased this sentence to be "*The ice core $\delta^{18}O$ is one of the most important paleoclimate proxies on the TP*"

p. 2704, line 12: Indicate the organization affiliated with the State Key Laboratory of Cryospheric Science?

As suggested, we indicated the organization in the revised text: "*State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science*"

p. 2705, first paragraph: It seems hasty to dismiss the precipitation signal from the delta-18-oxygen isotope ratio simply because there are not statistically signfiicant long term trends in the seasonal precipitation time-series. The words in lines 4-6 to describe this analysis 'time series for the proportions of both summer and winter precip' do not clearly describe what is shown in Fig. S1. Be more clear both in the text and the caption of Fig. S1 what is shown in this figure. What are the percentages on the y-axes? Is it the percent of the annual total precipitation? It would be nice to see the climatological precipitation cycle, or at least describe the regional seasonal cycle. Given the emphasis on Spring temperatures elsewhere in the paper, what might be the influence from non-solstice season precipitation?

In the revised manuscript, we examined the possible precipitation signal in $\delta^{18}O$ as follows:

"Stable oxygen isotope in precipitation could be affected by a variety of environmental factors. In addition to temperature, the $\delta^{18}O$ values in ice cores could also be affected by precipitation seasonality and amount (Dansgaard, 1964). To exclude possible influence of precipitation, we first examined whether the seasonal distribution of precipitation experienced any significant changes during the study period by using the precipitation records from the two nearby stations. Results showed weak positive trends for the proportion of precipitation in winter and spring, and no statistically significant trends for the proportions of precipitation in summer and fall (Fig. S1b and c). This suggests that changes in seasonal distribution of precipitation did not exert a major influence on the $\delta^{18}O$ values in ZK ice cores during the period 1961-2008. Besides, we found no significant correlation between the ZK $\delta^{18}O$ record and precipitation amount recorded at the stations (Table S1). Partial correlation analysis showed this to be true even when annual temperature was controlled ($r_{partial}$ = 0.01, p > 0.1). This suggests that precipitation amount had little influence on the ZK $\delta^{18}O$ values."

		Spring	Summer	Autumn	Winter	Annual
Correlation coefficients	Annual	0.14	0.07	-0.07	0.15	0.02
	5 year running average	0.33[a]	0.27	-0.20	0.22	-0.07

[a] $p < 0.05$

Table S1. Correlation coefficients and linear slopes between $\delta^{18}O$ values in the ZK ice core and instrumental precipitation (1961-2002) from the averaging records of the Gêrzê and Xainza stations.

The percentage on the y-axes means the proportions of the seasonal precipitation in the annual total mean precipitation, we added this in the revised caption of Fig. S1. We also added the regional climatic precipitation cycle in Fig. S1a.

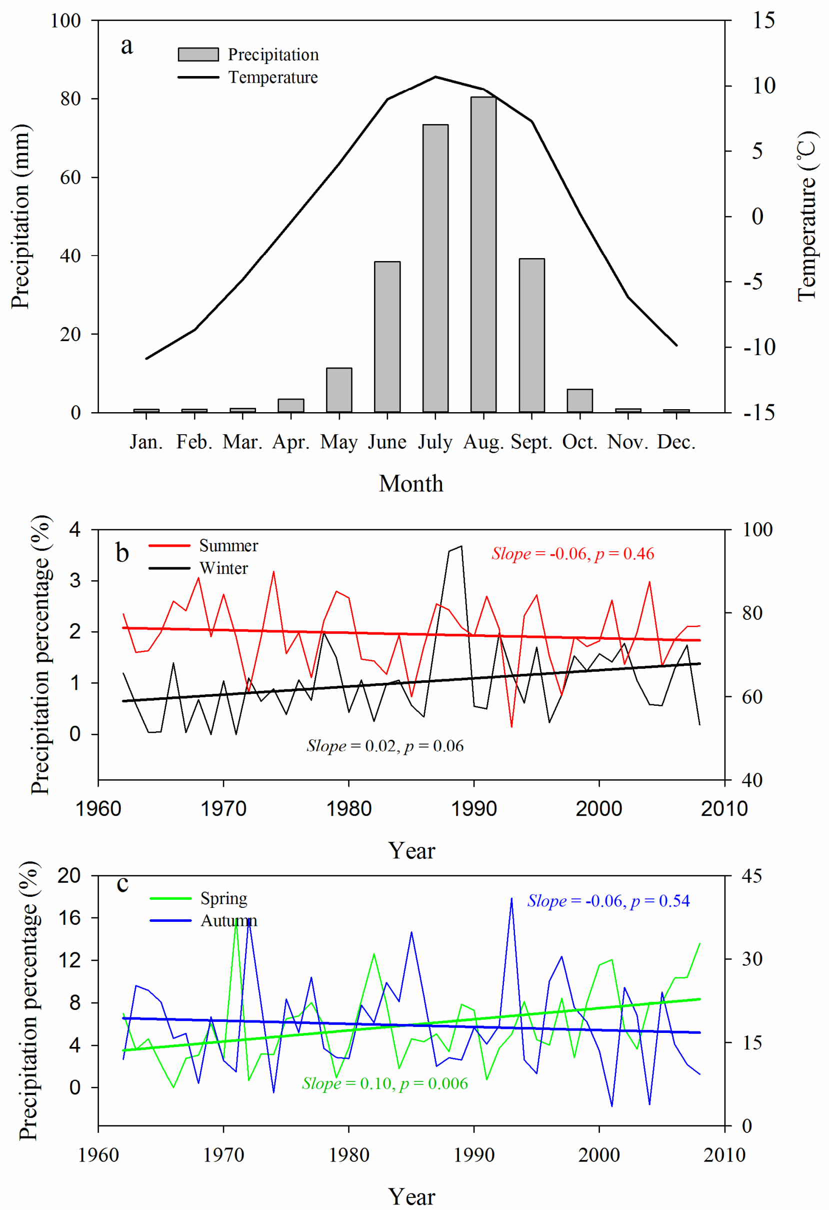


Figure S1. (a) Regional monthly mean temperature and precipitation values from 1961 to 2008 calculated from the average of precipitation data from closest Gêrzê and Xainza stations. (b, c) Variations in the percentage of annual total precipitation of regional precipitation during different seasons from 1961 to 2008. The thin and the thick lines in b and c indicate the raw values and the linear regression result, respectively.

Rather than, or in conjunction with, temperature, how may the northern TP d18O record relate to upstream convection (see He et al 2015, JGR-Atmospheres doi:10.1002/2014JD022180) either over India or to westerly synoptic systems over the mid-latitudes? Basically, where does the vapor come from and what is its history?

Likewise, in addition to temperature, how may the northern TP d18O records relate to changes in the large-scale circulation and the transport or mixing of water vapor by those circulations?

The Tibetan Plateau (TP) climate is influenced by Asian monsoon (i.e. Indian summer monsoon and East Asian summer monsoon) and convective precipitation (westerly circulation), as well as local evaporation (Yao et al., 2013). Recent studies indicated that $\delta^{18}O$ in the precipitation at the southern TP is strongly controlled by integrated upstream convection processes, rather than temperature variations (Gao et al., 2013; He et al., 2015). Gao et al. (2015) found that large-scale atmospheric circulation variabilities have played important roles in modulating ice core $\delta^{18}O$ from the Noijinkansang glacier on the southern TP. In contrast to the southern TP, in the central TP, Li et al. (2015) confirmed the contribution of westerlies and monsoon moisture to the ice core accumulation on the Xiao Dongkemadi glacier, but the XD ice core $\delta^{18}O$ record is still mainly a proxy of regional temperature changes. Based on observations from the TP, Yao et al. (2013) found that the influence of large-scale atmospheric circulation on $\delta^{18}O$ in the precipitation is weaker in the northern TP than that in the southern TP, where the influence of monsoon activities are more stronger. These results suggest the influence of atmospheric circulation on regional $\delta^{18}O$ values over the northern TP, and this influence may partly responsible for the relatively low correlations between $\delta^{18}O$ in the precipitation and temperature. However, due to the long distance from moisture sources, such influence on the northern TP is not evident and unstable, and the regional $\delta^{18}O$ values mainly reflect regional temperature signal.

Related references:

Gao, J., Masson-Delmotte, V., Risi, C., He, Y., Yao, T. D.: What controls precipitation $\delta^{18}O$ in the southern Tibetan Plateau at seasonal and intra-seasonal scales? A case study at Lhasa and Nyalam, Tellus B, 65, 21043, doi: 10.3402/tellusb.v65i0.2104, 2013.

Gao, J., Risi, C., Masson-Delmotte, V., He, Y., Xu, B. Q.: Southern Tibetan Plateau ice core $\delta^{18}O$ reflects abrupt shifts in atmospheric circulation in the late 1970s, Clim. Dyn., doi:10.1007/s00382-015-2584-3, 2015.

