Replies to the comments on "Significant recent warming over the northern Tibetan Plateau from ice core $\delta^{18}O$ records" (CP-2015-69) by W. An et al.

Note: The reviewer's comments are in blue, our replies in black, and the changes in the text marked in red.

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

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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)*."

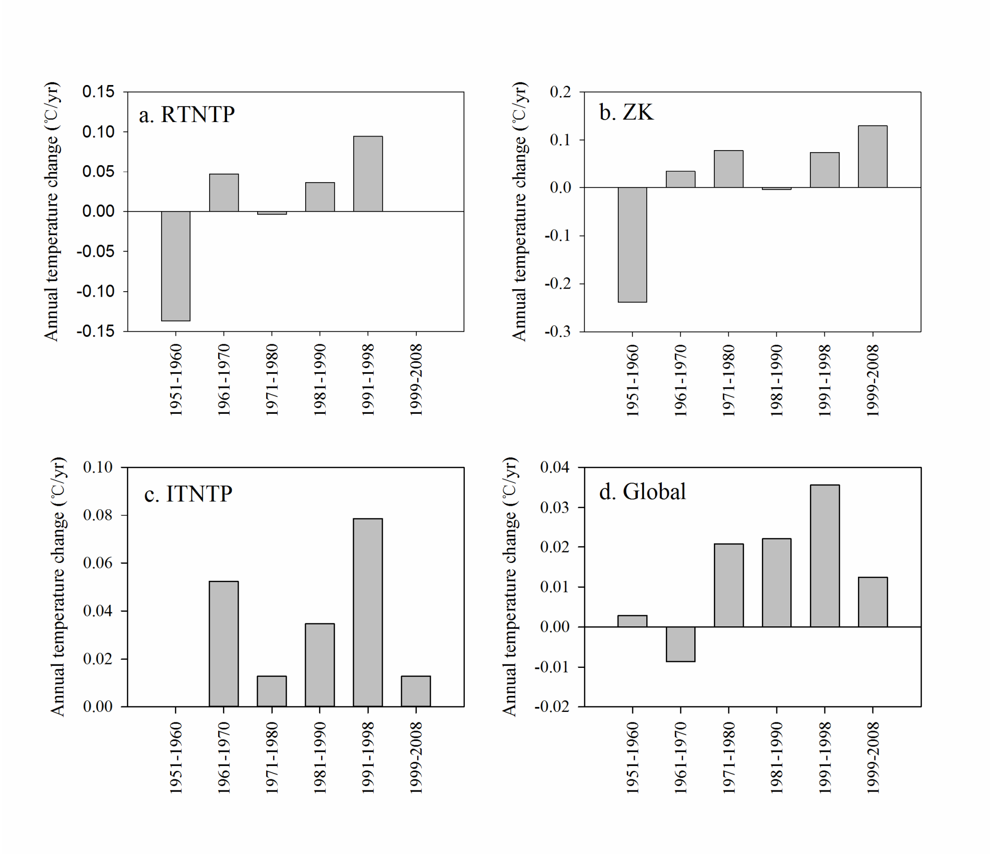

Figure 7. Decadal mean annual change rates for the regional temperature reconstruction series for northern TP (RTNTP) from ZK, Muztagata, Puruogangri and Geladaindong ice core $\delta^{18}O$ records (a), the temperature reconstruction only from ZK ice core $\delta^{18}O$ record (b, ZK), the instrumental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

