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 #3

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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} δ^{18}O-temperature relationship, which was used to convert the δ^{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 δ^{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 δ^{18}O records and the average temperature records of the two nearby stations (Figure S3).

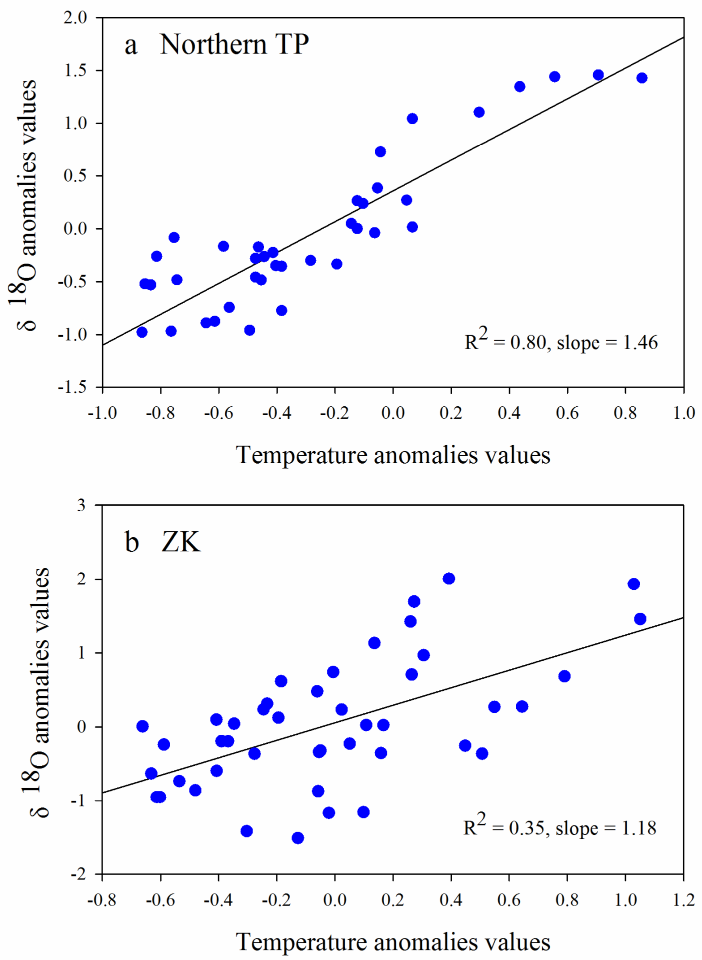

Figure S3. Scatter plots between regional $\delta^{18}O$ and regional instrumental temperature of the northern TP (RTNTP) (5 year running averages) (a), and scatter plots between ZK $\delta^{18}O$ and regional instrumental temperature (averaged from Gêrzê and Xainza) (5 year running averages) (b).

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.