Li, X. Y., Ding, Y. J., Yu, Z. B., Mika, S., Liu, S. Y., Shangguan, D. H., and Lu, C. Y.: An 80-year summer temperature history from the Xiao Dongkemadi ice core in the central Tibetan Plateau and its association with atmospheric circulation, J. Asian Earth Sci., 98, 285–295, doi: 10.1016/j.jseaes.2014.09.025, 2015.

Yao, T. D., Masson-Delmotte, V., Gao, J., Yu, W. S., Yang, X. X., Risi, C., Sturm, C., Werner, M., Zhao, H. B., He, Y., Ren, W., Tian, L. D., Shi, C. M., and Hou, S. G.: A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations, Rev. Geophys., 51(4), 525-548, doi:10.1002/rog.20023, 2013.

In the revised manuscript, we discussed the possible influence of atmospheric circulation activities on Zangser Kangri $\delta^{18}O$. In consideration of the focus of the manuscript, we did not discuss it thoroughly. The related contents are discussed in the text:

"On the other hand, precipitation $\delta^{18}O$ in monsoon season could be affected by a variety of factors other than temperature, including the convection intensity, distance from moisture sources and amount effect (He et al., 2015; Tang et al., 2015). This could obscure the relationship between $\delta^{18}O$ and air temperatures (Joswiak et al., 2013)."

p. 2706, line 8-10: The low correlation coefficients between d18O and instrumental temperature suggest that d18O variability is not wholly temperature dependent.

Relative weak correlations between ice core $\delta^{18}O$ and instrumental temperature records are quite common for the Tibetan ice cores, such as in cases of Puruogangri and Geladaindong ice cores. This could be partly caused by the relatively large distance and elevation difference between meteorological stations and ice core drilling site. Weak correlations could also be a result of uncertainties in ice core dating. In order to reduce the impact of such dating uncertainties, we used 5 year running average instead of annual series to examine the relationships between ice core $\delta^{18}O$ and temperature. This significantly increased the correlation between the two time series (Table 1).

		Gêrzê		Xainza		Stations averaging		ITNTP
		March-May	Annual	March-May	Annual	March-May	Annual	Annual
Correlation coefficients	Annual	0.52[c]	0.34[a]	0.45[c]	0.34[a]	0.48[c]	0.34[a]	0.35[a]
	5 year running average	0.63 [c]	0.53 [c]	0.73 [c]	0.60 [c]	0.73 [c]	0.60 [c]	0.61 [c]
Slope	Annual	0.93[b]	0.67[a]	0.93[b]	0.98[a]	1.00[c]	0.88[a]	0.87[a]
	5 year running average	0.87 [c]	0.76 [c]	1.54 [c]	1.32 [c]	1.37 [c]	1.18 [c]	0.40 [c]

Table 1. Correlation coefficients and linear slopes between the $\delta^{18}O$ values in the ZK ice core and instrumental spring (March–May) and annual temperature from closest Gêrzê (1973–2008) and Xainza stations (1961–2008), the averaged records of the two stations (1961–2008), and the ITNTP series (1961–2008).

Do the high rates of reconstructed decadal warming correspond with observed changes in mass balance for northern TP glaciers? or, do mass balance changes in the glaciers more closely agree with TP instrumental temperature observations?

Yes, the mass balance changes agree with the significant warming over the northern Tibetan Plateau (TP). Most glaciers on the northern TP have experienced significant reduction in area, length and volume with rapidly increasing temperatures (Yao et al., 2012). The ZK glacier has decreased by 2.26% during 1971-2005, which agrees with temperature increase recorded in the ice core. Pu et al. (2008) found that the mass balance of the Dongkemadi Glacier, in the central TP, changed from a significantly positive mass balance to a strongly negative mass balance since 1994. Neckel et al. (2013) found a slightly negative mass budget of −44±15 and −38±23 mmw. eq. yr^{-1} for the Purogangri Ice Cap during 2000-2012. Moreover, during the period of 2003-2009, most negative mass budgets of -0.77±0:35m w.e.yr^{-1} were found for the Qilian Mountains and eastern Kunlun Mountains in the north-eastern part of the TP (Neckel et al., 2014).

Related references:

Neckel, N., Braun, A., Kropáček, J., and Hochschild, V.: Recent mass balance of the Purogangri ice cap, central Tibetan Plateau, by means of differential X-band SAR interferometry, The Cryosphere, 7, 1623–1633, doi:10.5194/tc-7-1623-2013, 2013.

Neckel, N., Kropáček, J., Bolch, T., and Hochschild, V.: Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements, Environ. Res. Lett., 9, 014009, doi:10.1088/1748-9326/9/1/014009, 2014.

Pu, J. C., Yao, T. D., Yang, M. X., Tian, L. D., Wang, N. L., Ageta, Y., and Fujita, K.: Rapid decrease of mass balance observed in the Xiao (Lesser) Dongkemadi Glacier, in the central Tibetan Plateau, Hydrol. Process., 22, 2953–2958, 2008.

Yao, T. D., Thompson, L., Yang, W., Yu, W. S., Gao, Y., Guo, X. J., Yang, X. X., Duan, K. Q., Zhao, H. B., Baiqing Xu, B. Q., Pu, J. C., Anxin Lu, A. X., Xiang, Y., Kattel D. B., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nature Clim. Change, 2, 663-667, doi:10.1038/nclimate1580, 2012.

Further discuss the snow-albedo feedback and how it may influence warming rates. Can we quantify or estimate (back-of-the-envelope) how much of the 1.12-1.31 degrees per decade may be attributed to the snow-albedo feedback?

In the revised manuscript, we discussed the influence of snow/ice albedo feedback on the warming trend in more details, as follows:

"*The persistent rapid warming in the northern TP could have been caused by the regional radiative and energy budget changes (Yan and Liu, 2014; Duan and Xiao, 2015). Many studies show that the snow/ice-albedo feedback is an important mechanism for enhanced warming at high elevation regions (Liu and Chen, 2000; Pepin and Lundquist, 2008; Rangwala and Miller, 2012). Ghatak et al. (2014) found that the surface albedo decreases more at higher elevations than lower elevations over the TP in recent years. Qu et al. (2013) observed a decreasing trend for the snow/ice albedo at the Nyainquentanglha glacier region, central TP, for the period 2000 to 2010. Wang et al. (2014) found that the glacier albedo for the nine glaciers in western China has decreased during the period 2000-2011, especially for the central TP. For example, the glacial albedo of Dongkemadi and Puruogangri glaciers decreased at a rate of 0.0043-0.0059 yr^{-1} and 0.001-0.004 yr^{-1} respectively. Reduced surface albedo increases the surface absorption of solar radiation, and may have contributed to the continued warming over the high elevation regions of the northern TP. Further research is needed to identify and quantify the exact mechanisms* *accounting for the temperature variations over the Plateau.*"

p. 2711, line 11-14: Rewrite this sentence, it is a bit unclear.

This sentence was deleted in the revised manuscript.

Section 3.2: What is the basis of the per mil per degrees relationship used to calculate the degrees per decade values? Can the authors somehow constrain an estimate of the isotope sensitivity on the time-scale of decades? What is the change in isotope ratio per degrees Celsius per decade?

Yes, we revised the manuscript as suggested. The details are provided in our response to your first comment on page 2.

p. 2711, line 18: Be clear on what is meant by southwest monsoon, particularly in the context of the Asian monsoon system that is referenced in the previous sentence.

The southwest monsoon means the Indian summer monsoon. In the revised manuscript, we focused on the influence of regional radiative and energy changes on local temperature changes. Therefore, this sentence was deleted.

Discussion: Reduce the speculative discussion of how the distance between the TP and equatorial ocean circulations dilute the warming hiatus signal.

This discussion was deleted, as suggested. The discussion section was completely revised to incorporate reviewers' suggestions.

Further discuss the significance of the stronger relationship between the isotope records and spring temperatures? What would be a physical explanation for this relationship?