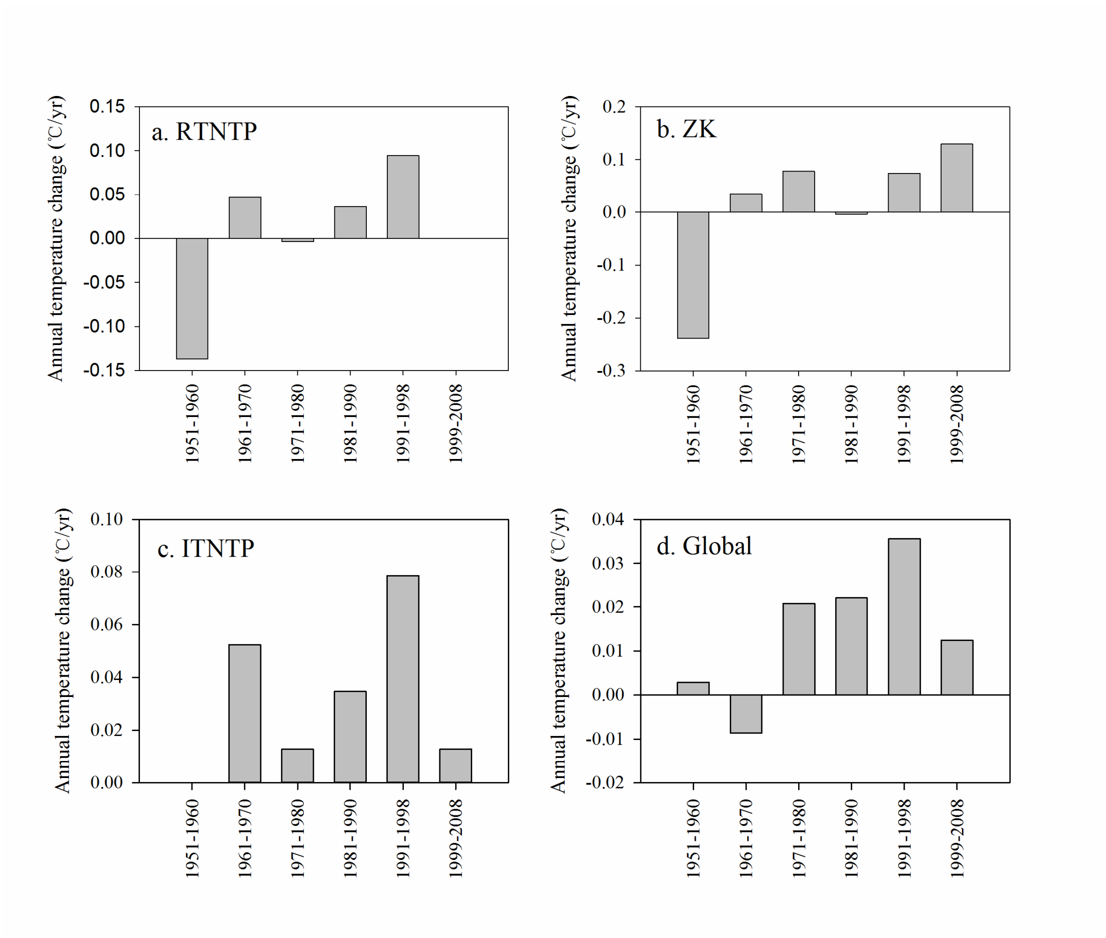

Figure 7. Decadal mean annual change rates for the regional temperature reconstruction series for northern TP (RTNTP) from ZK, Muztagata, Puruogangri and Geladaindong ice core $\delta^{18}O$ records (a), the temperature reconstruction only from ZK ice core $\delta^{18}O$ record (b, ZK), the instrumental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

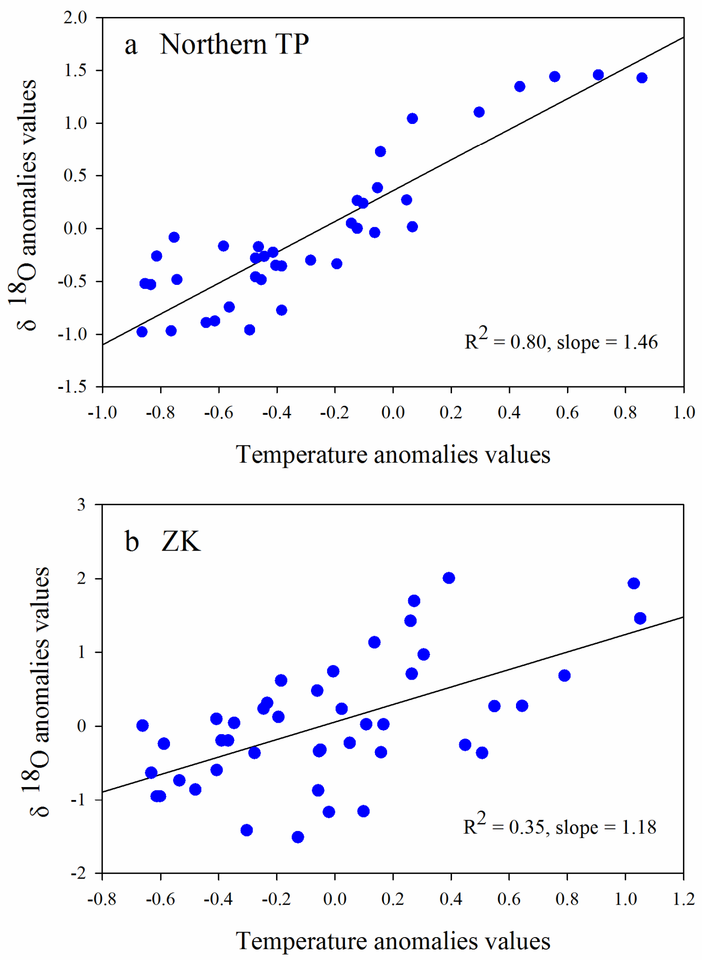

Figure S3. Scatter plots between regional $\delta^{18}O$ and regional instrumental temperature of the northern TP (RTNTP) (5 year running averages) (a), and scatter plots between ZK $\delta^{18}O$ and regional instrumental temperature (averaged from Gêrzê and Xainza) (5 year running averages) (b).

