Interactive comment on “Decapitation of high-altitude glaciers on the Tibetan Plateau revealed by ice core tritium and mercury records”

by S. C. Kang et al.

Anonymous Referee #1

Received and published: 11 February 2015

With their paper “Decapitation of high-altitude glaciers on the Tibetan Plateau revealed by ice core tritium and mercury records” Kang and others provide data from two high elevation ice cores and relate these to presumably negative mass balance at those sites during recent decades. The paper is generally well written, clear and provides interesting results. It certainly deserves publication in the journal. Nevertheless, I am concerned regarding six major issues, a series of smaller points and some deficiencies regarding figures. I recommend that these points are well looked after before final acceptance of the paper in TC.

Answer: We very much appreciated the constructive and detailed comments from this reviewer, and have incorporated all of them in the revised ms. Below we provide a point-by-point reply to the comments.

The six major points are the following:

1. Wording and Title: I think that the wording in the title and in subsequent phrases in the manuscript needs a little revision. To my understanding “decapitation” is in this case an inappropriate word that relates to killing of living creatures. In most circumstances, in civilization, people would associate a criminal offense with such kind of action. I don’t think glaciology should make use of such martial wording. In contrast to this, climate is a physical system that does not act in the sense living creatures can act. Furthermore, a glacier is a dead body of frozen water. Regardless of the fact that it moves under the influence of gravity it is not a living thing that can be decollated. Therefore, and with respect for anything that is actually an animate being on the planet, I strongly recommend replacing the word “decapitation” with for example “loss of accumulation area” or “diminishing accumulation area” or something similar.

Answer: Agreed. The title has been changed to “Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records”

2. Overall conclusions and generalization of results from only two sites to the whole region: Since both ice cores have been collected from sites at 5800 m asl you cannot really say anything regarding higher altitude accumulation areas above 5800 m asl. Therefore, maybe there is no complete loss of accumulation area since there might be remaining bits of accumulation areas further up. Therefore, I strongly recommend to be precisely saying that there has been a loss of accumulation area probably up to about 5800 m asl at the two study sites. Anything that’s further up on the glaciers or related to other glaciers in the area is -

to my understanding - not covered by this study. In consequence, a complete loss of accumulation cannot be concluded from the study. That doesn't invalidate the study. It simply implies that - while "decapitation" shouldn't be used as a word anyway - even the complete loss of accumulation area is not a valid mature conclusion as long as it is solely based on the analysis of the two ice cores.

Answer: Agreed and we have avoided the use of "decapitation" throughout the revised ms.

3. In the section on methodology it is said that the ice cores were taken from slightly above or around the ELA (P421, L13) above the actual snowline. Isn't the area above the ELA part of the accumulation area? How can you obtain an ice core from above the ELA and at the same time reach the conclusion that there isn't any accumulation area on these glaciers since decades? If the latter would be the case the ELA should lie above the summit. Then it would not be possible to find any coring site above the ELA. Somehow this issue needs clarification.

Answer: The ice core drilling site was chosen in the accumulation area according to the ELA (equilibrium line altitude) of 5570 m a.s.l. in the northern region of Mt. Geladaindong in 1970s reported by Zhang (1981). However, the coring site was in the ablation area when the ice core was retrieved in 2005. Yao et al. (2012) reported that continuous deficit mass loss occurred since the 1990s in the central Tibetan Plateau due to dramatic warming. Therefore, the accumulation area of the glacier in the 1970s (Zhang, 1981) had most likely changed to the ablation area since the 1990s.

In the revision, we have clarified this.

References:

Yao, T., Thompson, L. G., Yang, W., Yu, W. S., Gao, Y., Guo, X. J., Yang, X., Duan, K. Q., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang. 2, 663-667, 2012.

Zhang, L.: Glacier at the source region of Tuotuohe River in the upper reaches of the Yangtze River and their evolution. J. Glaciol. Geocryol. 3, 1-9, 1981.

4. Counting annual layers backwards from the nuclear bomb horizon could imply that there are years without accumulation before 1982, in such that 1982 not necessarily needs to be the last year of positive accumulation. Maybe the last year with accumulation was later and there have been years without accumulation before 1982? Is it possible to constrain the Hg-records to better than +/- 10 years? Please at least discuss this issue.

Answer: We agree.

Dating of counting annual layers was verified by the ^{210}Pb dating which suggested that the top of the core was dated to 1982 ±5 years as shown in our Fig. 3b. The resolution of Hg record is ~ 5 yrs, thus the Hg records showed maximum values which referred to 1980s.

One assumption in dating by counting annual layers backwards from the 1963 AD nuclear bomb horizon to 1982 AD is that there was annual net ice accumulation during this period. Uncertainties in the chronology will thus rise should there be no net accumulation in one or some of the years due to ice melt. This does not appear to be the case for the Geladaindong ice core, as the annual variation patterns and amplitudes in the main ion concentrations were similar upward and downward from the 1963 AD layer, suggesting no occurrence of strong melt (Fig. 4). Furthermore, the air temperatures were much lower before 1980s than those in the last three decades according to the data observed from the nearby meteorological stations such as Amdo. Indeed, the continuously deficit mass balance (cumulative negative mass balance) has only been reported since the 1990s in the central Tibetan Plateau (e.g., Xiaodongkemadi glacier (Fig. 6), near to the Geladaindong region; Yao et al. 2012), as well as in the northern neighboring region (e.g., Glacier No. 1 (Fig. S1), Tienshan Mts.; Zhang and others, 2014), due to dramatic warming in recent decades. Therefore, we might suggest that the mass loss of the coring site occurred mainly from the 1990s in the central Tibetan Plateau. Then, a continuous deficit mass balance caused the surface of the ice core up to 1980s.

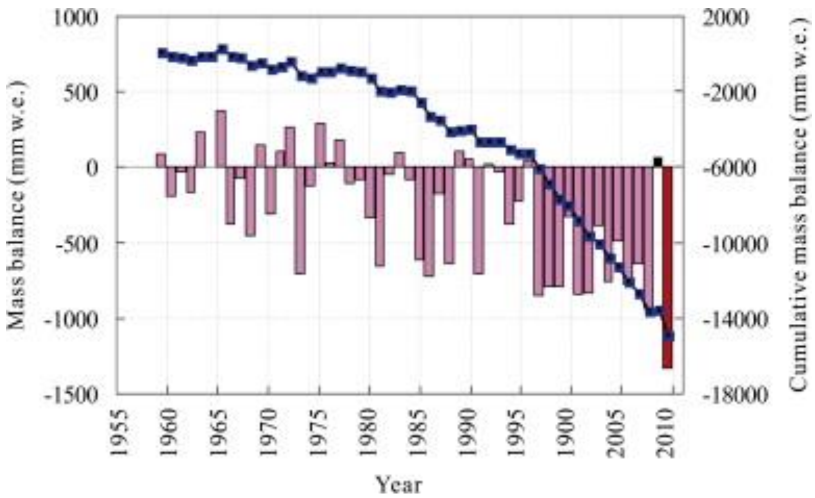


Fig. S1 The annual (pink bar) and cumulative (blue line) mass balance of the Urumqi glacier No. 1 located in the astern Tienshan Mts. (Zhang et al., 2014).

We have added discussions in the revision.

References:

Yao, T., Thompson, L. G., Yang, W., Yu, W. S., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang. 2, 663-667, 2012.

Yao, T., Wang, Y., Liu, S., Pu, J., Shen, Y., and Lu, A.: Recent glacial retreat in high Asia in China and its impact on water resource in Northwest China, Sci. China (D), 47(12), 1065-1075, 2004.

Zhang, G., Li, Z., Wang, W., and Wang W.: Rapid decrease of observed mass balance in the Urumqi glacierNo.1 Tianshan Mountians, central Aisa, Quatern. Intern. 349, 135-141, 2014.

5. Most of the time a DDF for snow will need to be used at high elevation sites that have almost permanent snow cover. DDFs of 3 to 8 mm/_C for snow seem to be reasonable to my knowledge, but certainly not DDFs above 10 mm/_C. Otherwise, please cite the references that justify a DDF for snow that is higher than 10 mm/_C. I think that the analysis of uncertainty regarding upper and lower limits of the melting according to the degree day modelling is not sufficient. You should provide three records of melting with the lowest, the middle and the highest reasonable DDF combined with the lowest, middle and highest reasonable temperature lapse rate - making up nine calculations at the least. This would provide the range of uncertainty with respect to the DDM. However, the uncertainty is much larger because a DDM is only a rough estimate of the melting since it does not fully cover all relevant physical processes. Further, the uncertainty in the precipitation estimate must be stated more clearly. The plus in precipitation at a high altitude site compared to stations further down in the forelands can easily reach 100%! Do not just give ranges but provide the full range of data in a Figure or a Table. The data provided in Figure 8 is not sufficient for this purpose.

Answer: We have added more detailed info re DDM in the revised ms, including two new tables (Tables 1 and 2). Daily temperature and positive cumulative temperature at the two sites were calculated based on the minimum (0.5 ℃/100 m) and maximum (0.72 ℃/100 m) temperature lapse rate reported by Li and Xie (2006) and Yang et al. (2011), respectively, for the Tibetan Plateau (Tables 1 and 2, Fig. 7). The Medium value was set as the global average of 0.6 ℃/100 m. Due to the differences in the surface energy-balance characteristics of snow and ice (including albedo, shortwave penetration, thermal conductivity and surface roughness), reported DDFs vary greatly among regions and times. Based on previous work in the southern and central Tibetan Plateau (Wu et al., 2010; Zhang et al., 2006), we selected DDF values of 3.0 (minimum for snow), 5.3 (medium for snow), 9.2 (medium for ice) and 14 (maximum for ice) mm ℃$^{-1}$ d^{-1}, respectively (Tables 1 and 2).

The change rate of precipitation ranged from 0.87 to 11 mm /100 m in the high elevations of the Qilian and Tienshan Mts. (Liu et al., 2011). However, there are no observed data available for the central Tibetan Plateau. Thus we assumed that precipitation was the same at the coring site as at the nearby station when using DDM, although in reality it might be higher at the coring site than that at the nearby station.

Table 1 Calculated annual net mass balance (mm w.e. yr^{-1}) during 1966-2013 AD based on various degree-day factor (DDF) values (mm ℃$^{-1}$ d^{-1}) and temperature lapse rates (℃/100 m) at the Geladaindong ice core site. Negative values represent deficit mass balances.

Temperature lapse rate \ DDF[a, b]	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Minimum (Tr1)[c] 0.5	-386±220	-1025±369 -2108±625	-3441±944
Medium (Tr2) 0.6	-121±192	-925±576	-2203±811
Maximum (Tr3)[d] 0.72	132±157	-109±247 -518±408	-1021±610

a: Wu et al., 2010; b: Zhang et al., 2006; c: Li and Xie, 2006; d: Yang et al., 2011.

Table 2 Calculated annual net mass balance (mm w.e. yr^{-1}) during 1966-2013 AD based on various degree-day factor (DDF) values (mm ℃$^{-1}$ d^{-1}) and temperature lapse rates (℃/100 m) at the Nyainqentanglha ice core site. Negative values represent deficit mass balances.

Temperature lapse rate \ DDF[a, b]	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Minimum (Tr1)[c] 0.5	-469±249	-1189±400 -2410±663	-3912±992
Medium (Tr2) 0.6	-2.57±212	-671±538	-1733±791
Maximum (Tr3)[d] 0.72	336±150	234±207 60.4±313	-153±450

a: Wu et al., 2010; b: Zhang et al., 2006; c: Li and Xie, 2006; d: Yang et al., 2011.

References:

Li, Q. and Xie, Z.: Analyses on the characteristics of the vertical lapse rates of temperature- taking Tibetan Plateau and its adjacent area as an example, J. Shihezi University (Natural Sci.), 24(6), 719-723, 2006.

Liu, J., Chen, R., Qin W., and Yang, Y.: Study on the vertical distribution of precipitation in mountainous regions usingTRMM data, Advances in Water Science, 22(4), 447-454, 2011.