The better relationship between spring temperature and ZK $\delta^{18}O$ record as explained in the revised text:

"*The stronger spring temperature signal recorded in ZK $\delta^{18}O$ record may be attributed to the different seasonal moisture sources in this region. At Shiquanhe and Gêrzê, Yu et al. (2009) found that during the non-monsoon period (October–June) when local moisture recycling and the westerlies dominate the moisture sources, air temperature correlates more strongly with $\delta^{18}O$ in precipitation. On the other hand, precipitation $\delta^{18}O$ in monsoon season could be affected by a variety of factors other than temperature, including the convection intensity, distance from moisture sources and amount effect (Y. He et al., 2015; Tang et al., 2015). This could obscure the relationship between $\delta^{18}O$ and air temperatures (Joswiak et al., 2013). In addition, previous studies in the central Himalayas found that high elevation areas (> 3000ma.s.l.) can receive up to 40% of their annual precipitation during cold season because of terrain locked low pressure systems and orographically forced precipitation (Lang and Barros, 2004), a much higher percentage than that of surrounding low altitude areas of the same region (Pang et al., 2014). Therefore, the ZK ice core (located at 6226 m a.s.l.) could have had more cold-season (non-monsoonal) precipitation than that indicated by nearby meteorological stations, located at much lower elevations. Both factors could result in a stronger signal of spring temperature in the ZK ice core $\delta^{18}O$ record.*"

TABLES AND FIGURES Table 3. There are no 'a' notes ($p<0.05$) is this right? Its listed below the table but I see no instances of its use?

This was corrected in the revised text.

Fig. 1. The black rectangle (study region) boundary shown in the inset does not correspond to the area shown in the larger map, make the inset black rectangle match the area shown in the larger map.

Changed as suggested.

Fig. 1. The red arrows seem to be for near surface and lower troposphere boreal summer winds, whereas the blue arrows appear to be for mid to upper troposphere boreal winter winds and this

needs to be clear in the caption that you are showing horizontal winds for different pressure levels in the atmosphere. Also, the different lengths of the red and blue arrows may erroneously suggest relative wind speeds that are more nearly opposite to what is shown, so I would suggest common arrow lengths to avoid confusion. Mid to upper troposphere winds (those above the plateau, assuming that is what you are showing) are not so dramatically wrapped around the plateau.

We revised figure 1. In the caption, we indicated the corresponding pressure levels for the atmospheric circulation patterns in summer and in winter. However, in consideration of the trajectory and the different influence area of circulation pattern in summer and winter, it was not appropriate to adopt common lengths for red and blue arrows. To avoid the confusion, we gave a clear indication that the red and blue arrows only represent the direction of the relative circulation in the caption. The westerlies circulation pattern for mid to upper troposphere boreal winter winds was redrawn according to previous studies. Lines: 645-648.

Fig. 2. Ca2+ (and Mg2+) concentrations appear to decrease while d18O increases over the past few decades? Could these reflect changes in circulation from a dustier/colder source to a less dusty/warmer source, or from a dustier extratropical source to a less dusty tropical source?

The dust concentrations in Zangser Kangri (ZK) did show a decreasing trend from 1951 to 2008, and we investigated the variation of atmospheric dust in another paper (Zhang, W. B., Hou, S. G., An, W. L., Zhou, L. Y., and Pang, H. X.: Variations of atmospheric dust loading since 1951 AD recorded in an ice core from the North Tibet Plateau, Annals of Glaciology, 57(71), doi: 10.3189/2016AoG71A559, 2016). The analysis found that the Taklimakan Desert is the dominant source of dust deposited at the ZK glacier. The results indicate that the westerlies over the Northwestern China and the NTP were stronger during the years of high dust concentration in the ZK core, and the dust records in the ZK region may be strongly influenced by the westerlies in spring over this region.

Figs. 2 and 4. Not a major problem but you flipped the direction of the time/x axes between figs. 2 and 4. Make consistent.

Changed as suggested.

Fig. 4. Supplemental Figure indicates slopes and p-values for those slopes. The poor p-values of the seasonal precipitation trends are used to dismiss precipitation as important. Please also provide slopes and p-values to the trend lines shown in Fig.4. The slopes of these lines determine (along with the isotope sensitivity) the decadal warming rates that are so central to this manuscript. It would be important to see the significance of the trend lines for the ice core isotope records.

We added the relative slopes and p values in the revised figure 4.

Significant recent warming over the northern Tibetan Plateau from ice core $\delta^{18}O$ records

Wenling An[1], Shugui Hou[1,5*], Wangbin Zhang[1], Yetang Wang[2], Yaping Liu[3], Shuangye Wu[1,4], Hongxi Pang[1]

1 Key Laboratory of Coast and Island development of Ministry of Education, School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China

2 College of Population, Resources and Environment, Shandong Normal University, Jinan 250014, China

3 State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

4 Geology Department, University of Dayton, Ohio 45469-2364, USA

5 CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China

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

Abstract: Stable oxygen isotopic records in ice cores provide valuable information about past temperature, especially for regions with scarce instrumental measurements. This paper presents the $\delta^{18}O$ result of an ice core drilled to bedrock from Mt. Zangser Kangri (ZK), a remote area on the northern Tibetan Plateau (TP). We reconstructed the temperature series for 1951-2008 from the $\delta^{18}O$ records. In addition, we combined the ZK $\delta^{18}O$ records with those from three other ice cores in the northern TP (Muztagata, Puruogangri and Geladaindong) to reconstruct a regional temperature history for the period 1951-2002 (RTNTP). The RTNTP showed significant warming at 0.51±0.07°C$(10yr)^{-1}$ since 1970, a higher rate than the trend of instrumental records of the northern TP (0.43±0.08°C$(10yr)^{-1}$) and the global temperature trend (0.27±0.03°C$(10yr)^{-1}$) at the same time. In addition, the ZK temperature record, with extra length until 2008, seems to suggest that the rapid elevation-dependent warming continued for this region during the last decade, when the mean global temperature showed very little change. This could provide insights into the behavior of the recent warming hiatus at higher elevations, where instrumental climate records are lacking.

1. Introduction

With an average elevation over 4000 m a.s.l., the Tibetan Plateau (TP) is the highest and most extensive highland in the world. In recent decades, it has experienced rapid warming and drastic environmental changes such as fast glacier retreat and land deterioration (Yao et al., 2012). In recent years, the global average surface temperature has experienced relatively little change in recent years (Easterlin and Wehner, 2009), whereas accelerated warming continued on the TP for the same period of time (Yan and Liu, 2014; Duan and Wu, 2015). However, the rapid warming trend over the Plateau was established with data from meteorological stations located at relatively low elevations, and warming trend for higher elevation regions remains uncertain.

In addition, spatial biases also exist in the TP temperature records. Most instrumental records as well as various paleoclimate proxies are located in the eastern and southern Plateau (Thompson et al., 2000; B. Yang et al., 2014; Herzschuh et al., 2010; Pu et al., 2011). There is generally a lack of climate data in the northern, and particularly in the northwest TP, where meteorological stations were sparse, and long-term high-resolution climate records were difficult to obtain because of the formidable terrain and harsh environment. However, the northern TP (Fig. 1) is a climatologically important region involving complicated interactions between the mid-latitude westerlies and the subtropical Asia monsoon circulation. It may serve as a bridge linking the high and low latitude climatic processes (Y. X. He et al., 2013). It is therefore essential to evaluate the extent and magnitude of regional climate changes over this region without coverage bias.

The ice core $\delta^{18}O$ is an important paleoclimate proxy on the TP (Thompson et al., 2000; Qin et al., 2002), and has been generally considered to be a reliable indicator for past temperatures (Yao et al., 2006; Joswiak et al., 2010). However, great discrepancies still exist among different temperature reconstructions and instrumental records owing to the distinct geographic locations and atmospheric circulation conditions (Liu and Chen, 2000; N. Wang et al., 2003; Y. Q. Wang et al., 2003; Yao et al., 2006). Therefore, it is important to establish more high resolution temperature records on the TP, particularly over such extensive high elevation regions as the northern TP, in order to evaluate the warming trends at high elevations in light of the recent warming hiatus. In this study, we measured the $\delta^{18}O$ values in an ice core drilled from the Zangser Kangri (ZK) glacier on the northern TP, from which temperature changes in the past decades could be established. The ZK ice core $\delta^{18}O$ records made it possible to study the past climate variations over a relatively inaccessible part of the TP, where instrumental records are very limited. In addition, we also established the regional climate change history by combining ZK with the $\delta^{18}O$ records from other ice cores in the northern TP.

2 Methodology and Data

2.1 Research area and ice core dating

The ZK glacier is located in the northwest part of the TP, covering an area of 337.98 km^2 with a volume of 41.70 km^3 (2005 data, Shi, 2008). The snowline is about 5700～5940 m a.s.l.. In the April of 2009, two ice cores to bedrock (127.7m and 126.7m in length for Core 1 and Core 2 respectively) were recovered from the glacier (34°18′05.8″N, 85°51′14.2″E, 6226 m a.s.l., Fig.1). The glacier temperature ranged from -15.2°C to -9.2°C, with a mean temperature of -11.7°C, -12.4°C at 10 m depth and a basal temperature of -9.2°C.