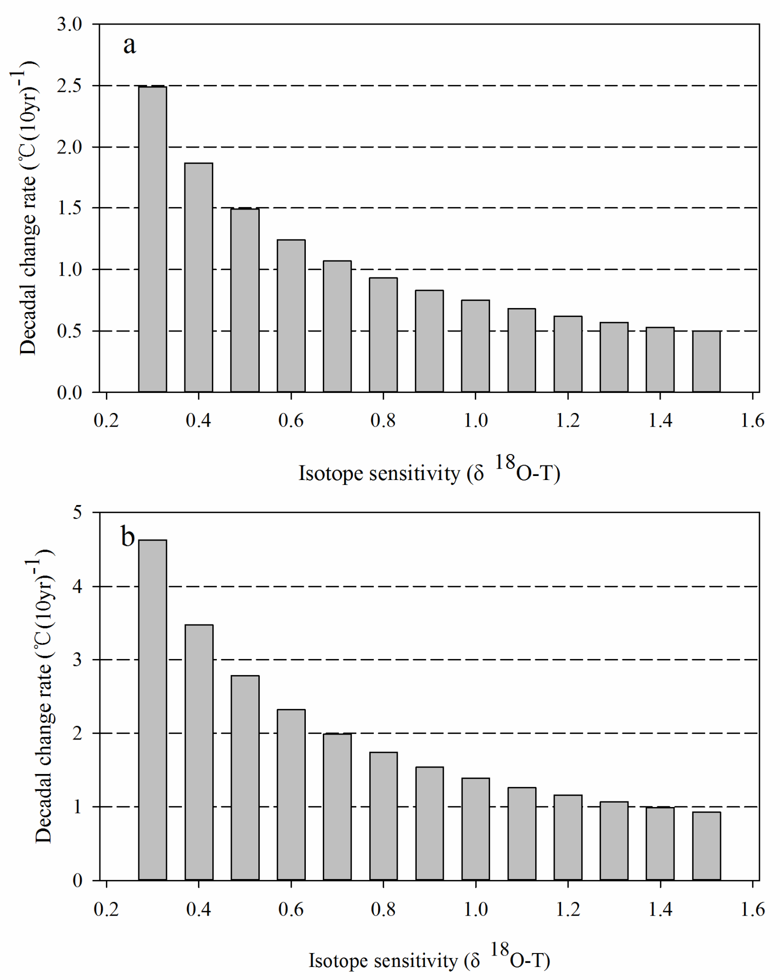

Figure S4. The variations of decadal warming rate with isotope sensitivity values range from 0.3 to 1.5 during 1970-2002 (a) and 1990-2002 (b), respectively. The decadal warming rates were calculated from the regional temperature reconstruction for the northern TP (RTNTP).

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.

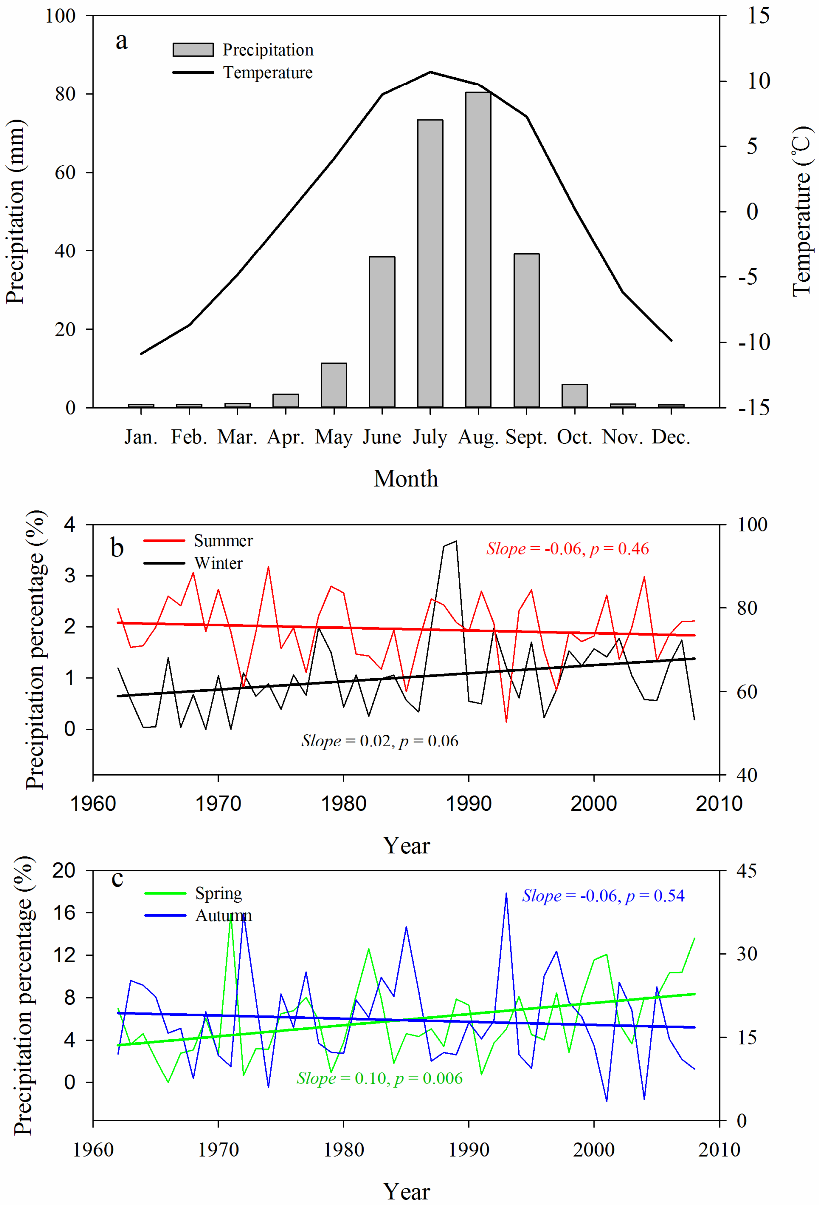

Figure S1. (a) Regional monthly mean temperature and precipitation values from 1961 to 2008 calculated from the average of precipitation data from closest Gêrzê and Xainza stations. (b, c) Variations in the percentage of annual total precipitation of regional precipitation during different seasons from 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.