Wu, Q., Kang, S., Gao, T., and Zhang, Y.: The characteristics of the positive degree-day factors of the Zhadang Glacier on the Nyainqêngtanglha Range of Tibetan Plateau, and its application, J. Glaciol. Geocryol., 32(5), 891-897, 2010. (in Chinese with English abstract)

Yang, X., Zhang, T., Qin, D., Kang, S., and Qin, X.: Characteristics and changes in Air Temperature and Glacier's Response on the North Slope of Mt. Qomolangma (Mt. Everest), Arct. Antarct. Alpine Res., 43(1), 147-160, 2011.

Zhang, Y., Liu, S. Y., and Ding, Y.: Spatial variation of degree-day factors on the observed glaciers in western China, Acta Geographica Sinica, 61(1), 89-98, 2006.

6. It may be a possibility that there were some warm years that removed the nuclear signal from the accumulation area while after that other years still had a positive mass balance. I understand that the Hg-record is a further indication that this is not the case. However, the temporal constraint of the Hg-record is not so clearly provided in the text. I would argue that the authors should more cautiously discuss any possible flaws in their chain of arguments so that the reader gets a better understanding of the reasoning behind the conclusion. There is a chance that overall the case is not quite as simple as it appears according to the manuscript. I believe it would strengthen the paper quite a bit if you could elaborate on this in more detail.

Answer: As per our reply to Comment 4 above, strong melt (or mass loss) might have been happening since the 1990s according to the observed continuous deficit mass balance in the central Tibetan Plateau. We suggest that the nuclear bomb signal can be reserved in the deposited layers. In the revised ms, we have clarified that the surface age (1982) had an uncertainty as indicated by ^{210}Pb dating.

Smaller points that still need consideration:

P419, L11; P420 L15, P424, L26, P427, L20, P428, L6: replace "glacier decapitation" and similar wording with more appropriate wording – see my comment above

Answer: We have replaced "glacier decapitation" throughout the revision.

P420, L1: insert "the before "last decade".

Done.

P420, L9: "marker horizons" not "maker horizons".

Done.

P424, L6: "Faïn" instead of "Fain".

Done.

P424, L17: "Hylander" instead of "Hyland".

Done.

P424, L25-27 and hereafter: The conclusions or rather generalizing statements based on only few measurement sites should be avoided. I would strictly limit the statement to findings refereeing to the investigation sites of this paper since individual glaciers in the same region may heterogeneously respond to climate forcing.

Answer: We agree and have revised the ms accordingly.

P425, L10: "in the order" instead of "on the order".

Done.

P424, L20: replace “tracks” with “matches” or “agrees”.

Done.

P425, L25: replace “at” with “of”.

Done.

P 425, L19: “Since 1995, the cumulative mass loss reached 5000 mm with an annual mass loss rate of about 300 mm w.e.”: What is the end date of the period in which mass loss piled up to 5000 mm?

Answer: The period is from 1995 to 2010 for the observation of Xiaodongkemadi glacier mass balance. We have added this info in the revised ms.

P426, L3: skip the word “to” in “confirm to widespread glacier : : :”. The statement anyway is a bit strong since from your study you can only draw conclusions for the two study sites. Maybe better say that mass loss is in “in agreement” or “consistent” with your finding but refrain from drawing an overall conclusion for the whole region.

Answer: We agree and have revised the conclusion accordingly.

P426, L20: skip “of glacier area” in “may occur at the higher elevations of glacier area compared with : : :”

Answer: We agree and have revised the conclusion accordingly.

P226, L25: skip “the” in ”according to the previous works : : :”.

Done.

P427, L3: "mass loss" instead of "mass losing".

Done.

P427, L15: change to “oF glacierS during the last decade ranging from THE Himalayas : : :”.

Done.

P427, L16: "northwestern TP" instead of "northwestern of the TP"

Done.

Figures:

Fig.1: Number the three parts of the figure (e.g. a,b,c) and give proper explanations in the figure capture. Insert a color legend in the uppermost map. You should overlay altitude lines so that the reader can see the topography and general altitude. Please provide a coordinate system and glacier outlines for the glaciers interesting for your study in the two lower pictures. The lower right picture is of bad quality. Choose a better satellite image. Please use consistent naming of the glaciers (e.g. Xiaodongkemadi in the map and Dongkemadi in the figure caption).

Answer: We have modified the figure.

Reviesed Figure 1

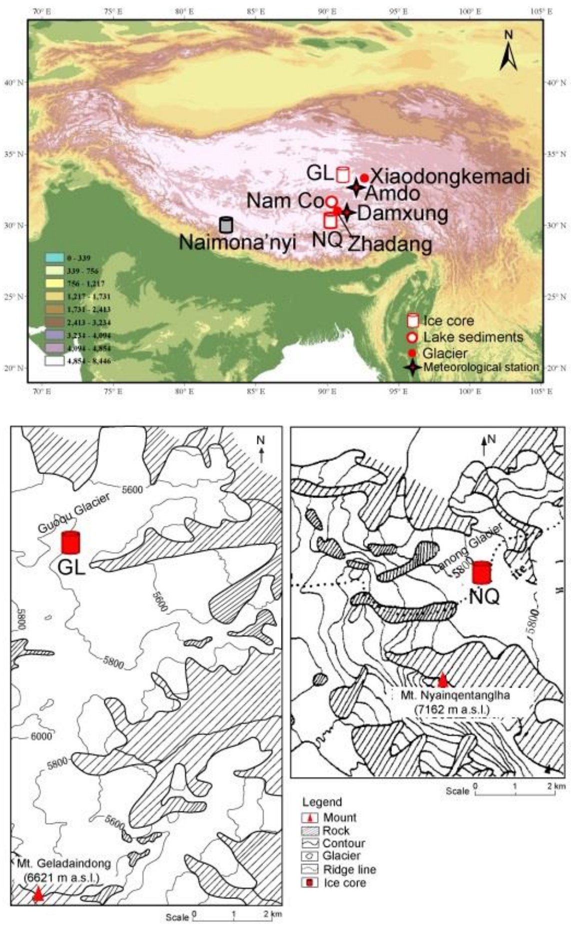


Fig. 6: Clearly indicate in the figure caption if these are measured or modelled mass balance data. Change "Mt. Nyainqentanglha" to "western Nyainqentanglha Mts."

Answer: Done.

Fig. 8: This figure gives no additional information because the numbers are already given in the text. I suggest removing this figure. The definition of Min and Max is confusing. Min should be more negative, but in your case it is the least negative (most positive) mass balance.

Answer: We have deleted Fig. 8 and added Tables 1 and 2 concluding calculated results.

Interactive comment on "Decapitation of high-altitude glaciers on the Tibetan Plateau revealed by ice core tritium and mercury records"

by S. C. Kang et al.

Anonymous Referee #2

Received and published: 5 March 2015

Glacier volume loss through high-elevation thinning is a major research conclusion, and the strength of this paper lies in expanding the already documented Himalayan glacier thinning to other locations in the Tibetan Plateau. The revision of the paper should concentrate more on this point, which may require significantly shortening the paper. The research adds valuable additional locations demonstrating high-altitude glacier thinning and therefore contributes to our scientific understanding of current freshwater volume stored in Tibetan Plateau glaciers.

Answer: We very much appreciated the constructive and detailed comments from this reviewer, and have incorporated all of them in the revised ms. Below we provide a point-by-point reply to the comments.

Comment 1: I am not convinced by the chronology of the Geladaindong ice core, as Figure 4 demonstrates what is likely a melt layer immediately deeper than the AD 1963 radioactivity peak. This likely melt then influences the comparison of Hg records in Figure 5. Do modern studies demonstrate a seasonal deposition of Ca^{2+} on these ice fields? Is there any evidence for melt above AD 1963? If the top of this glacier is thinning due to melt, it is likely that the melt influenced the upper strata of the glacier ice. Such melt may explain the offset in Hg records, where the Geladaindong Hg spike appears to occur 5-10 years earlier than the NamCo Hg spike (the geographically closest Hg record with which to compare the results). While comparing Hg records is an interesting approach, the errors associated with this approach (Figures 4 and 5) need to be expressly addressed throughout the paper.

Answer:

1) Based on the three snowpit records in the Guoqu glacier, Mt. Geladaindong, Zhang et al. (2007) reported seasonal variations in the concentration of Ca^{2+} and other major ions in snowpits, with higher values during the winter half year. At the Geladaindong ice core site, there were firn layers (snowpit) with a depth of 78 cm. The bottom of the snowpit was glacier superimposed ice, indicating one year transferring from snow to ice. Thus, melt could happen during the summer but seasonal signals were still reserved in the ice layers. In other words, the melt water (or percolation) should not disturb the layers deposited in previous years as other studies suggested (Namazawa and Fujita, 2006; Eichler et al., 2001).

2) The temperature was much lower before the 1980s than in the last three decades observed from the nearby meteorological stations (such as Tuotuohe and Amdo). The continuous deficit mass balance (i.e., cumulative negative mass balance) only happened since the 1990s in the central Tibetan Plateau (e.g., Xiaodongkemadi glacier, near to the GL region)

as reported by Yao et al., (2012) (Fig. 6) due to dramatic warming (Fig. 7). There is another example: the longest mass balance observation from Glacier No. 1 at the headwater of the Urumqi River (see Fig. S1 below), Tienshan Mts., China, suggested that the mass balance was fluctuating during 1950s to 1970s, and more deficit mass balance appeared in the 1980s, while almost continuously negative mass balance occurred since the mid-1990s (Zhang et al., 2014). Therefore, it is highly possible that the mass loss of the coring site occurred mainly from the 1990s in the central Tibetan Plateau, and this continuous deficit mass balance caused the surface of the ice core up to the 1980s.

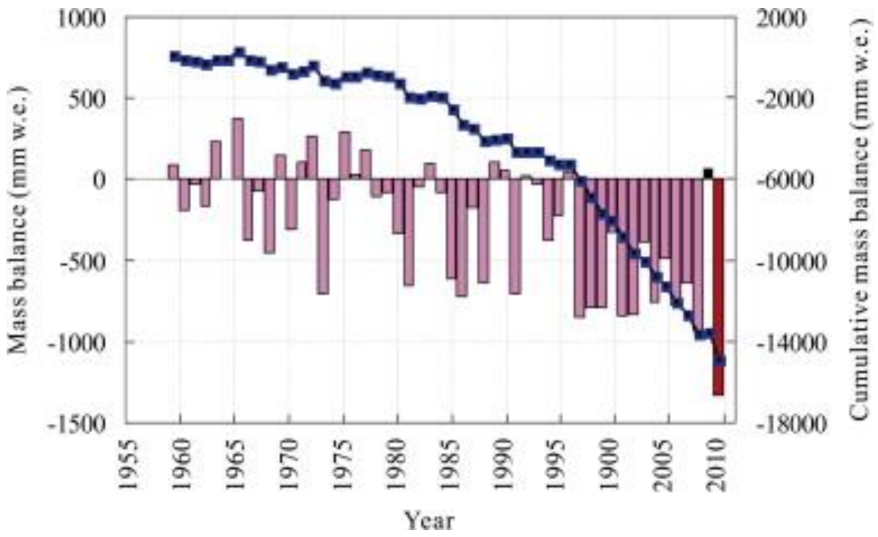


Fig. S1 The annual (pink bar) and cumulative (blue line) mass balance of the Urumqi glacier No. 1 located in the astern Tienshan Mts. (Zhang et al., 2014).

3) The resolution of the Hg records from the Nam Co lake sediment is around 5 year, thus the timing of the peak may not exactly match that of the ice core records.

We have included these discussions in the revised ms.

References:

Eichler, A., Schwikowski, M., Gäggeler, H.: Meltwater-induced relocation of chemical species in Alpine firn, Tellus B, 53 (2), 192-203, 2001. (DOI: 10.1034/j.1600-0889.2001.d01-15.x)

Nakazawa, F. and Fujita, K.: Use of ice cores from glaciers with melting for reconstructing mean summer temperature variations, Ann. Glaciol., 43, 167-171, 2006.

Yao, T., Thompson, L. G., Yang, W., Yu, W. S., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang. 2, 663-667, 2012.

Zhang, G., Li, Z., Wang, W., and Wang W.: Rapid decrease of observed mass balance in the Urumqi glacierNo.1 Tianshan Mountians, central Aisa, Quatern. Intern. 349, 135-141, 2014.