These two ice cores were kept frozen and transported to the State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences for processing. This study was based upon the analysis of Core 1. A total of 2884 samples were taken from Core 1 at a resolution of 4~6 cm. The outer ~2 cm of each sample was removed for stable oxygen isotope analysis. The inner portion of the ice core was collected in pre-cleaned polyethylene sample containers for chemical and dust particle analyses. Stable oxygen isotope ratio ($\delta^{18}O$) was determined using a Picarro Wavelength Scanned Cavity Ring-Down Spectrometer (WS-CRDS, model L2120i). Major cations and anions were analyzed using a Dionex-600 and ICS-2500 ion chromatograph respectively.

In the northern TP, the annual cycle of $\delta^{18}O$ along the ice core profile is primarily related to temperature variations (Araguás-Araguás et al., 1998; Yao et al., 2013). The $\delta^{18}O$ compositions in modern precipitation samples collected at northern TP show marked seasonal patterns with the high values in summer and low values in winter (Yu et al., 2009). In addition, the major ions (e.g., Mg^{2+} and $SO4^{2-}$) also show clear seasonal cycles with high concentrations in winter/spring and low concentrations in summer (Zheng et al., 2010). They have been used in past studies as complementary tools in ice core dating in the northern TP (Kang et al., 2007). Therefore, the ZK ice core was dated by using the seasonality of $\delta^{18}O$ in conjunction with the seasonal variations of major ions, including Mg^{2+}, Ca^{2+} and $SO4^{2-}$, with a reference layer of β activity peak in 1963 (Fig. 2). The core 1 was dated back to 1951 at 16.38 m depth with uncertainty estimated within 1 year (Fig. 2, Zhang et al., 2016). Based on the dating result and density of the ice core profile, the mean annual net accumulation rate was estimated to be low for ZK glaciers (190 kg H_2O m^{-1} yr^{-1}). This study focused on the $\delta^{18}O$ records in the top 16.38 m of the ice core, corresponding to the time period 1951-2008.

2.2 Climate data

The ZK glacier is located at a transition zone with shifting influences between the westerlies and the Indian summer monsoon (Yao et al., 2013). Based on the climate records from the two nearby meteorological stations, at Gêrzê (32°09′, 84°25′, 4414.9m a.s.l., 1973-2008) and Xainza (30°57′, 88°38′, 4800m a.s.l., 1961-2008) (Fig. 1), the local mean monthly temperature ranges from -10.8°C in January to 10.7°C in July, with an annual average of 0°C. Precipitation averages 257 mm per year, of which 75% falls between June and September (Fig. S1a).

In order to establish the representativeness of the ZK ice core $\delta^{18}O$ for the regional climate, we performed correlation analysis, using Pearson's correlation coefficient (*r*), between the ice core $\delta^{18}O$ time series and temperature records from the nearby meteorological stations (Gêrzê and Xainza), and the instrumental temperature series from a network of meteorological stations in the northern TP (hereafter, ITNTP). The ITNTP time series was derived from 14 climate stations used in Guo and Wang (2011), and was extended to 2014 based on the data provided by the Data and Information Center, China Meteorological Administration. It should be noted that most of the stations used in ITNTP time series were located on the eastern part of the northern TP with altitudes ranging from 2767 to 3367 m (Guo and Wang, 2011), whereas this study focused on the higher (> 5700 m) and more extensive western part of the northern TP (Fig. 1). In addition, spatial correlations were carried out between ZK $\delta^{18}O$ and the CRU 4 gridded temperature reanalysis data (Mitchell and Jones, 2005) on the KNMI Climate Explorer (http://climexp.knmi.nl).

In this study, in addition to the ZK series, we also attempted to reconstruct a regional temperature series by combining ZK with other ice core $\delta^{18}O$ records in the northern TP, including Muztagata (Tian et al., 2006), Puruogangri (Yao et al., 2006), Geladaindong (Kang et al., 2007) and Malan (N. Wang et al., 2003) (Fig. 4 and Table 2). We first examined the consistency of these ice core records and excluded Malan from the reconstruction because of its drastically different temporal patterns from the rest of the records. To combine the remaining 4 ice core records, we derived the $\delta^{18}O$ anomalies for each ice core series to eliminate the difference in the absolute values, and calculated their average (Fig. S2), which was then used to reconstruct the regional temperature time series.

3 Results and Discussion

3.1 The ZK ice core $\delta^{18}O$ variation and its relationship with regional meteorological data

The raw $\delta^{18}O$ values throughout the ZK ice core profile from 1951 to 2008 were presented in Figure 2. For this section, the $\delta^{18}O$ values ranged from -17.65‰ at 13.8 m to -3.79‰ at 6.85 m, with an average value of -10.97‰ (Fig. 2). The $\delta^{18}O$ values were relatively low in the 1960s, followed by an increasing trend from 1970s to the end of the record.

Stable oxygen isotope in precipitation could be affected by a variety of environmental factors. In addition to temperature, the $\delta^{18}O$ values in ice cores could also be affected by precipitation seasonality and amount (Dansgaard, 1964). To exclude possible influence of precipitation, we first examined whether the seasonal distribution of precipitation experienced any significant changes during the study period by using the precipitation records from the two nearby stations. Results showed weak positive trends for the proportion of precipitation in winter and spring, and no statistically significant trends for the proportions of precipitation in summer and fall (Fig. S1b and c). This suggests that changes in seasonal distribution of precipitation did not exert a major influence on the $\delta^{18}O$ values in ZK ice cores during the period 1961-2008. Besides, we found no significant correlation between the ZK $\delta^{18}O$ record and precipitation amount recorded at the stations (Table S1). Partial correlation analysis showed this to be true even when annual temperature was controlled ($r_{partial}$ = 0.01, p > 0.1). This suggests that precipitation amount had little influence on the ZK $\delta^{18}O$ values.

On the other hand, the ZK $\delta^{18}O$ time series showed positive correlation with annual temperature measured at each of the nearby stations (r = 0.31, p = 0.07 for the Gêrzê station; r = 0.43, p = 0.002 for the Xainza station), the mean annual temperature of the two stations (r = 0.34, p = 0.01), and ITNTP (r = 0.35, p = 0.02) (Table 1). Stronger correlation existed between the ZK $\delta^{18}O$ and spring (March-May) temperature of the stations (Table 1). Linear regressions led to a mean $\delta^{18}O$-temperature slope of 0.85‰ $°C^{-1}$ with values ranging from 0.67 to 0.98‰ $°C^{-1}$ (Table 1). This is consistent with the published $\delta^{18}O$-temperature relationships derived from ice cores over the northern TP (X. X. Yang et al., 2014).

Significant spatial correlation existed between the ZK $\delta^{18}O$ series and the CRU gridded temperature data in the region surrounding the drilling site. The ZK $\delta^{18}O$ series showed positive correlations with annual mean and minimum temperatures for most part of the northern TP (Fig. 3). The most significant and spatially extensive correlations were found between the ZK $\delta^{18}O$ and spring temperatures (Fig. 3c and d), which were consistent with previous results between the ZK $\delta^{18}O$ series and station temperature records (Table 1). The stronger spring temperature signal recorded in ZK $\delta^{18}O$ record may be attributed to the different seasonal moisture sources in this region. At Shiquanhe and Gêrzê, Yu et al. (2009) found that during the non-monsoon period (October–June) when local moisture recycling and the westerlies dominate the moisture sources, air temperature correlates more strongly with $\delta^{18}O$ in precipitation. On the other hand, precipitation $\delta^{18}O$ in monsoon season could be affected by a variety of factors other than temperature, including the convection intensity, distance from moisture sources and amount effect (Y. He et al., 2015; Tang et al., 2015). This could obscure the relationship between $\delta^{18}O$ and air temperatures (Joswiak et al., 2013). In addition, previous studies in the central Himalayas found that high elevation areas (> 3000ma.s.l.) can receive up to 40% of their annual precipitation during cold season because of terrain locked low pressure systems and orographically forced precipitation (Lang and Barros, 2004), a much higher percentage than that of surrounding low altitude areas of the same region (Pang et al., 2014). Therefore, the ZK ice core (located at 6226 m a.s.l.) could have had more cold-season (non-monsoonal) precipitation than that indicated by nearby meteorological stations, located at much lower elevations. Both factors could result in a stronger signal of spring temperature in the ZK ice core $\delta^{18}O$ record.

3.2 Regional temperature reconstruction

Detailed comparisons were made between the ZK $\delta^{18}O$ and the $\delta^{18}O$ time series of four nearby ice cores, including Muztagata, Puruogangri, Geladaindong and Malan (Fig. 4 and Table 2). The cooling around 1960s was present in all ice cores, and this was consistent with the observed cold period during this time over the entire TP (Liu and Chen, 2000). Moreover, the significant increasing trend from 1970s to present was observed in all except Malan ice core $\delta^{18}O$ series. We calculated the Pearson correlation coefficients among these ice core $\delta^{18}O$ series (Table 3). The results showed weak correlations between the annual values of these series. This lack of correlation could result from the differences in location, elevation and hence local climates. It could also arise from uncertainties in ice core dating. In order to reduce the impact of dating uncertainties, we used the 5 year running averages instead of annual values, and these series showed much stronger correlations, suggesting possible common regional climate patterns preserved in these ice core series. This coherence is important when we use the average of multiple sites to develop a regional composite.

