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.

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 δ^{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 δ^{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) δ^{18}O and spring temperature, as following:

"The stronger spring temperature signal recorded in ZK δ^{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 δ^{18}O in precipitation. On the other hand, precipitation δ^{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 δ^{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.*"

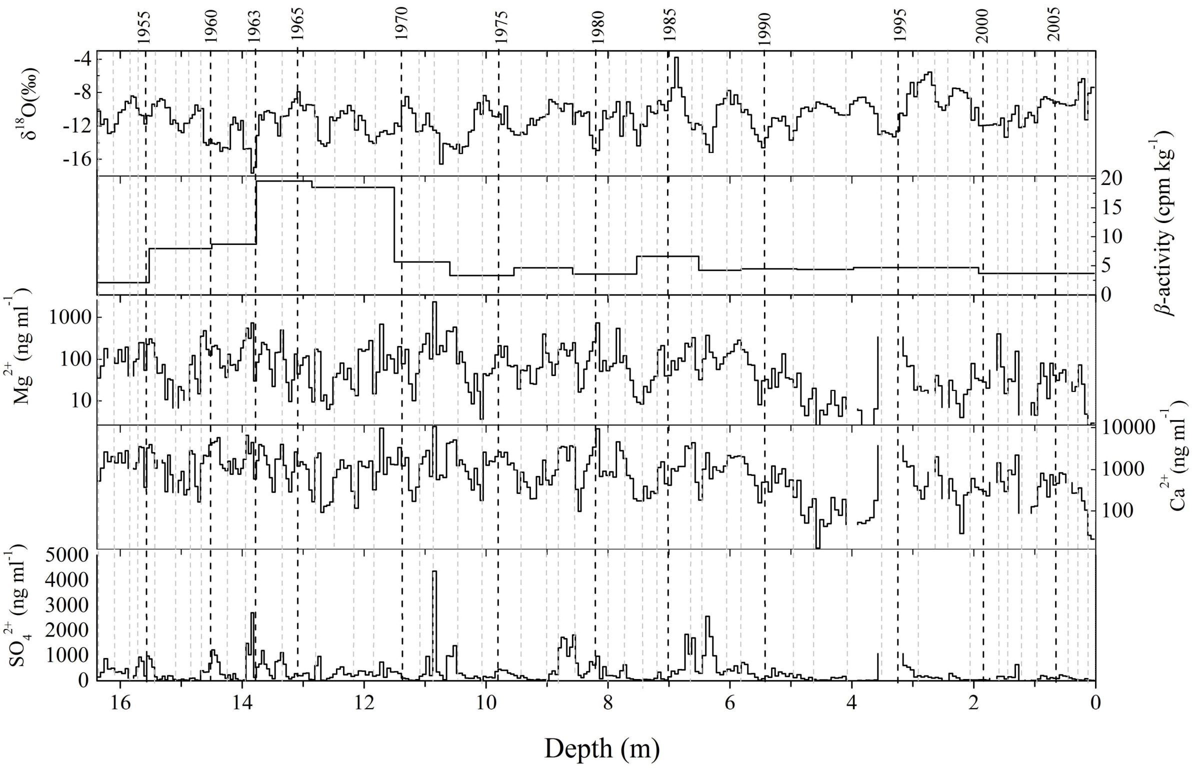
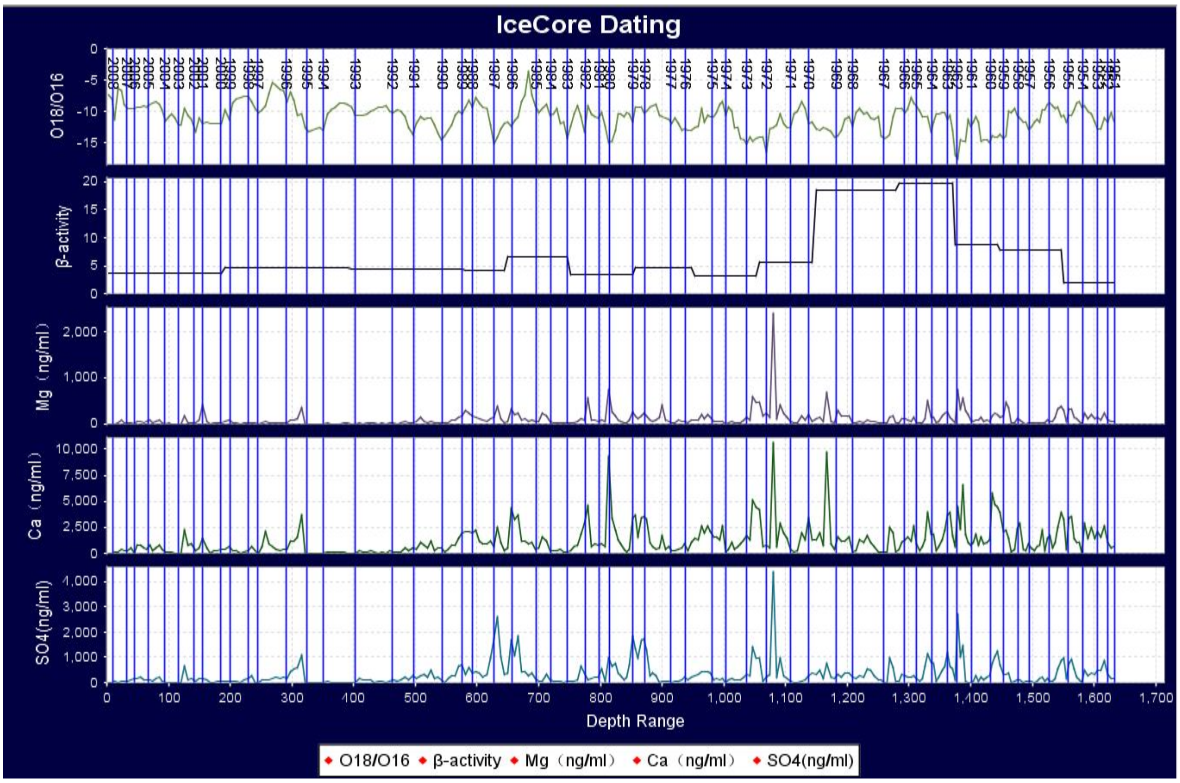


Figure 2. Variations of $\delta^{18}O$ in the ZK ice core and data used in dating: beta activity and major ion concentrations. We calculated the logarithm to the base 10 of the concentrations of the Ca^{2+} and Mg^{2+} to facilitate dating.

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 δ^{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.*"