Zhang, Y., Kang, S., Zhang, Q., Cong, Z., and Zhang, Y.: Snow/ice records on Mt. Geladaindong in the central Tibetan Plateau, J. Glaciol. Geocryol., **29**(5), 685-693, 2007. (In Chinese with English abstract)

Major points:

P. 423 and Figure 2: You mention that some samples at 31 m were contaminated with tritium during sampling. How were the samples contaminated? Please define. This contamination needs to be explained because otherwise these elevated tritium concentrations at 31 m significantly affect the findings and conclusions.

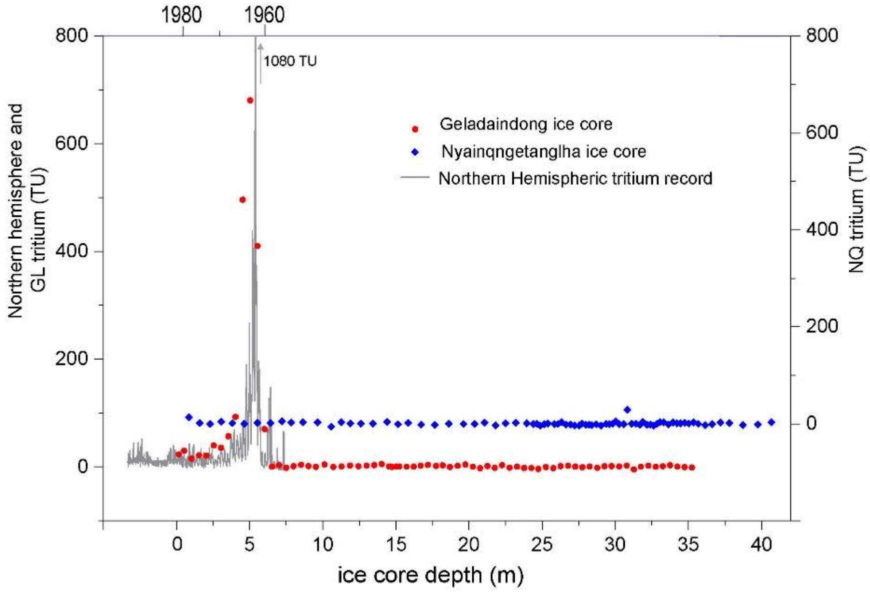
Answer: The elevated tritium concentration (29.1 TU) at 31 m of the Nyainqentanglha ice core is clearly not representing the horizon from the atmospheric nuclear bomb testing between 1953 and 1972. Only one isolated sample has a tritium concentration elevated compared to the background (Figure 2). If this sample would represent the 1963 bomb horizon, the tritium concentration would have to be much higher (>200 TU), and the spike would need to be much broader as the atmospheric nuclear bomb testing occurred over more than a decade; all the samples from above (younger than) the 1963 bomb horizon would need to have a tritium concentration of 10 TU. This is clearly not the case.

Tritium contamination in the laboratory can be excluded; no other sample showed elevated tritium concentrations, and the depth horizon at 31 m was re-sampled later with the similar tritium concentration confirmed.

P. 423 and Figure 2: In the figure caption, you note that the peak in Northern Hemisphere tritium is mid-1963. However, on page 423, you mention that this peak is “during the thermonuclear bomb testing era” which also includes the 1950s. It is essential to be more explicit of the actual years in the paragraph on page 423, as all resulting chronologies are dependent upon this assumption. Also, Figure 2 could be greatly improved if you visually separated the three records.

Answer: We agree and have edited the statement accordingly. Fig. 2 has been modified.

The revised Fig. 2.



Figures 4 and 5: The annual layer counting in this figure is completely based on the Ca^{2+} peaks. While the $d^{18}O$, Cl^- and Fe variations can help support this information, it is not correct to say that they form the annual layer counting. What do the dust records show at the peak at 6 m depth? Is there any evidence of melt and refreezing that causes this large increase in Ca^{2+}, Cl^- and Fe? If so, the dating below 1963 AD may be incorrect. If this dating below 1963 AD is incorrect, then the comparison in Hg records in figure 5 may also be flawed.

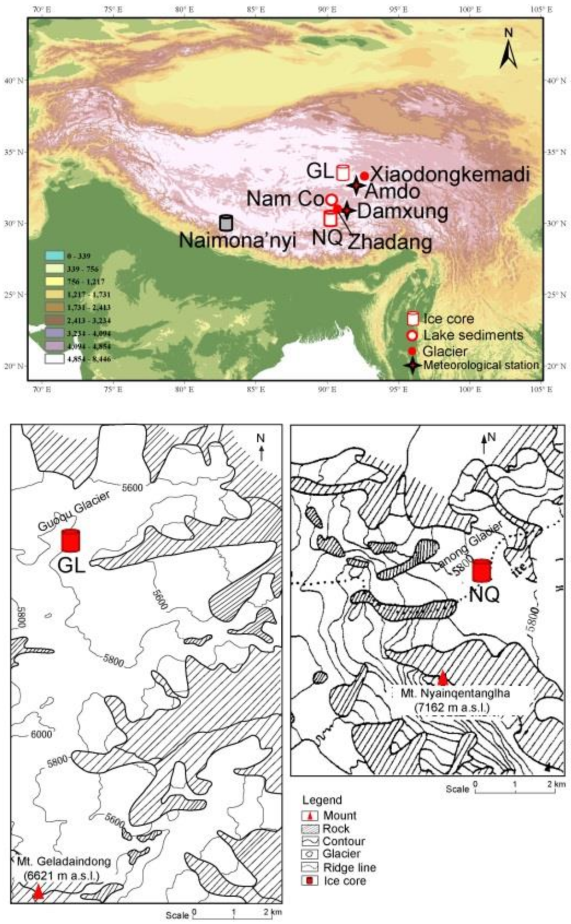
Answer: We agree that there was melting in the summer at the coring site. However, as per our answer to Comment 1 above, we believe the melt water (or percolation) did not disturb the layers deposited in previous years.

Minor points:

Figure 1: The map in the upper panel needs to show much more detail: (ie topographic lines, country borders, cities, etc.) that help the reader place the ice core sites into context. Such details are especially important since the meteorological stations are approximately 2000 meters lower than the ice core sites, as well as the fact that the authors extrapolate in to regional applications in the conclusions section.

Answer: We have revised Figure 1. It is around 950-1500 meters between the ice core sites and the nearby stations.

Reviesed Figure 1



P. 421 Line 1: This sentence contains two separate ideas that are not linked (as they currently are in the paper). Yes, the Tibetan Plateau influences the intensity of the monsoon. The monsoon itself is a reversal of weather patterns, but this reversal happens regardless of the intensity of the monsoon. Perhaps you would like to stay that the increasing the spatial extension of the monsoon may change weather patterns in regions (ie to the north) that are currently not influenced by the monsoon?

Answer: We have corrected the sentence in the manuscript as follows:
"The plateau is also a major forcing factor on the intensity of the Asian monsoons, and mainly influenced by the Indian monsoon during the summer season."

P. 424 Lines 5-10 and Figure 2: All of these assumptions are based on the fact that mercury has an atmospheric lifetime of months. This long lifetime needs to be explicitly stated, so that the reader knows that these assumptions are valid.

Answer: The lifetime of mercury is about 0.5-2 years. We have added this and corresponding reference in the revised text.

P. 425 Lines 25-26: Are these mass losses total mass losses for all glaciers? Or mass loss over a region? Or for a specific glacier?

Answer: It was an averaged mass loss per year over the central Tibetan Plateau (Neckel et al., 2014). In the study, glaciers were grouped into eight compact sub-regions where they assumed climatologically homogeneous conditions. The eight sub-regions are covered relatively well by the ICESat dataset (Neckel et al., 2014).

References:

Neckel, N., Kropacek, 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, doi: 10.1088/1748-9326/9/1/014009, 2014.

427 Lines 6 to 10. This sentence is confusing. In the previous paragraphs you suggest that ice and snow have different surface energy-balance characteristics both from each other and from surrounding non-glaciated terrain, which are both true. However, you need to expressly then mention these aspects if you move into the "possibly larger lapse rate in the glacier regions" argument. Or is the possibly larger lapse rate mentioned in the cited publication?

Answer: The larger lapse rate occurred in the glacier regions when comparing with the global average of 0.6 ℃ $(100\ m)^{-1}$ which was observed by other researchers (Yang et al., 2011). Note that we have revised the DDM section with more detailed info according to the suggestion from reviewer 1.

Miscellaneous:

P. 419 Line 13: Please define the altitude(s) of the summit regions.

Answer: The altitudes of the summit regions are up to about 5800 m a.s.l. We have added this in the revised ms.

P. 419 Line 14: Define "this" at the beginning of the sentence. E.g. "This mass loss"

Answer: We have corrected this.

P. 419 Line 17: Please omit the abbreviation "TP" for "Tibetan Plateau" throughout the paper. You are not limited for space. It is easier and more clear to read sentences without acronyms.

Answer: We have corrected this.

P. 419 Line 24: Define "several percent". 2%? 20%?

Answer: "several percent" is about 4.8%. We have clarified this in the revision.

P. 419 Line 22: Replace "retreating" with "retreat".

Done.

P. 419 Line 24: Include “Tibetan Plateau” after “central”.

Done.

P. 419 Line 26: Include “the” before “last”

Done.

P. 420 Line 13: Add “thinning” after “this”.

Done.

P. 420 Line 16: This is not “Ice accumulation chronology”. The major point is that the ice is not accumulating over timescales of more than the seasonal surface snow. A better phrase could be “timing of ablation”.

Done

P. 420 Line 18: Omit these acronyms from the entire paper. These acronyms only serve to confuse the reader. Your goal is to be as clear as possible, and the acronyms work against you.

Done.

P. 420 Lines 24 and 25: Replace “Climatically the southern and central TP is influenced primarily” with “The southern and central Tibetan Plateau is climatically influenced by”.

Done.

P. 420 Line 27: Omit “respectively”.

Done.

P. 421 Line 5: Change to: “by drilling to the bedrock depth of 124 m”.

Done.

P. 421 Line 17: Change “frozen” to “in a frozen state”.

Done.

P. 421 Line 21: Describe how much of the ice core was scraped away during the decontamination process.

Answer: Approximately 1 cm of the outer sections was scraped away. We have added this in the revision.

P. 421 Line 21: Replace “parts” with “sections”.

Done.

P. 421 Line 24: Place “the” before “outer”.
Done.

P. 421 Line 26: Place “of” before “the samples”.
Done.

P. 422 Line 12: Replace “showed good agreement of differences within 15%” to “agreed within 15% of each other”.
Done.

P. 422 Line 25: Place “bomb” after “thermonuclear”.
Done.

P. 423 Line 7: Place “the” before “central”.
Done.

P. 424 Lines 5-10: All of these assumptions are based on the fact that mercury has an atmospheric lifetime of months. This long lifetime needs to be explicitly stated, so that the reader knows that these assumptions are valid.
Done

P. 424 Line11: Replace “emissions” with “concentrations”.
Done.

P. 424 Line 27: Please replace “experiencing shrinkage” with “retreating”.
Done.

P. 425 Line 3: Please omit “where ice cores were retrieved for reconstructing paleoclimate”.
Done.

P. 425 Line 6: Omit “hoever”.
Done.

P. 425 Lines 9-10. Replace “Suggest that the annual mass losses from upper glacier areas are at least on the order of several hundred millimeter water equivalent (mm w.e.) with “This data suggests that the glaciers have a net loss of at least several hundred millimeters water equivalent (mm w.e.) each year.

Done.

P. 425 Line 24: Please replace “they” with “these authors”.
Done.

P. 425 Line 26: The total mass loss?
Done.

P. 426 Line 4: Please replace “to” with “with”.
Done.

P 426 Line 8: Replace “DDM” with “DDMs”.
Done.

P 426 Line 10: Place “as” before “the”.
Done.

P. 426 Line 16: Replace “station” with “stations”.
Done.

P. 426 Line 25: Replace “the previous works” with “the previous work”.
Done.

P. 426 Line 27: Please replace “ shows a dramatic increasing trend in positive accumulated temperature” with “shows a dramatic positive trend in increasing temperatures”.
Done.

P. 427 Line 3: Replace “glacier mass losing” with “glacier mass loss”.
Done.

P. 427 Line 15: Replace “glacier” with “glaciers”.
Done.

P. 427 Line 16: Replace “northwestern of the TP” with “northwestern section of the Tibetan Plateau”.
Done.

P 428 Line 1: What do you mean by “inland” ? Do you mean the southern section of the Tibetan Plateau?