In contrast to the rest of the ice cores, the Malan $\delta^{18}O$ record showed a cooling trend since 1970s (Fig. 4e). Such continuous low level of $\delta^{18}O$ could be caused by the change of local climate conditions (Y. Q. Wang et al., 2003), but could also result from post-depositional processes on the chemical profiles, such as summer melting, evaporation and condensation, all of which could modify the relationship between ice core $\delta^{18}O$ and temperature (Hou et al., 2006). Furthermore, the correlation analysis showed that the Malan time series was negatively correlated with other four time series, and the negative relationships were more significant after 5 year running averaging (Table 3). Therefore, we excluded the Malan record from further analysis.

Moreover, the correlations between Geladaindong and three other ice cores, i.e. ZK, Muztagata, Puruogangri were relatively low even after 5 year running averages (Table 3). The lack of correlation could be attributed to its local climate conditions (Table 3), such as the influence of local convective vapor due to its more northern location (Kang et al., 2007). However, the ice cores of ZK, Muztagata, Puruogangri and Geladaindong shared similar patterns of $\delta^{18}O$ variations, especially their increasing trends since 1970s (Fig. 4). Moreover, regional composite with Geladaindong records correlates very strongly with that without Geladaindong (r = 0.95, 1951-2002, $p < 0.0001$), and two series showed very similar temporal patterns (Fig. S2). Therefore, we decided to include the Geladaindong ice core $\delta^{18}O$, so that the final regional reconstruction could have larger spatial coverage to better represent the regional climate of the northern TP. The regional temperature series was reconstructed for 1951-2002, the common period covered by the four ice core $\delta^{18}O$ records. Meanwhile, a temperature reconstruction based solely on ZK ice core $\delta^{18}O$ record was constructed for 1951-2008 to investigate the temperature variations since the late 1990s.

Before establishing the temperature reconstructions, it was necessary to derive the $\delta^{18}O$-temperature relationship to understand the magnitude of the temperature variation over the northern TP. Yu et al. (2009) calculated the isotope sensitivity between monthly mean $\delta^{18}O$ values in precipitation and the monthly mean temperatures at Gêrzê and Shiquanhe (Fig. 1) as 0.33 and 0.37‰ °C^{-1} respectively. State of the art atmospheric models with integrated water isotopes modeling suggested an average isotope sensitivity of 0.53‰ °C^{-1} for the present-day precipitation falling at the grid where the ZK core was recovered (Risi et al., 2010). Tian et al. (2006) used the range of 0.6 to 0.7‰ °C^{-1} to convert the $\delta^{18}O$ values to temperature for the Muztagata ice core. The isotope sensitivity usually increases with elevation as indicated by Rayleigh-type equilibrium fractionation model (Rowley et al., 2001). Kang et al. (2007) obtained 1.40‰ °C^{-1} $\delta^{18}O$-temperature relationship from the linear regression between the 5 year running average of Geladaindong $\delta^{18}O$ records and regional instrumental temperature records. In our study, the strongest correlation was found between the 5 year running average of the regional $\delta^{18}O$ record and ITNTP (r = 0.89, p < 0.001) (Fig. S3). The ZK $\delta^{18}O$ correlates most strongly with the 5 year running average of the mean temperature from two nearby stations (Gêrzê and Xainza, r = 0.60, p < 0.001) (Table 1). Based on these significant relationships, the isotope sensitivities were determined as 1.46‰ °C^{-1} for the regional $\delta^{18}O$ series and 1.18‰ °C^{-1} for ZK $\delta^{18}O$ series, and were used to reconstruct regional temperature series for the northern TP (RTNTP) and the ZK temperature series respectively. Additional analysis showed that as isotope sensitivity value increases, the response of decadal warming rate decreases, especially for the isotope sensitivity values greater than 1.0 (Fig. S4).

The reconstructed regional temperature for the northern TP (RTNTP) was presented in Figure 5a together with the temperature reconstruction for the ZK ice core (Fig. 5b), ITNTP (Fig. 5c) and the global temperature series (Fig. 5d) for comparison. We first compared the RTNTP with the ITNTP, and found strong between the two temperature series (r = 0.65, p < 0.001). Spatially, significant correlations also existed between the CRU gridded surface temperatures and the ITNTP (r = 0.50 to 0.60, n = 42, p < 0.01), as well as between CRU and the RTNTP (r = 0.40 to 0.60, n = 52, p < 0.01) over a large region (Fig. 6). The study area had the strongest correlations (r > 0.50, p < 0.01). This suggested that the regional reconstruction adequately captured temperature variation on the northern TP.

3.3 Recent rapid warming trend over the northern TP

The regional reconstruction was compared with the global annual temperature series (Fig. 5d) and the ITNTP (Fig. 5c) in order to investigate the recent warming trend since 1970s. LOESS regression was used to smooth the data and estimate the general trend. The reconstruction captured the cooling period during 1960s, as well as the prominent warming since the 1970s to the end of the record, with the highest rate of increase in the late 1990s (Fig. 5). For the period from 1970 to 2002, the RTNTP showed more rapid warming trend at the rate of 0.51±0.07°C(10yr)$^{-1}$ than that of the global temperature (0.27±0.03°C(10yr)$^{-1}$). The RTNTP rate was also higher than the ITNTP rate of increase at 0.43±0.08°C(10yr)$^{-1}$ for the same time period. From 1990 to 2002, the warming accelerated on the northern TP with rates of temperature increase at 0.95±0.21°C(10yr)$^{-1}$ for the RTNTP and 0.90±0.29°C(10yr)$^{-1}$ for the ITNTP, much higher than the warming rate of the global temperature (0.37±0.13°C(10yr)$^{-1}$). These results seemed to indicate enhanced warming at the high elevation regions on the northern TP.

Since the late 1990s, the global temperature showed very little change and even decreasing trend since 2005 (Fig. 5d). The relatively flat warming trend was also recorded in the ITNTP (Fig. 5b). However, the ZK series revealed a continued warming trend in recent years after a brief pause during the early 2000s (Fig. 5b). We calculated mean decadal annual temperature change based on the LOESS regression model for all three time series (Fig. 7). For both the global temperature and ITNTP series, the highest average warming rates occurred during 1990s, and then decreased significantly since 1999 (Fig. 7c and d). The reduction of warming rate in the ITNTP series was consistent with results by Duan and Xiao (2015), who found weaker warming trend during the period 1998-2013 in the northern TP based on the instrumental temperature records. However, the rates of increase remained high for the temperature records in the ZK series since 1999 (Fig. 7b), in contrast to the slowdown of climate warming observed for the global mean and ITNTP temperature records since 1999 (Fig. 7d). The persistent high warming rates derived from our regional reconstructions seem to suggest that the elevation-dependent warming is still evident over the high elevations of the northern TP despite the reduced warming rates observed at lower stations in ITNTP (Fig. S5).

The persistent rapid warming in the northern TP could have been caused by the regional radiative and energy budget changes (K. Yang et al., 2014; Yan and Liu, 2014; Duan and Xiao, 2015). Many studies show that the snow/ice-albedo feedback is an important mechanism for enhanced warming at high elevation regions (Liu and Chen, 2000; Pepin and Lundquist, 2008; Rangwala and Miller, 2012). Ghatak et al. (2014) found that the surface albedo decreases more at higher elevations than lower elevations over the TP in recent years. Qu et al. (2013) observed a decreasing trend for the snow/ice albedo at the Nyainquentanglha glacier region, central TP, for the period 2000 to 2010. It has been found that the glacier albedo for the nine glaciers in western China has decreased during the period 2000-2011, especially for the central TP (J. Wang et al., 2014). For example, the glacial albedo of Dongkemadi and Puruogangri glaciers decreased at a rate of 0.0043-0.0059 yr^{-1} and 0.001-0.004 yr^{-1} respectively. Reduced surface albedo increases the surface absorption of solar radiation, and may have contributed to the continued warming over the high elevation regions of the northern TP. Further research is needed to identify and quantify the exact mechanisms accounting for the temperature variations over the Plateau.

4 Conclusions

This study presented a $\delta^{18}O$ time series of the ZK ice core from the northern TP, based on which a temperature record was reconstructed for the period 1951-2008. Moreover, by combining the ZK $\delta^{18}O$ with three other ice cores from the northern TP, a regional temperature history was established from 1951 to 2002. These temperature reconstructions captured the rapid warming trend since 1970, and showed continued warming since 1999 at much higher rates than those of the global average temperature and the instrumental temperature records for the northern TP.