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.

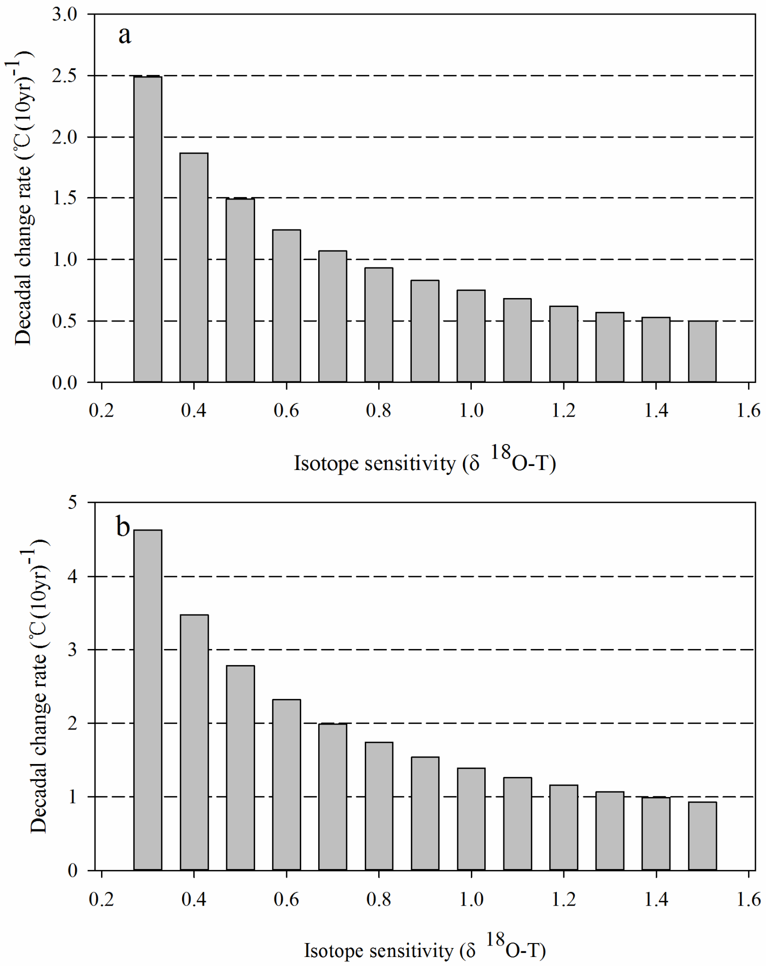

Figure S4. The variations of decadal warming rate with isotope sensitivity values range from 0.3 to 1.5 during 1970-2002 (a) and 1990-2002 (b), respectively. The decadal warming rates were calculated from the RTNTP.

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.

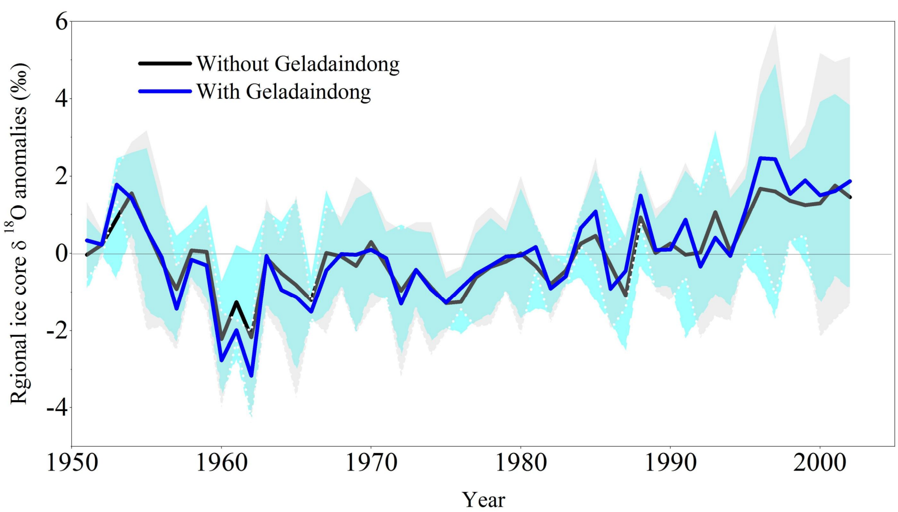

Figure S2. The regional ice core $\delta^{18}O$ time series (from 1951 to 2002) averaged from three ice cores (including ZK, Muztagata and Puruogangri, without Geladaindong), and from four ice cores (with Geladaidong). The shadowed area indicates the range of one standard deviation from the mean.

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.