Done.

P 428 Line 5: Replace “outburst” with “outbursts”.

Done.

Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records

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Abstract

Two ice cores were retrieved from high elevations (~5800 m a.s.l.) at Mt. Nyainqentanglha and Mt. Geladaindong in the southern and central Tibetan Plateau region. The combined tracer analysis of tritium (^3H), ^{210}Pb and mercury, along with other chemical records, provided multiple lines of evidence supporting that the two coring sites had not received net ice accumulation since at least the 1950s and 1980s, respectively. These results implied an annual ice loss rate of more than several hundred millimeter water equivalent over the past 30-60 years. Both mass balance modeling at the sites and in situ data from the nearby glaciers confirmed a continuously negative mass balance (or mass loss) in the region due to the dramatic warming in the last decades. Along with a recent report on Naimona'nyi Glacier in the Himalaya, the findings suggest that the loss of accumulation area of glacier is a possibility from the southern to central Tibetan Plateau at the high elevations probably up to about 5800 m a.s.l. This mass loss raises concerns over the rapid rate of glacier ice loss and associated changes in surface glacier runoff, water availability, and sea levels.

1. Introduction

Data from remote sensing and in situ observations suggest that glacier shrinking has been prevailing over the Tibetan Plateau (including the Himalaya hereafter) in the past decades (e.g., Liu et al., 2006; Kang et al., 2010; Fujita and Nuimura, 2011; Bolch et al., 2012; Kääb et al., 2012; Yao et al., 2012; Neckel et al., 2014), raising major concerns over their impact on water supplies to some 1.4 billion people in Asia (Immerzeel et al., 2010), and on global sea level rise (Jacob et al., 2012; Gardner et al., 2013; Neckel et al., 2014). It has been estimated that glacier retreat has been occurring to more than 82% of the total glaciers in the region (Liu et al., 2006), and thus since the 1970s glacier areas have reduced by several percent (about 4.8%) in the central Tibetan Plateau (Ye et al., 2006) and up to 20% in the northeastern marginal regions of the Tibetan Plateau (Cao et al., 2010; Pan et al., 2012). In situ stake observations have also confirmed a continuously negative mass balance during the last decade in the region (Yao et al., 2012; Zhang et al., 2014). However, quantitative changes in the glacier ice volume, a key parameter for assessing retreating glaciers' impact on water supply or sea level rise, remain poorly known due to the lack of in situ measurements on glacier thickness through time. Although remote sensing techniques have provided some assessments in glacier thickness globally, especially in the last decade, the application of those techniques to the Tibetan Plateau region is rather limited due to complexity of the regional topography (Jacob et al., 2012; Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014).

Based on the lack of distinctive marker horizons of atmospheric thermonuclear bomb testing (e.g., beta radioactivity, ^{36}Cl, and tritium (^{3}H)) in an ice core retrieved from Naimona'nyi (6050 m a.s.l.) in the Himalaya, a recent study suggests that there might not have been a net accumulation of glacier mass at the site since at least the 1950s (Kehrwald et al., 2008). This thinning could be very significant considering that the mass loss occurred at the upper part of the glacier where it is normally considered as the accumulation area (Shi et al., 2005). To test whether such loss of glacier accumulation area is occurring at high elevations over the Tibetan Plateau, here we report the two ice core records taken from high elevations (~5800 m a.s.l.) at Mt. Nyainqentanglha and Mt. Geladaindong in the Tibetan Plateau. In addition to radioisotopes ^{3}H and ^{210}Pb and other geochemical tracers, the depth profile of mercury (Hg) is used as a new marker for the last century based on known atmospheric depositional histories.

2. Methodology

With an average elevation of over 4000 m a.s.l., the Tibetan Plateau is home to the largest volume of glacier ice outside the polar regions (Grinsted, 2013). The Tibetan Plateau blocks mid-latitude Westerlies, splitting the jet into two currents that flow the south and north of the plateau. The plateau is also a major forcing factor on the intensity of the Asian monsoons. The southern and central Tibetan Plateau is climatically influenced primarily by the Indian monsoon during the summer monsoon season and the Westerlies during the non-monsoon season (Bryson, 1986; Tang, 1998).

Two ice cores were retrieved as part of the Sino-US Cooperation Expedition (Fig. 1). The Nyainqentanglha ice core (30°24.59′N, 90°34.29′E, 5850 m a.s.l.), by drilling to the bedrock depth of 124 m, was collected in September of 2003 from the Lanong glacier pass on the eastern saddle of Mt. Nyainqentanglha (peak height: 7162 m a.s.l.) in the southern Tibetan Plateau. The Geladaindong core (33°34.60′N, 91°10.76′E, 5750 m a.s.l.), 147 m in length (did not reach to the bedrock), was collected in October 2005 from the Guoqu glacier on the northern slope of Mt. Geladaindong (peak height: 6621 m a.s.l.), which is the summit of the Tanggula Mts. in the central Tibetan Plateau and the headwater region of the Yangtze river. Elevations of both ice coring sites are higher than the snow line altitudes (close to the equilibrium line altitudes (ELAs)) of around 5700 m a.s.l. in the Mt. Nyainqentanglha region (Shi et al., 2005) and 5570 m. a.s.l. in the Mt. Geladaindong region (Zhang, 1981). However, these ELAs were retrieved from the glacier area data from several decades ago (e.g., data in 1980s and 1970s for the Mt. Nyainqentanglha and Mt. Geladaindong region respectively), and may not reflect present-day ELAs. Snowpits, with a depth of 40 cm and 78 cm at the Nyainqentanglha and Geladaindong coring sites, respectively, were also sampled at a 10-cm depth interval.

The Nyainqentanglha ice core was transported in a frozen state to the Climate Change Institute at the University of Maine, USA, whereas the Geladaindong ice core to the State Key Laboratory of Cryospheric Sciences of the Chinese Academy of Sciences, Lanzhou, China. The cores were sectioned at 3 to 5 cm intervals in a cold (-20 ℃) room, with the outer sections (approximately 1 cm) being scraped off using a pre-cleaned ceramic knife. The inner sections were placed into whirl-pak bags. After being melted at room temperature, the water samples were collected into HDPE vials for subsequent analyses. Ice chips from the outer sections of the cores were collected at an interval of 1 m from the upper 40 m of the cores for the analysis of ^{210}Pb.

All of the samples were measured for $\delta^{18}O$ on a MAT-253 isotope mass spectrometer (±0.1‰ precision) via the standard CO_2 equilibration technique at the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of

Tibetan Plateau Research, Chinese Academy Sciences, Beijing. Soluble major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, Cl^-, and NO_3^-) were measured by ion chromatography (Dionex DX-500), and elemental analysis (e.g., Bi, Fe, Al) was done by inductively coupled plasma sector field mass spectrometry at the Climate Change Institute (Kaspari et al., 2009).

Total Hg concentration was analyzed following U.S. EPA Method 1631 using a Tekran® 2600 at the Ultra-Clean Trace Elements Laboratory at the University of Manitoba, Canada, or Jena® MERCUR in a metal-free Class 100 laminar flow hood placed in a Class 1000 cleanroom laboratory at the Key Laboratory of Tibetan Environment Changes and Land Surface Processes. Field blank samples were collected during each sampling and their Hg concentrations were always lower than 0.3 ng L^{-1}. Certified reference materials ORMS-2 and ORMS-3 (National Research Council of Canada) were used for QA/QC, and the recoveries were within 5% of their certified values. To further ensure the data quality, samples were measured in both labs and agreed within 15% of each other (Loewen et al., 2007; Zhang et al., 2012).

The ^3H was measured by using Quantulus Low-level Liquid Scintillation Counters (Morgenstern and Taylor, 2009) at the Institute of Geological and Nuclear Science, National Isotope Centre, New Zealand. The ^{210}Pb activity was indirectly analyzed by measuring α decay of ^{210}Po at an energy of 5.3 MeV using alpha-spectrometry at Paul Scherrer Institut, Switzerland (Gäggeler et al., 1983).

3. Results and Discussion

3.1. Ice Core Chronology

Some of the most prominent global stratigraphic markers recorded in ice cores over the last century are radionuclides (e.g., ^{3}H) released during nuclear bomb tests (Kotzer et al., 2000; Pinglot et al., 2003; Kehrwald et al., 2008; Van Der Wel et al., 2011). Large amounts of ^{3}H, in increasing amounts, were released into the atmosphere by above-ground thermonuclear bomb tests during 1952-1963 AD, resulting in atmospheric levels several orders of magnitude above natural cosmogenic concentrations (Clark and Fritz, 1997). Remarkably, this global ^{3}H marker is not present in the Nyainqentanglha ice core (Fig. 2). All samples collected from the Nyainqentanglha core had ^{3}H activity below the detection limit of 0.1 TU with the exceptions of two samples, one at the surface (13.4 TU), and the other at a depth of 31 m (29.1 TU). The slightly elevated ^{3}H concentration at 31 m of this core cannot represent the 1963 AD nuclear bomb horizon for several reasons. If this sample would represent the 1963 AD bomb horizon, the ^{3}H concentration would have been much higher (> 200 TU), and there would have been broader ^{3}H spikes in that depth region as the atmospheric nuclear bomb testing occurred over more than a decade. This is clearly not the case (Fig. 2). The absence of anthropogenic ^{3}H markers below surface samples has recently been reported in an ice cores taken from the Naimona'nyi Glacier in the central Himalayas (Kehrwald et al., 2008). Therefore, similar to the Naimona'nyi Glacier, the Nyainqentanglha site might not have received net ice accumulation since at least the 1950s AD.

To further test this hypothesis, we analyzed ^{210}Pb activity in the Nyainqentanglha ice core. Radioactive decay of ^{210}Pb, a product of natural ^{238}U decay series with a half-life of 22.3 yr, has been successfully applied to ice core dating on a century time-scale (Gäggeler et al., 1983; Olivier et al., 2006). The ^{210}Pb activity was 940.5 mBq kg^{-1} at the topmost sampling layer at a depth of 0-0.9 m; however, it decreased sharply to near the background level (7.6 mBq kg^{-1}) in the next sampling layer at 5.6 m depth (Fig. 3a). High ^{210}Pb activity in the upper layer indicates enrichment due to the negative mass balance. Based on the extremely low ^{3}H and ^{210}Pb activities immediately beneath the surface layer, we conclude that there has been no net ice accumulation at the Nyainqentanglha site since at least 1950s AD.

In contrast, the Geladaindong ice core exhibited a classic ^{3}H profile, with a sharp spike of up to 680 TU at a depth of 5.22-6.23 m (Fig. 2), suggesting that the ice accumulated at this site during the 1963 AD thermonuclear bomb testing era is still present. We assign the 5.74 m depth, which shows the highest ^{3}H level, to the year 1963 AD when above-ground nuclear tests peaked just prior to the Nuclear Test Ban Treaty (Van Der Wel et al., 2011). Based on this ^{3}H bomb test horizon, we establish the chronology of the Geladaindong ice core by counting annual layers according to the seasonal cycles of δ^{18}O, major ions, and elemental concentrations upward to the top of the core (Fig. 4). The uppermost ice layer is designated as 1982 AD based on annual layer counting above the 1963 AD ^{3}H marker, and is further constrained by ^{210}Pb estimation of 1982 ±5 years for the surface of the core (Fig. 3b).

The Geladaindong ice core dating by counting annual layers is in agreement with previous work in the region. Based on snowpit records in the Guoqu glacier, Mt.

Geladaindong, Zhang et al. (2007) reported that Ca^{2+} and other major ions in snowpits varied seasonally with higher values during the winter half year. At our coring site, there were firn layers (snowpit) with a depth of 78 cm. The bottom of the snowpit was glacier superimposed ice, indicating one year transferring from snow to ice. Thus, melt could happen during the summer but seasonal signals were still preserved in ice layers. In other words, the melt water (or percolation) should not disturb the layers deposited in previous years as suggested in other studies (Namazawa and Fujita, 2006; Eichler et al., 2001).