Possible explanations for this continued warming might lie in the regional radiative and energy changes at higher elevations over the northern TP. However, the exact physical mechanisms responsible for the consistently significant warming at higher elevations remain unclear, partly due to the scarcity of available observations. Further studies are needed to understand the specific characteristics of this warming trend on the TP, as well as the response mechanisms of high elevations regions to global changes.

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Figures

Figure 1. Location of the ice core drilling site of ZK, two nearby meteorological station sites, and the location of other ice cores described in the text: Muztagata (Tian et al., 2006), Puruogangri (Yao et al., 2006), Geladaindong (Kang et al., 2007) and Malan (Wang et al., 2003) over the northern TP. The inset shows the relative location of the northern TP to the entire TP. The black rectangle indicates the study area. Red and blue arrows represent the circulation patterns for the study region. Red arrows indicate the direction of the Indian monsoon (near surface) in summer, and blue arrows indicate the dominant westerlies (mid to upper troposphere) in winter.

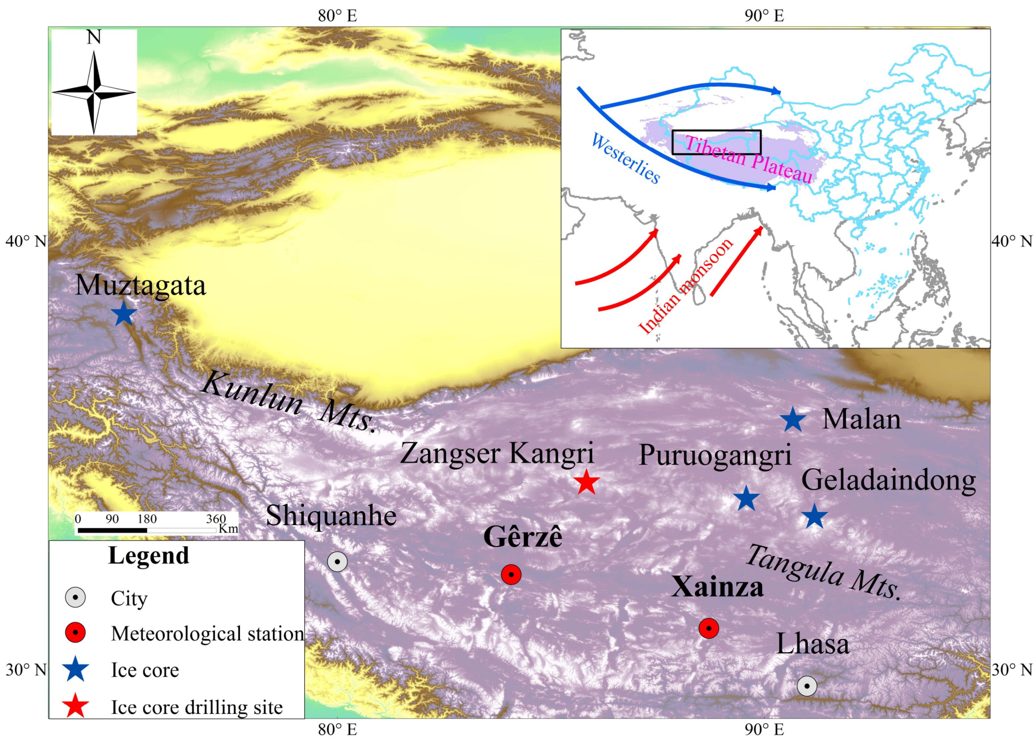

Figure 2. Variations of $\delta^{18}O$ in the ZK ice core and other data used for dating, including beta activity and major ion concentrations. We calculated the logarithm to the base 10 for the concentrations of the Ca^{2+} and Mg^{2+} to facilitate dating.

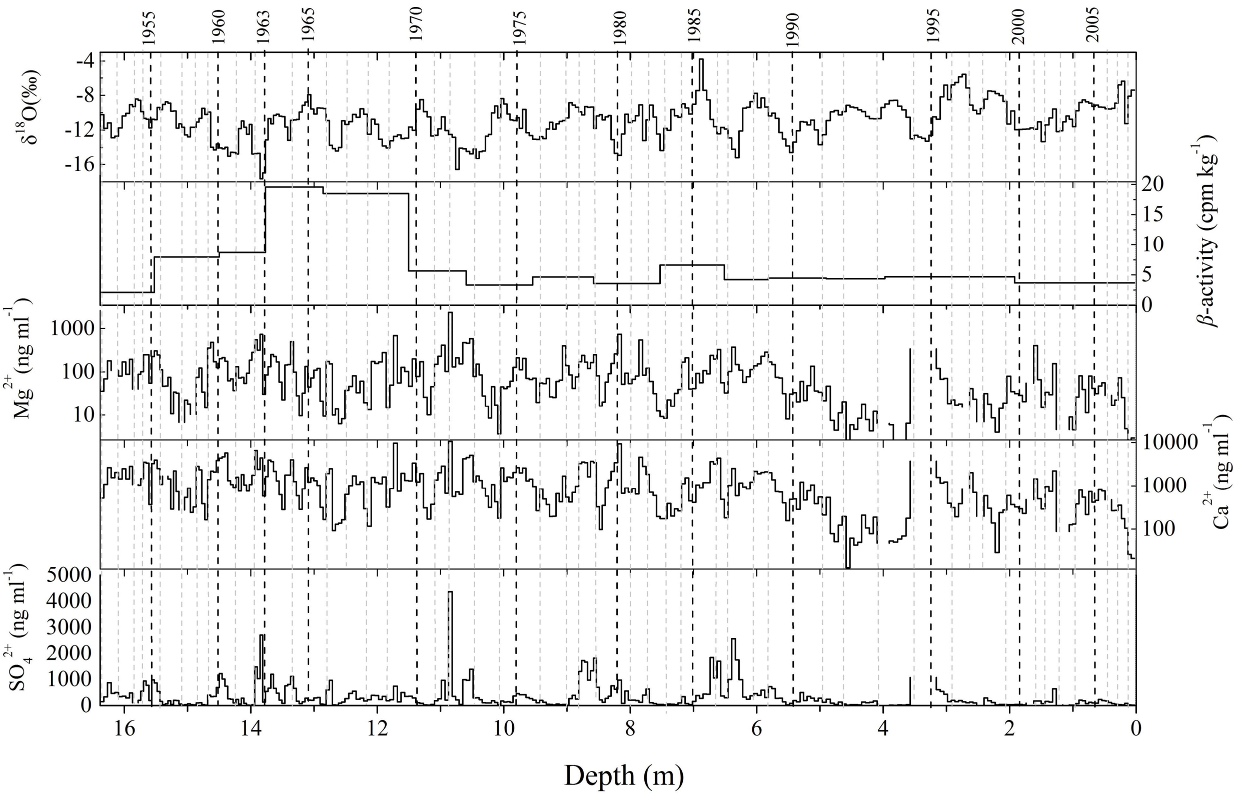

Figure 3. Spatial correlations of ZK ice core $\delta^{18}O$ record with CRU-gridded (Mitchell and Jones, 2005) annual mean temperature (a), annual minimum temperature (b), spring mean temperature (c), and spring minimum temperature (d) for the period 1951-2008. Only correlation coefficients significant at $p < 0.01$ are shown. The black rectangle indicates the ZK ice core site.