One assumption in dating by counting annual layers backwards from the 1963 AD nuclear bomb horizon to 1982 AD is that there was annual net ice accumulation during this period. Uncertainties in the chronology will thus rise should there be no net accumulation in one or some of the years due to ice melt. This does not appear to be the case for the Geladaindong ice core, as the annual variation patterns and amplitudes in the main ion concentrations were similar upward and downward from the 1963 AD layer, suggesting no occurrence of strong melt (Fig. 4). Furthermore, the air temperatures were much lower before 1980s than those in the last three decades according to the data observed from the nearby meteorological stations such as Amdo. Indeed, the continuously deficit mass balance (cumulative negative mass balance) has only been reported since the 1990s in the central Tibetan Plateau (e.g., Xiaodongkemadi glacier, near to the Geladaindong region; Yao et al. 2012), as well as in the northern neighboring region (e.g., Glacier No. 1, Tienshan Mts.; Zhang and others, 2014), due to dramatic warming in recent decades. Therefore, we might suggest that the mass loss of the coring site occurred mainly from the 1990s in the central Tibetan Plateau.

To further investigate whether the lack of net ice accumulation at the Geladaindong site occurred since the 1980s, we examined the profile of Hg in the ice core. Although naturally occurring in the Earth's crust, Hg emission (especially the gaseous elemental mercury) into the atmosphere has been greatly enhanced coinciding with the rise in anthropogenic activities (e.g., mining, burning of fossil fuels). Mercury has a lifetime of approximately 0.5-2 years (Holmes et al. 2010) and can be transported globally via atmospheric circulation. Hg profiles in ice cores from high (Faïn, et al. 2008) and mid-latitude (Schuster et al., 2002) regions have matched the general chronological trends of global atmospheric Hg emissions or global industrial Hg use. As atmospheric transport is essentially the only transport pathway for anthropogenic Hg to the Tibetan Plateau, due to the region's high altitudes and minimal to nonexistent local industrial activities (Loewen et al., 2007), ice cores from the region could provide a useful indicator for atmospheric Hg concentrations, as demonstrated by Hg profiles in snowpacks overlying the glaciers across the plateau (Loewen et al., 2007; Zhang et al., 2012).

As shown in Fig. 5, the Hg profile in the Geladaindong ice core, with the upper-most layer dated to around 1982 AD, matches the atmospheric Hg depositional chronology established from sediment records in Nam Co (Li, 2011), a large alpine lake (4710 m a.s.l.) on the Tibetan Plateau, as well as the history of regional and global Hg production (Hylander and Goodsite, 2006), showing low and stable background levels prior to ~1850 AD, with a steady concentration increase from the mid-20th century to the 1980s.

Beyond the 1980s, the Nam Co sediment record shows a decline in Hg concentrations, which matches the global and regional emission trends. Such declining trends are absent in the Geladaindong ice core, supporting that this site has not received net ice accumulation since the 1980s. There are some secondary timing differences of the Hg trend between the lake sediment and the ice core (e.g., during the 1970s), which might be attributed to the lower resolution of the lake sediment record (about 5 yrs) compared to that of the ice core record (1 yr).

The lack of recent deposition of mass (ice) at the Nyainqentanglha and Geladaindong glaciers, as well as at the Naimona'nyi glacier (Kehrwald et al., 2008), suggests that the melting and/or loss of the accumulation area of glacier occurred in at least these three ice coring regions of the Tibetan Plateau. Although there is a consensus that glaciers in the Tibetan Plateau are largely retreating (Yao et al., 2004, 2012; Bolch et al., 2012; Neckel et al., 2014), ^{3}H and Hg records reported herein provide direct evidence of dramatic thinning occurring at the upper regions of glaciers (probably up to about 5800 m a.s.l.) that had traditionally been considered as net accumulation areas (Zhang et al., 1981; Shi et al., 2005).

3.2. Observed and Modeled Mass Balance

Due to a lack of precipitation data at the coring sites, we cannot directly quantify the annual ice loss in these high-altitude glaciers. The annual precipitation data from local lower elevation meteorological stations are 444 mm at Damxung (50 km southeast of Nyainqentanglha but at an elevation of 4300 m a.s.l.) and 467 mm at Amdo (120 km south of Geladaindong but at an elevation of 4800 m a.s.l.) (Fig. 1). These data suggest that the glaciers have experienced a net loss of at least several hundred millimeters each year (mm w.e. yr^{-1}). The estimate is considered as the lower limit as glacier areas in high mountainous regions generally receive more precipitation (accumulation) than at lower elevation stations (Shen and Liang, 2004; Wang et al., 2009; Liu et al., 2011). Although no observational data are available for the central Tibetan Plateau region, precipitation has been shown to increase 0.87 to 11 mm with every 100 m increase in elevation in the neighboring Qilian and Tienshan Mts. (Liu et al., 2011).

In situ observational data using mass balance stakes close to our coring sites are available only for a short time period in the recent past (Kang et al., 2009; Yao et al., 2012; Qu et al., 2014). Mass balance measurements of Xiaodongkemadi glacier (80 km south of Mt. Geladaindong, Fig. 1), started in 1989, showed slightly positive mass accumulation until the mid-1990s, then changed to a net mass loss over time (Yao et al., 2012) (Fig. 6). During the period 1995-2010 AD, the cumulative mass loss reached 5000 mm with an annual mass loss rate of about 300 mm w.e. A much higher mass loss rate was observed in situ at Zhadang glacier (5 km east of the Mt. Nyainqentanglha, Fig. 1) in the southern Tibetan Plateau; over the period 2005-2011 AD mass loss rate at this glacier averaged approximately at1200 mm w.e. yr^{-1} (Qu et al., 2014). More recently, Neckel et al. (2014) reported the glacier mass changes during 2003-2009 AD for the eight sub-regions in the Tibetan Plateau using ICESat laser altimetry measurements. These authors estimated that a regional average mass balance of -580 $\pm$ 310 mm w.e. yr^{-1} was observed in the central Tibetan Plateau sub-region covering the

Geladaindong coring site. The mass balance of glaciers varies due to different measurements and time periods. Over the entire Tibetan Plateau, in situ observed glacier mass balances ranged from -400 mm w.e. yr^{-1} to -1100 mm w.e. yr^{-1} during the last decade with an exception of slight mass gain in the northwestern of the Tibetan Plateau (e.g. western Kunlun Mts. and Karakoram regions) (Yao et al., 2012; Bolch et al., 2012; Gardelle et al., 2012; Neckel et al., 2014). The clear deficit mass balances of Zhadang and Xiaodongkemadi glaciers are consistent with our findings from the two ice core records.

In order to further assess whether the intensive melting could happen in the high elevations of the coring sites, a degree-day model (DDMs) was applied to estimate glacier melt at the two ice core sites. DDMs can determine the daily quantity of snow/ice melt (m_t, mm w.e.) as a function of the mean daily air temperature (Tt, ℃) using a factor of proportionality referred to the degree-day factor (DDF, mm ℃$^{-1}$ d^{-1}) (Gardner and Sharp, 2009).

$$\mathrm{m}_t = \mathrm{DDF} \times \mathrm{T}_t \qquad \mathrm{T_t} \geq 0$$

$$\mathrm{m}_t = 0 \qquad \mathrm{T}_t < 0$$

To detect the net mass balance at the Nyainqentanglha and Geladaindong coring sites by DDMs, we selected daily temperature and precipitation data from the two meteorological stations, Damxung and Amdo, which are the nearest stations to the Nyainqentanglha and Geladaindong sites (Fig. 1), respectively. Daily temperature and positive cumulative temperature at the two sites were calculated based on the minimum (0.5 ℃/100 m) and maximum (0.72 ℃/100 m) temperature lapse rate reported by Li and Xie (2006) and Yang et al.(2011), respectively, for the Tibetan Plateau (Tables 1 and 2, Fig. 7). The medium value was set as the global average of 0.6 ℃/100 m. The accumulation rate at each coring site was considered the same as the precipitation amount at the stations nearby, although more precipitation is likely to occur at the higher elevations as discussed before. Due to the differences in the surface energy-balance characteristics of snow and ice (including albedo, shortwave penetration, thermal conductivity and surface roughness), reported DDFs vary greatly among regions and times. Based on previous work in the southern and central Tibetan Plateau (Wu et al., 2010; Zhang et al., 2006), we selected DDF values of 3.0 (minimum for snow), 5.3 (medium for snow), 9.2 (medium for ice) and 14 (maximum for ice) mm ℃$^{-1}$ d^{-1}, respectively (Tables 1 and 2).

As shown in Fig. 7, there is a statistically significant ($p<0.01$) increase trend in annual positive cumulative temperatures at the Geladaindong ($r=0.5$) and Nyainqentanglha ($r=0.6$) coring sites during 1966-2013 AD, but not in precipitation. DDM modeling shows clear decrease trends in the cumulative net mass balance at both sites under most of the scenarios except when the maximum of temperature lapse rate and the minimum DDF were applied (Fig. 7). The calculated averaged annual net mass balance (medium) during 1966-2013 AD was -925±576 mm w.e. yr^{-1} (range from 132 ±157 to -3441±944 mm w.e. yr^{-1}) at the Geladaindong coring site (Table 1) and -671 ±538 mm w.e. yr^{-1} (range from 336±150 to -3912±992 mm w.e. yr^{-1}) at the Nyaingentanglha site (Table 2). Since there is likely more precipitation (Shen and Liang, 2004) in the glacier regions, the actual mass loss rates at the two sites might be slightly less than these estimated values. Nevertheless, the mostly deficit mass balances suggest that mass loss most likely occurred at both coring sites during the last decades, which is consistent with the two ice core records. Furthermore, in situ observed mass balance of the central Tibetan Plateau (e.g., the Xiaodongkemadi glacier) shows a continuous deficit mass balance (or cumulative negative mass balance) since the 1990s (Fig. 6) (Yao et al., 2012), which agrees with a dramatic warming as shown in Fig.7 (positive cumulative temperature) in the same period.

4. Conclusion

Meteorological data suggest dramatic warming has occurred in the Tibetan Plateau since the late 1980s and that the magnitude of warming is much greater than that in the low-elevation regions (Kang et al., 2010). This warming has resulted in a continuous negative mass balance (or mass loss) of glaciers during the last decade ranging from Himalayas to the north of the Tibetan Plateau except for the northwestern Tibetan Plateau (e.g., Yao et al., 2012; Bolch et al., 2012; Gardelle et al., 2012; Neckel et al., 2014). In recent years, the altitude of the equilibrium line for some of the observed glaciers has risen beyond the highest elevations of the glaciers; that is, there is no more net accumulation area and subsequently the entire glacier is becoming ablation area (Yao et al., 2012). Although glacier mass balance varies depending on climate change and geographical conditions as shown on the Tibetan Plateau (e.g. Yao et al., 2012; Bolch et al., 2012), our ^3H and Hg ice core records confirm that the upper glacier areas (e.g. about 5750-6000 m a.s.l.) are rapidly transforming into ablation areas in recent decades. In particular, extensive ablation has caused substantial mass loss of the Nyainqentanglha and Geladaindong glaciers since at least the 1950s in the southern part and the 1980s in the central part of the Tibetan Plateau, respectively.

We suggest that the glaciers on the southern to the central Tibetan Plateau might be melting faster than previous data show (Liu et al., 2006; Jacob et al., 2012; Gardner et al., 2013). Ice losses on such a large scale and at such a fast rate could have substantial impacts on regional hydrology and water availability (Immerzeel et al., 2010), as well as causing possible floods due to glacier lake outbursts (Richardson and Reynolds, 2000; Zhang et al., 2009). Further, the loss of glacier accumulation area warns us that recent climatic and environmental information archived in the ice cores is threatened and rapidly disappearing in the mid and low latitudes. As such, there is an urgent need to collect and study these valuable ice core records before they are gone forever.

Author Contributions. S. Kang was the lead scientist of the entire project and F. Wang was the principal investigator of the mercury sub-project. S. Kang and F. Wang wrote the first draft of the manuscript, with inputs from all other co-authors. U. Morgenstern did the tritium measurement and interpretation. M. Schwikowski did the ^{210}Pb measurement and interpretation. Y. Zhang, B. Grigholm, S. Kaspari and S. Kang did the major ions, elements, and stable oxygen isotope measurements and analyzed the data. J. Ren, T. Yao, D. Qin and P.A. Mayewski conceived and designed the experiments.

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References

Bolch, T., Kulkarni, A., Kääb, A., Hugge, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The state and fate of Himalayan glaciers, Science, 336, 310-314, 2012.

Bryson, R.: Airstream climatology of Asia, in Proceedings of International Symposium on the Qinghai-Xizang Plateau and Mountain Meteorology, American Meteorological Society, Boston., pp604-617, 1986.

Cao, B., Pan, B., Gao, H., Jiang, S., Wen, Y., and Shangguan, D.: Glacier variation in the Lenglongling Range of eastern Qilian Mountains from 1972 to 2007, J. Glaciol. Geocryol., 32, 242-248, 2010.

Clark, I. D. and Fritz, P.: Environmental Isotopes in Hydrogeology, Lewis, New York, 1997.

Eichler, A., Schwikowski, M., Gäggeler, H.: Meltwater-induced relocation of chemical species in Alpine firn, Tellus B, 53 (2), 192-203, 2001. (DOI: 10.1034/j.1600-0889.2001.d01-15.x)

Faïn, X., Ferrari, C. P., Dommergue, A., Albert, M., Battle, M., Arnaud, L., Barnola, J. M., Cairns, W., Barbante, C., and Boutron, C.: Mercury in the snow and firn at Summit Station, Central Greenland, and implications for the study of past atmospheric mercury levels, Atmos. Chem. Phys., 8, 3441-3457, 2008.

Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, Proc. Natl. Acad. Sci. USA, 108(34),14011-14014, 2011.

Gäggeler, H., von Gunten, H. R., Rossler, E., Oeschger, H., and Schotterer, U.: ^{210}Pb-dating of cold Alpine firn/ice cores from Colle Gnifetti, Switzerland, J. Glaciol., 29, 165-177, 1983.

Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early twenty-first century, Nat. Geosci., 5, 322-325, 2012.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., and Paul, F.: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009, Science, 340, 852-857, 2013.

Gardner, A. S. and Sharp, M.: Sensitivity of net mass-balance estimates to near-surface temperature lapse rates when employing the degree-day method to estimate glacier melt, Ann. Glaciol., 50(50), 80-86, 2009.

Grinsted, A.: An estimate of global glacier volume, Cryosphere, 7, 141-151, 2013.

Holmes, C. D., Jacob, D. J., Corbitt, E. S., Mao, J., Yang, X., Talbot, R., and Slemr, F.: Global atmospheric model for mercury including oxidation by bromine atoms. Atmos. Chem. Phys., 10, 12037-12057, 2010

Hylander, L. D. and Goodsite, M. E.: Environmental costs of mercury pollution, Sci. Total. Environ., 368, 352-370, 2006.

Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate change will affect the Asian water towers, Science, 328, 1382-1385, 2010.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 336, 310-314, 2012.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488, 495-498, 2012.

Kang, S., Chen, F., Gao, T., Zhang, Y., Yang, W., Yu, W., and Yao T.: Early onset of rainy season suppresses glacier melt: A case study on the Zhadang Glacier, Tibetan Plateau, J. Glaciol., 192(55): 755-758, 2009.

Kang, S., Xu, Y., You, Q., Flügel, W., Pepin, N., and Yao, T.: Review of climate and cryospheric change in the Tibetan Plateau, Environ. Res. Lett., 5, 015101, doi:10.1088/1748-9326/5/1/015101, 2010.

Kaspari, S., Mayewski, P. A., Handley, M., Osterberg, E., Kang, S., Sneed, S., Hou, S., and Qin, D.: Recent increases in atmospheric concentrations of Bi, U, Cs, S and Ca from a 350-year Mount Everest ice core record, J. Geophys. Res., 114, D04302, doi: 10.1029/2008JD011088, 2009.

Kehrwald, N. M., Thompson, L. G., Yao, T., Mosley-Thompson, E., Schotterer, U., Alfimov, V., Beer, J., Eikenberg, J., and Davis, M. E.: Mass loss on Himalayan glacier endangers water resources, Geophys. Res. Lett., 35, L22503, doi:10.1029/2008GL035556, 2008.

Kotzer, T. G., Kudo, A., Zheng, J., and Workman, W.: Natural and anthropogenic levels of tritium in a Canadian Arctic ice core, Agassiz Ice Cap, Ellesmere Island, and comparison with other radionuclides, J. Glaciol., 46, 35-40, 2000.

Li, Q.: Environmental changes retrieved from lake sediments across the Himalayas, Post-Doc. Report, Institute of Tibetan Research, Chinese Academy of Science, Beijing, 2011.

Li, Q. and Xie, Z.: Analyses on the characteristics of the vertical lapse rates of temperature- taking Tibetan Plateau and its adjacent area as an example, J. Shihezi University (Natural Sci.), 24(6), 719-723, 2006.

Liu, S., Ding, Y., Li, J., Shangguan, D., and Zhang, Y.: Glaciers in response to recent climate warming in western China, Quat. Sci., 26, 762-771, 2006.

Liu, J., Chen, R., Qin, W., and Yang, Y.: Study on the vertical distribution of precipitation in mountainous regions using TRMM data, Adv. Water Sci., 22(4), 447-454, 2011.

Loewen, M., Kang, S., Armstrong, D., Zhang, Q., Tomy, G., and Wang, F..: Atmospheric transport of mercury to the Tibetan Plateau, Environ. Sci. Technol., 41, 7632-7638, 2007.

Morgenstern, U. and Taylor, C. B.: Ultra low-level tritium measurement using electrolytic enrichment and LSC, Isotopes Environ. Health Studies, 45, 96-117, 2009.

Nakazawa, F. and Fujita, K.: Use of ice cores from glaciers with melting for reconstructing mean summer temperature variations, Ann. Glaciol., 43, 167-171, 2006.

Neckel, N., Kropacek, 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, doi: 10.1088/1748-9326/9/1/014009, 2014.

Olivier, S., Blaser, C., Brutsch, S., Frolova, N., Gaggeler, H. W., Henderson, K. A., Palmer, A. S., Papina, T., and Schwikowski, M.: Temporal variations of mineral dust, biogenic tracers, and anthropogenic species during the past two centuries from Belukha ice core, Siberian Altai, J. Geophys. Res., 111, D05309, doi: 10.1029/2005JD005830, 2006.

Pan, B., Zhang, G., Wang, J., Cao, B., Geng, H., Wang, J., Zhang, C., and Ji, Y.: Glacier changes from 1966-2009 in the Gongga Mountains, on the south-eastern margin of the Qinghai-Tibetan Plateau and their climatic forcing, Cryosphere, 6, 1087-1101, 2012.

Pinglot, J. F., Vaikmae, R. A., Kamiyama, K., Igarashi, M., Fritzsche, D., Wilhelms, F., Koerner, R., Henderson, L., Isaksson, E., Winther, J.-G., Van de Wal, R. S. W., Fournier, M., Bouisset, P., and

Meijer, H. A. J.: Ice cores from Arctic sub-polar glaciers: chronology and post-depositional processes deduced from radioactivity measurements, J. Glaciol., 49, 149-158, 2003.

Qu, B., Ming, J., Kang, S., Zhang, G., Li, Y., Li, C., Zhao, S., Ji, Z. M., and Cao, J.: The decreasing albedo of Zhadang glacier on western Nyainqentanglha and the role of light-absorbing impurities, Atmos. Chem. Phys., 14, 11117-11128, 2014.

Richardson, S. D. and Reynolds, J. M.: An overview of glacial hazards in the Himalayas, Quat. Int., 65, 31-47, 2000.

Schuster, P. F., Krabbenhoft, D. P., Naftz, D. L., Cecil, L. D., Olson, M. L., Dewild, J. F., Susong, D. D., Green, J. R., and Abbott, M. L.: Atmospheric mercury deposition during the last 270 years: a glacial ice core record of natural and anthropogenic sources, Environ. Sci. Technol., 36(11), 2303-2310, 2002.

Shen, Y. and Liang, H.: High precipitation in glacial region of high mountains in High Asia: Possible cause, J. Glaciol. Geocryol., 26, 806-809, 2004.

Shi, Y, Liu, C., and Wang, Z.: Brief Glacier Inventory in China, Shanghai Popular Science Press, Shanghai, 2005.

Tang, M.: Formation, evolution and variability characteristics of Qinghai-Tibetan Plateau Monsoon, in Contemporary climatic variations over Qinghai-Tibetan Plateau and their influences on environments, edited by M. Tang, G. Chen, and Z. Lin, pp. 161-182, Guangdong Sciences and Technology Press, Guangzhou, 1998.

Van Der Wel, L. G., Streurman, H. J., Isaksson, E., Helsen, M. M., Van De Wal, R. S. W., Martma, T., Pohjola, V. A., Moore, J. C., and Meijer, H. A. J.: Using high-resolution tritium profiles to quantify the effects of melt on two Spitsbergen ice cores, J. Glaciol., 57(206), 1087-1097, 2011.

Wang, N., He, J., Jiang, X., Song, G., Pu, J., Wu, X., and Chen, L.: Study on the zone of maximum precipitation in the north slopes of the central Qilian mountains, J. Glaciol. Geocryol., 31, 395-403, 2009.

Wu, Q., Kang, S., Gao, T., and Zhang, Y.: The characteristics of the positive degree-day factors of the Zhadang Glacier on the Nyainqêngtanglha Range of Tibetan Plateau, and its application, J. Glaciol. Geocryol., 32(5), 891-897, 2010. (in Chinese with English abstract)

Yang, X., Zhang, T., Qin, D., Kang, S., and Qin, X.: Characteristics and changes in Air Temperature and Glacier's Response on the North Slope of Mt. Qomolangma (Mt. Everest), Arct. Antarct. Alpine Res., 43(1), 147-160, 2011.

Yao, T., Thompson, L. G., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang., 2, 663-667, 2012.

Ye, Q., Kang, S., Chen, F., and Wang, J.: Monitoring glacier variations on Geladandong mountain, central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies, J. Glaciol., 52, 537-545, 2006.

Zhang, D., Xiao, C., and Qin, D.: Himalayan glaciers fluctuation over the latest decades and its impact on water resources, J. Glaciol. Geocryol., 31, 885-895, 2009.

Zhang, G., Li, Z., Wang, W., and Wang W.: Rapid decrease of observed mass balance in the Urumqi glacierNo.1 Tianshan Mountians, central Asia, Quatern. Int., 349, 135-141, 2014.

Zhang, L.: Glaciers at the source region of Tuotuo River in the upper reaches of the Changjiang (Tangtze River) and their evolution, J. Glaciol. Geocryol., 3(1), 1-9, 1981.

Zhang, Q., Huang, J., Wang, F., Mark, L., Xu, J., Armstrong, D., Li, C., Zhang, Y., and Kang, S.:

Mercury distribution and deposition in glacier snow over Western China, Environ. Sci. Technol., 46, 5404-5413, 2012.

Zhang, Y., Liu, S., and Ding, Y.: Spatial variation of degree-day factors on the observed glaciers in western China, Acta Geographica Sinica, 61(1), 89-98, 2006.

Zhang, Y., Kang, S., Zhang, Q., Cong, Z., and Zhang, Y.: Snow/ice records on Mt. Geladaindong in the central Tibetan Plateau, J. Glaciol. Geocryol., 29(5), 685-693, 2007. (In Chinese with English abstract)

Tables

Table 1 Calculated annual net mass balance (mm w.e. yr^{-1}) during 1966-2013 AD based on various degree-day factor (DDF) values (mm ℃$^{-1}$ d^{-1}) and temperature lapse rates (℃/100 m) at the Geladaindong ice core site. Negative values represent deficit mass balances.

Table 2 Calculated annual net mass balance (mm w.e. yr^{-1}) during 1966-2013 AD based on various degree-day factor (DDF) values (mm ℃$^{-1}$ d^{-1}) and temperature lapse rates (℃/100 m) at the Nyainqentanglha ice core site. Negative values represent deficit mass balances.

Table 1

Temperature lapse rate \ DDF[a, b]	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Minimum (Tr1)[c] 0.5	-386 ±220	-1025 ±369 -2108 ±625	-3441 ±944
Medium (Tr2) 0.6	-121 ±192	-925 ±576	-2203 ±811
Maximum (Tr3)[d] 0.72	132 ±157	-109 ±247 -518 ±408	-1021 ±610

a: Wu et al., 2010; b: Zhang et al., 2006; c: Li and Xie, 2006; d: Yang et al., 2011.