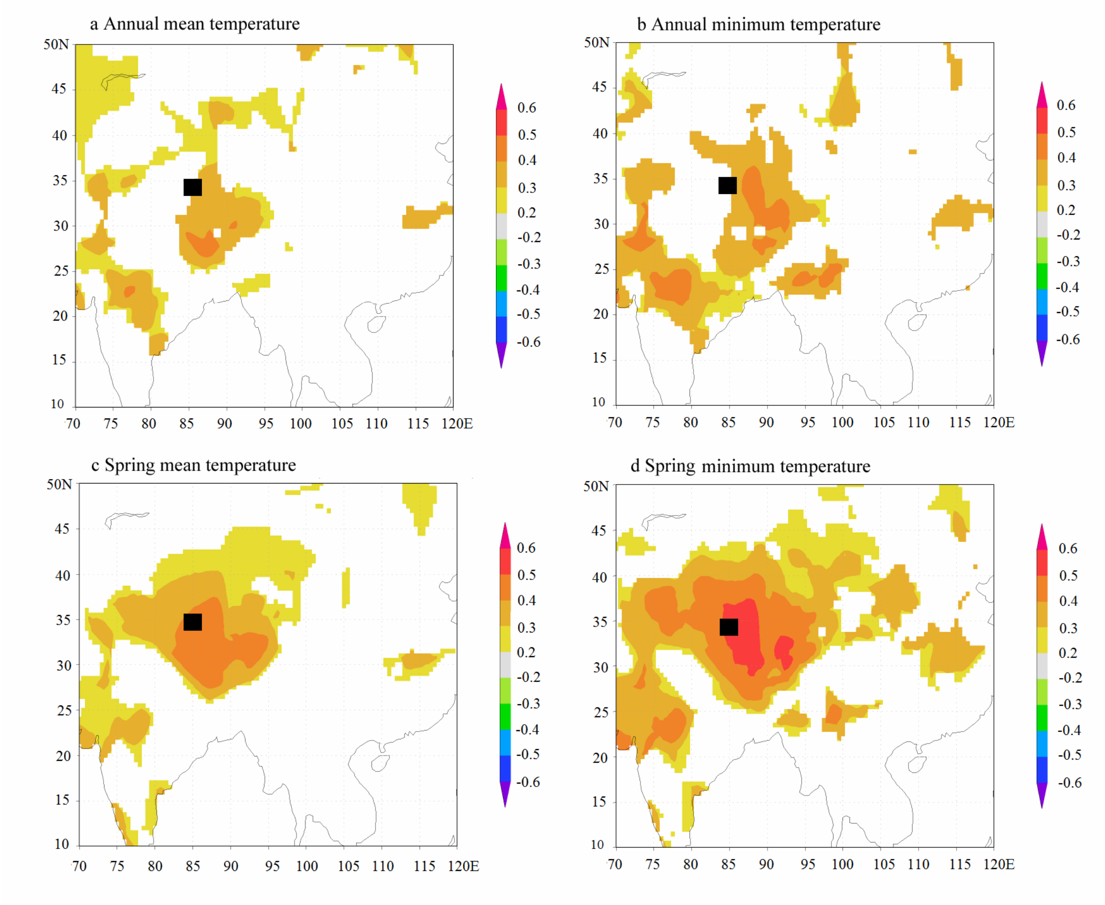

Figure 4. Comparison of the anomalies of $\delta^{18}O$ records in the ZK ice core (a) with $\delta^{18}O$ records from Muztagata (b), Puruogangri (c), Geladaindong (d) and Malan ice cores (e). Thin lines represent annual values, thick lines the 5-year running averages, and the dotted lines the linear trends since 1970.

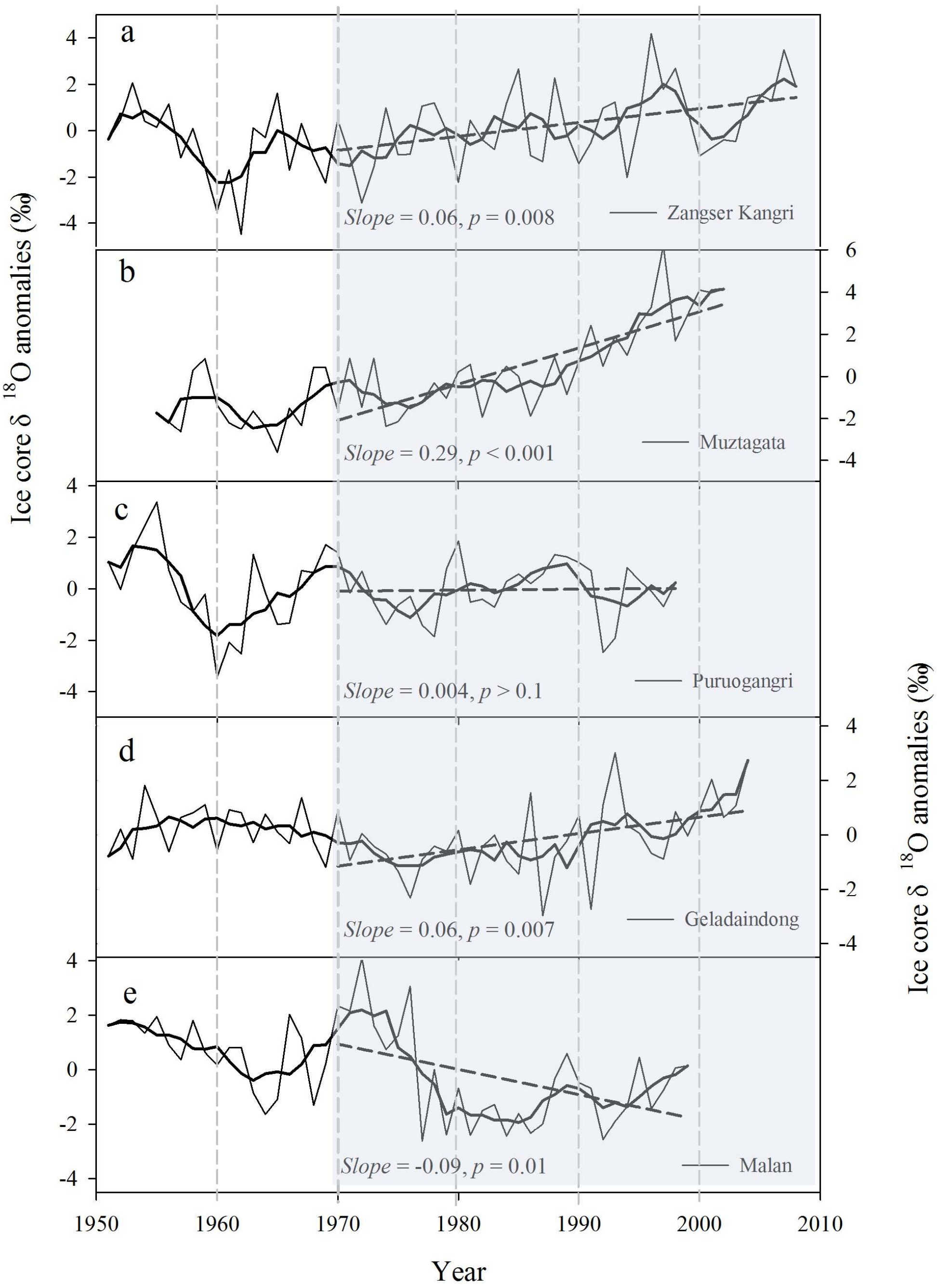

Figure 5. The reconstructed regional temperature series for northern Tibetan Plateau (RTNTP) from ZK, Muztagata, Puruogangri and Geladaindong ice core $\delta^{18}O$ records (a), the reconstructed temperature series from ZK ice core $\delta^{18}O$ record (b), the instrumental temperature record for the northern TP (ITNTP) (c), and global average temperature (d). Black trend lines were estimated using the non-parametric LOESS regression technique with a span of 0.4; the dots indicate the raw values of corresponding temperature series; shading represents the 95% confidence intervals of the estimated trends.