Table 2

Temperature lapse rate \ DDF[a, b]	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Minimum (Tr1)[c] 0.5	-469 ±249	-1189 ±400 -2410 ±663	-3912 ±992
Medium (Tr2) 0.6	-2.57 ±212	-671 ±538	-1733 ±791
Maximum (Tr3)[d] 0.72	336 ±150	234 ±207 60.4 ±313	-153 ±450

a: Wu et al., 2010; b: Zhang et al., 2006; c: Li and Xie, 2006; d: Yang et al., 2011.

Figure Captions

Figure 1. Location map of the glacier ice cores Geladiandong (GL) and Nyainqengtanglha (NQ) on the Tibetan Plateau. Also shown are the locations of the Naimona'nyi ice core by Kehrwald et al. (2008), Xiaodongkemadi glacier, Zhadang glacier, the meteorological stations and Lake Nam Co.

Figure 2. The tritium profiles of the Geladiandong and Nyainqengtanglha ice cores compared with tritium in the Northern Hemispheric precipitation. Error bars for the ice core samples are shown, but in most cases are only about half of the symbol size. To enable direct comparison, both the Geladaindong and precipitation tritium records are decay-corrected to the date of Geladaindong ice core drilling (October 2005). The record of tritium in precipitation (upper axis) shows the Ottawa precipitation record (International Atomic Energy Agency, 2013, WISER database: http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis. html) between 1982 and 1953. Tritium from before 1953 has now decayed to zero. The time of the Northern Hemispheric precipitation record is scaled to match the maximum tritium concentration in the ice core to mid-1963, and to start with 1982 (date of the surface ice, see text). To match the tritium concentrations in the Geladaindong ice core, the Ottawa precipitation record had to be multiplied by a factor of two. This indicates that the tritium concentration on the Tibetan Plateau is about twice of that of Ottawa, due to a more direct input of stratospheric air, which is the main

atmospheric tritium reservoir.

Figure 3. (a) ^{210}Pb activity profiles of the Geladaindong (GL) and Nyainqentanglha (NQ) ice cores; (b) ^{210}Pb activity versus depth for the GL core. The age-depth relationship was derived from an exponential regression of ^{210}Pb activity against depth. The uppermost two samples (open diamonds) were excluded (enrichment due to melt). This age-depth relation was anchored using the known age and depth of the tritium horizon. Extrapolation of the age fit to the surface allows estimating the surface age (green star). Error bars and the fine grey lines indicate the 1 sigma uncertainty of the given ages.

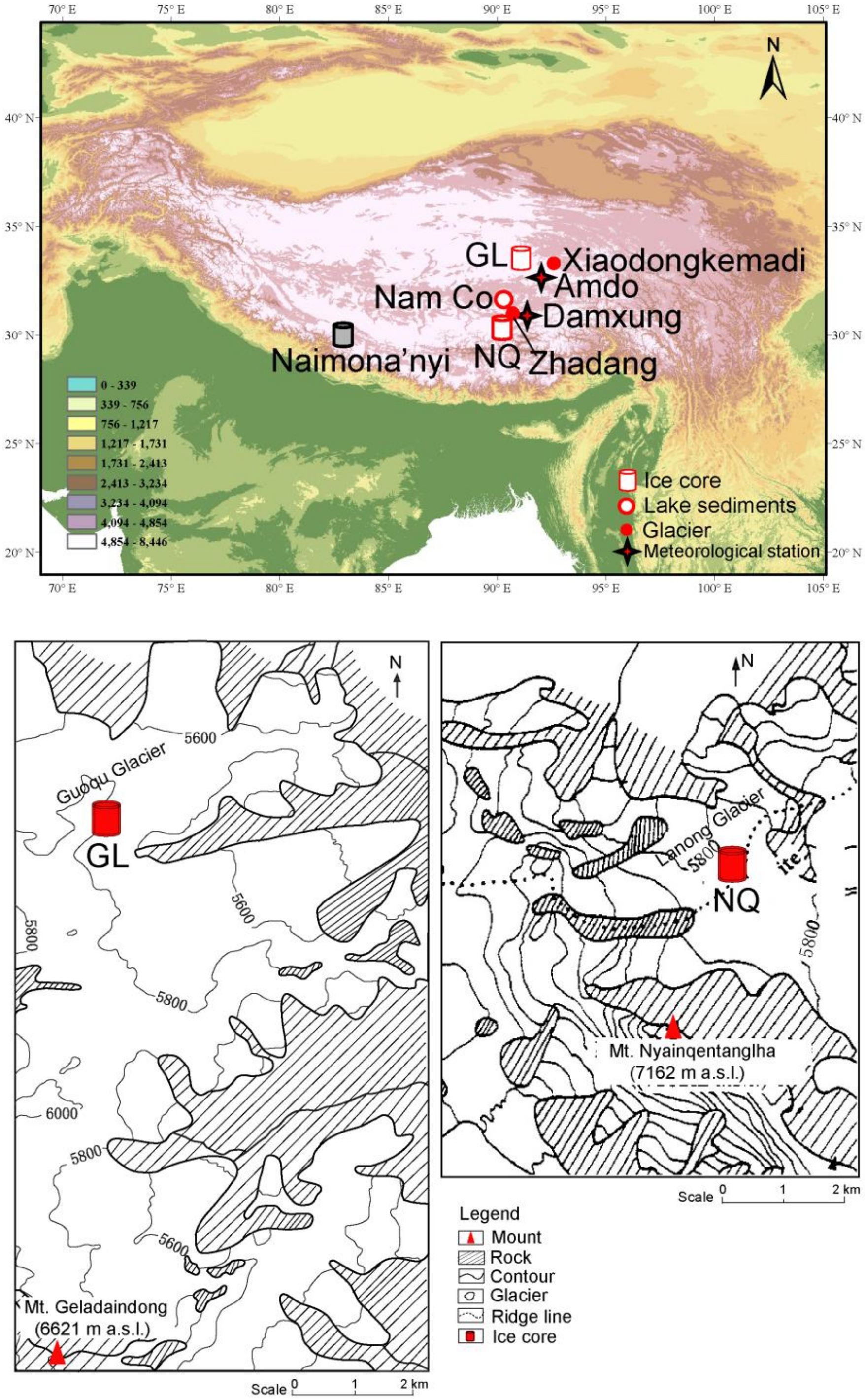
Figure 4. Dating of the Geladaindong ice core by annual layer counting based on the seasonal cycles of $\delta^{18}O$, Ca^{2+}, Cl^- and Fe according to the anchor of 1963 tritium peak (red star) (dashed lines represent the annual boundaries).

Figure 5. Comparisons of Hg records from the Geladaindong (GL) ice cores with those from Lake Nam Co sediments (Li, 2011), as well as with known history of the regional (Asia and USSR) and global Hg production (Hylander and Goodsite, 2006).

Figure 6. In situ observed annual and cumulative mass balance for the Xiaodongkemadi glacier in the Tanggula Mts. (Yao et al., 2012) and the Zhadang glacier in the Nyainqengtanglha Mts. (Qu et al., 2014).

Figure 7. Variations of annual positive cumulative temperature at the Nyainqentanglha and Geladaindong ice core sites, annual precipitation amount at Damxung and Amdo station, and the estimated cumulative net mass balance based on a degree-day model (DDM) at the two ice core sites during 1966-2013 AD. (Tr1, Tr2 and Tr3 as listed in Tables 1 and 2; dashed lines represent the average of the annual positive cumulative temperature before and after 1990 AD).

Figure 1



70° E
75° E
80° E
85° E
90° E
95° E
100° E
105° E
40° N
35° N
30° N
25° N
20° N
N
GL
Xiaodongkemadi
Amdo
Nam Co
Damxung
Naimona'nyi
NQ
Zhadang
0 - 339
339 - 756
756 - 1,217
1,217 - 1,731
1,731 - 2,413
2,413 - 3,234
3,234 - 4,094
4,094 - 4,854
4,854 - 8,446
Ice core
Lake sediments
Glacier
Meteorological station
Guoqu Glacier
GL
5600
5800
6000
Mt. Geladaindong
(6621 m a.s.l.)
Scale 0 1 2 km
Lanong Glacier
NQ
Mt. Nyainqentanglha
(7162 m a.s.l.)
Legend
Mount
Rock
Contour
Glacier
Ridge line
Ice core

Figure 2

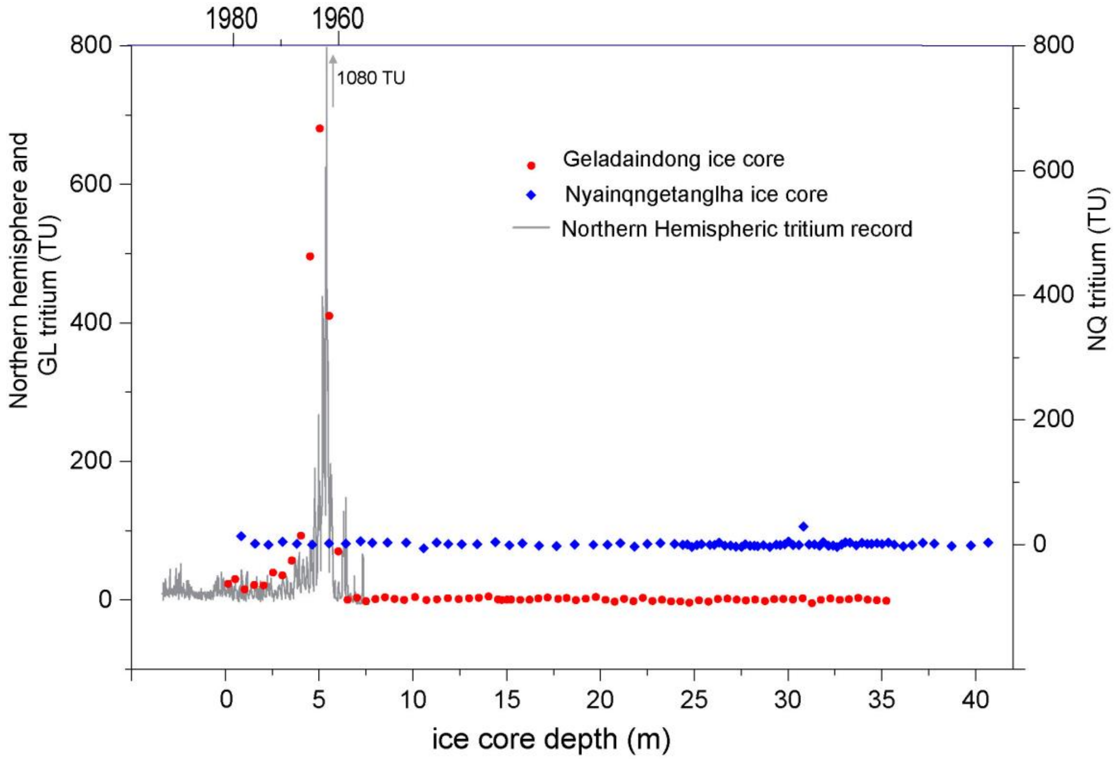
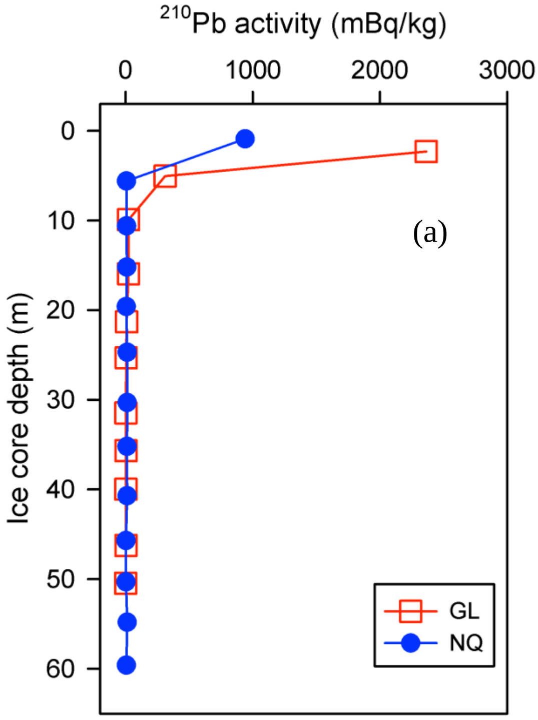
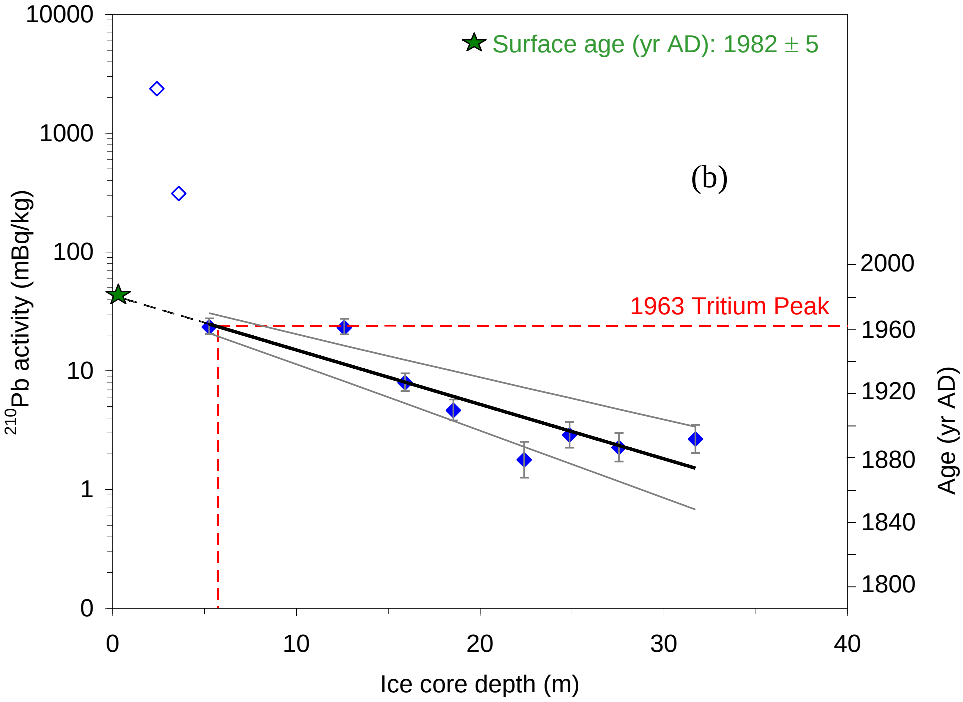