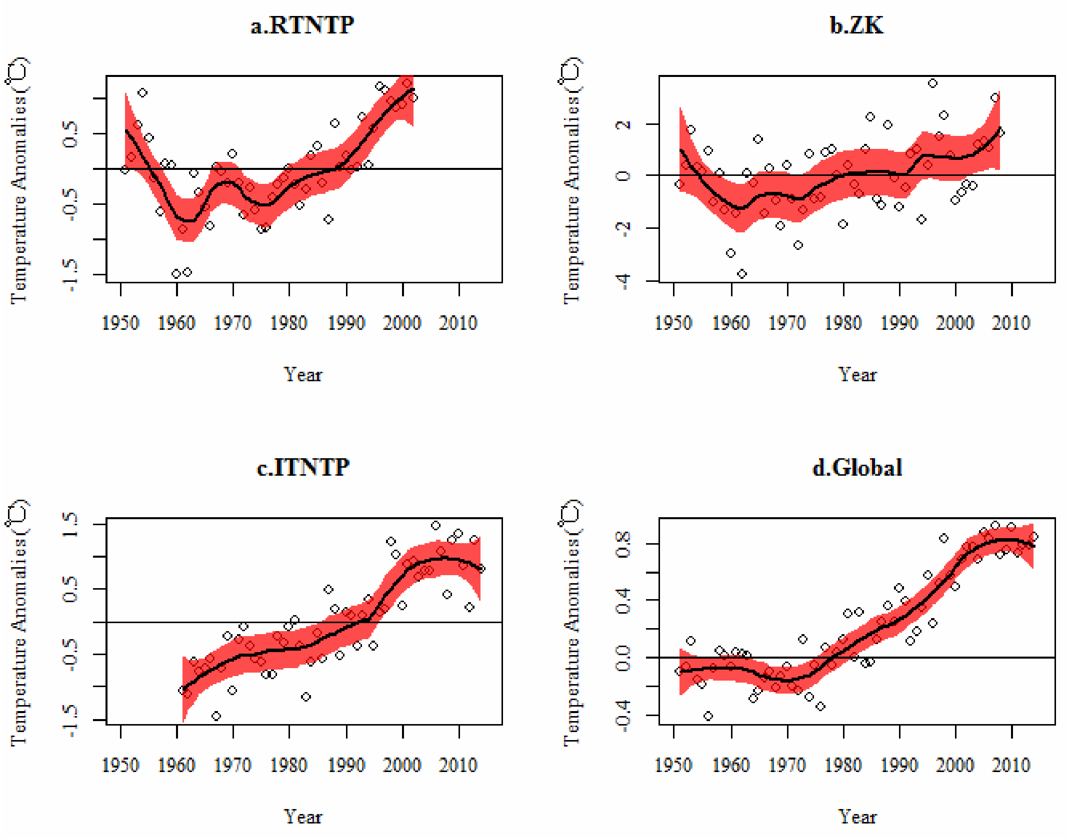

Figure 6. Spatial correlations (r values in color, $p < 0.01$) between the gridded annual mean temperature data (the CRU 4 temperature time series, 0.5° × 0.5° resolution, Mitchell and Jones, 2005) and the instrumental temperature record of the northern TP (ITNTP) (Guo and Wang, 2011) for the period 1961-2002 (a), and the regional temperature reconstruction series for the period 1961-2002 (b). The black rectangle indicates the study area and the blue rectangle indicates the region covered by ITNTP.

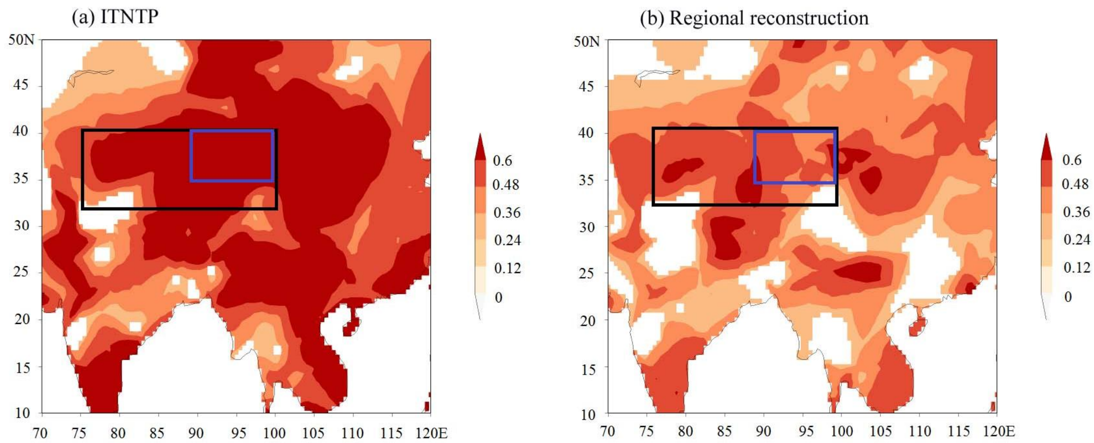

Figure 7. Decadal mean annual change rates for the regional temperature reconstruction series for northern TP (RTNTP) (a), the temperature reconstruction from ZK ice core $\delta^{18}O$ record (ZK) (b), the instrumental temperature record of the northern TP (ITNTP) (c), and global average temperature (d). The decadal mean annual change rates were estimated using the non-parametric LOESS regression model with a span of 0.4.

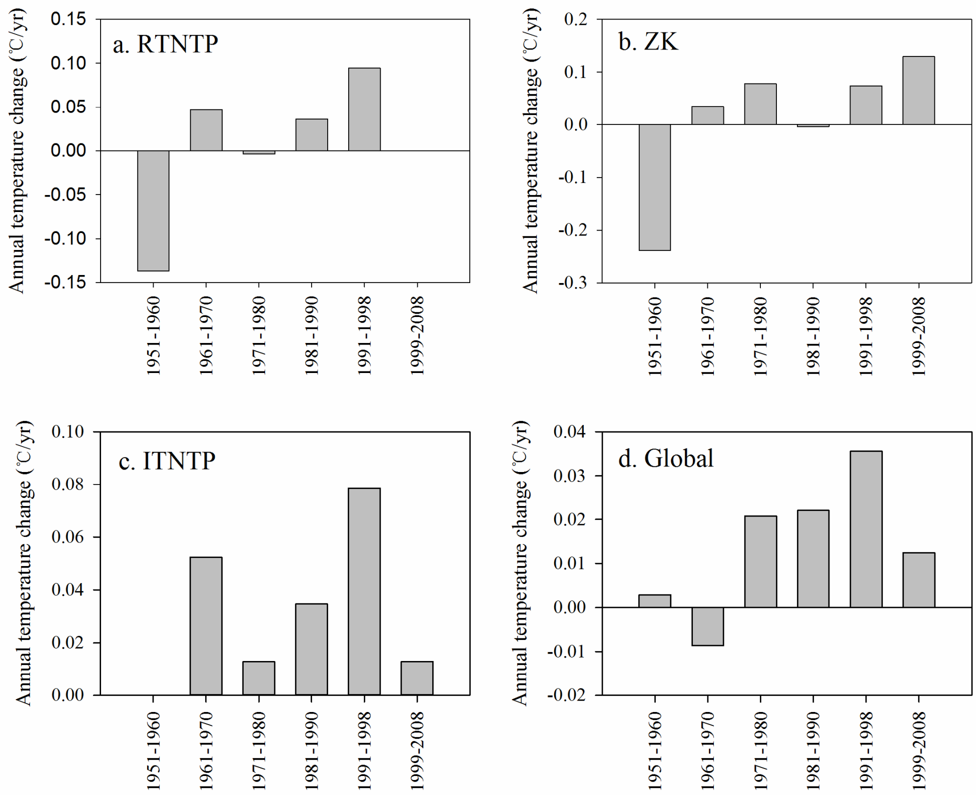

Table 1. Correlation coefficients and linear slopes between the $\delta^{18}O$ values in the ZK ice core and instrumental spring (March–May) and annual temperature from closest Gêrzê (1973–2008) and Xainza stations (1961–2008), the averaged records of the two stations (1961–2008), and the ITNTP series (1961–2008).

		Gêrzê		Xainza		Stations averaging		ITNTP
		March-May	Annual	March-May	Annual	March-May	Annual	Annual
Correlation coefficients	Annual	0.52[c]	0.34[a]	0.45[c]	0.34[a]	0.48[c]	0.34[a]	0.35[a]
	5 year running average	0.63 [c]	0.53 [c]	0.73 [c]	0.60 [c]	0.73 [c]	0.60 [c]	0.61 [c]
Slope	Annual	0.93[b]	0.67[a]	0.93[b]	0.98[a]	1.00[c]	0.88[a]	0.87[a]
	5 year running average	0.87 [c]	0.76 [c]	1.54 [c]	1.32 [c]	1.37 [c]	1.18 [c]	0.40 [c]

[a] $p < 0.05$; [b] $p < 0.01$; [c] $p < 0.001$.

Table 2. Basic information of ice cores from the northern TP.

Ice core	Muztagata	ZK	Purogangri	Geladaindong	Malan
Latitude (N)	38°17'N	34°18′05.8″N	33°54'N	33°34′37.8″N	35°50′N
Longitude (E)	75°06"E	85°51′14.2″E	86°06'E	91°10′35.3″E	90°40′E
Altitude (m)	7010	6226	6200	5720	5680

Table 3. Correlation coefficients between the $\delta^{18}O$ values in the ZK (1951–2008), Muztagata (1955–2002), Puruogangri (1951–1998), Geladaindong (1951–2004) and Malan (1951–1999) ice cores, and the regional $\delta^{18}O$ values (1951-2002) averaged from ZK, Muztagata, Puruogangri and Geladaindong ice cores. The values in bold are the correlation coefficients of annual values, and the values in italic are the correlation coefficients of 5 year running average values

	ZK	Muztagata	Puruogangri	Geladaindong	Malan	Regional average
ZK		**0.26**	**0.14**	**-0.02**	**-0.27**	**0.57**[c]
Muztagata	*0.68*[c]		**0.09**	**0.04**	**-0.20**	**0.80**[c]
Puruogangri	*0.46*[c]	*0.28*		**-0.08**	**0.17**	**0.53**[c]
Geladaindong	*-0.07*	*0.24*	*-0.12*		**0.05**	**0.30**[a]
Malan	*-0.40*[b]	*-0.33*	*0.14*	*0.18*		
Regional average	*0.79*[c]	*0.95*[c]	*0.54*[c]	*0.31*[a]		

[a] $p < 0.05$; [b] $p < 0.01$; [c] $p < 0.001$.