1980
1960
1080 TU
Geladaindong ice core
Nyainqngetanglha ice core
Northern Hemispheric tritium record
Northern hemisphere and GL tritium (TU)
NQ tritium (TU)
ice core depth (m)
800
600
400
200
0
0
5
10
15
20
25
30
35
40

Figure 3



^{210}Pb activity (mBq/kg)
0
1000
2000
3000
0
10
20
30
40
50
60
Ice core depth (m)
(a)
GL
NQ



10000
1000
100
10
1
0
Surface age (yr AD): 1982 ± 5
(b)
1963 Tritium Peak
2000
1960
1920
1880
1840
1800
Age (yr AD)
^{210}Pb activity (mBq/kg)
0
10
20
30
40
Ice core depth (m)

Figure 4

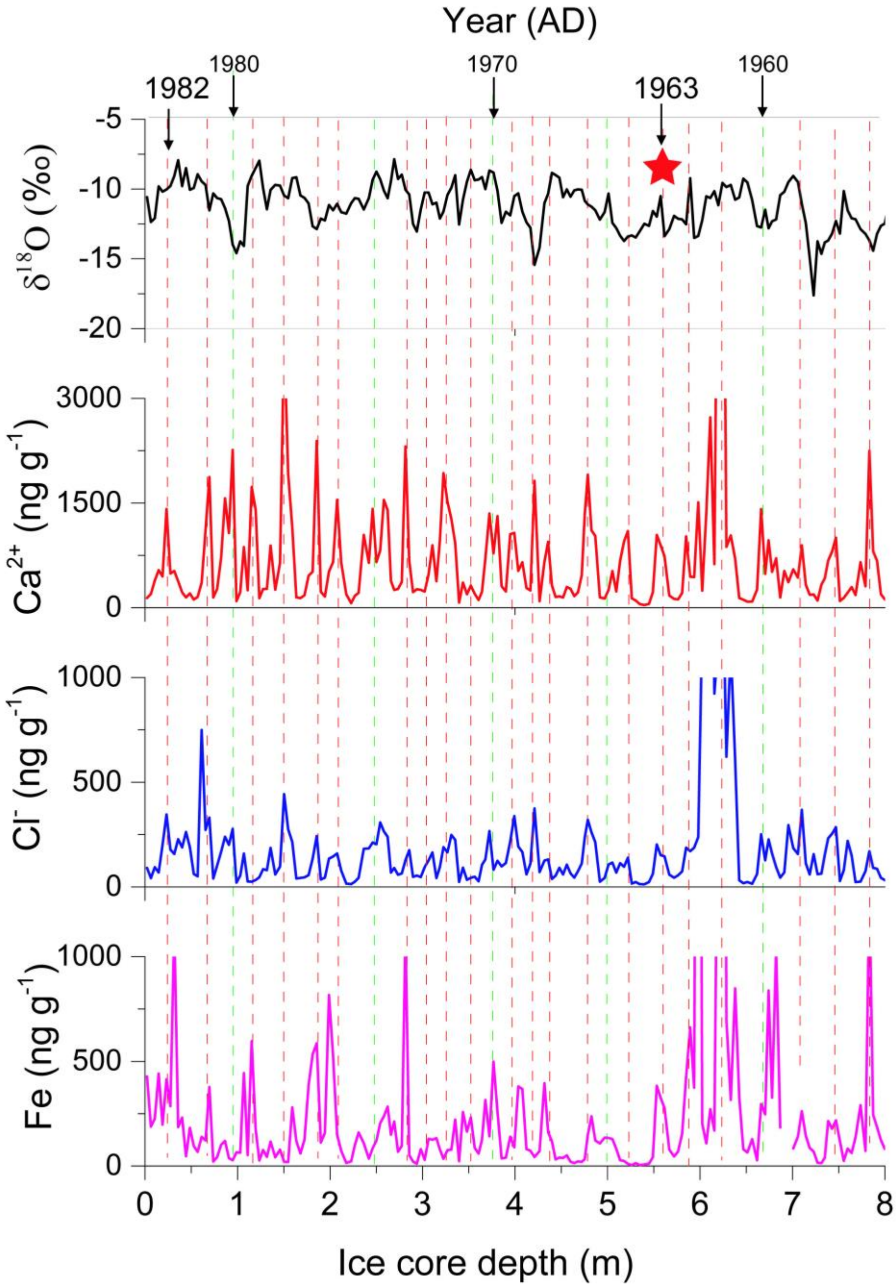
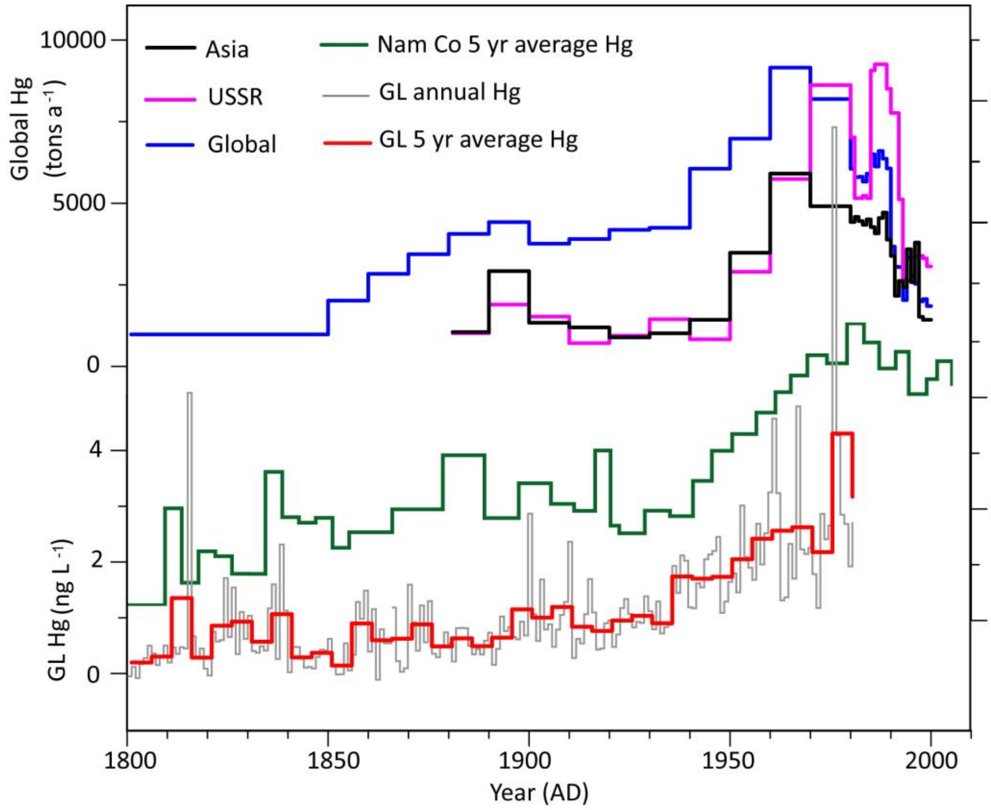
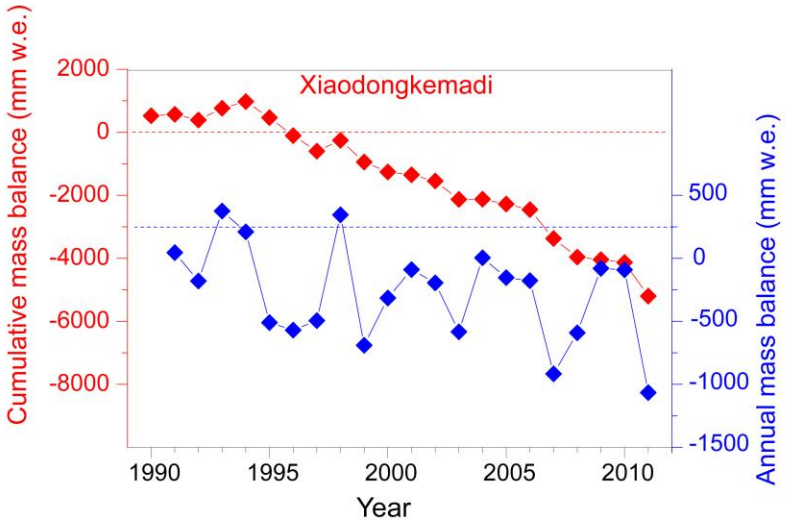

Year (AD)
1982
1980
1970
1963
1960
-5
-10
-15
-20
δ18O (‰)
3000
1500
0
Ca2+ (ng g-1)
1000
500
0
Cl- (ng g-1)
1000
500
0
Fe (ng g-1)
0
1
2
3
4
5
6
7
8
Ice core depth (m)

Figure 5

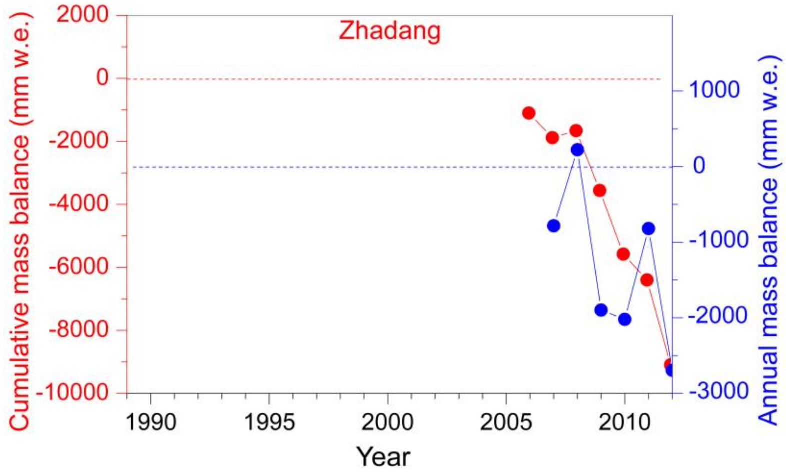


Asia
USSR
Global
Nam Co 5 yr average Hg
GL annual Hg
GL 5 yr average Hg
Global Hg (tons a-1)
10000
5000
0
Asia & USSR (tons a-1)
2000
1000
GL Hg (ng L-1)
4
2
0
Nam Co Hg (ng g-1)
40
30
20
1800
1850
1900
1950
2000
Year (AD)

Figure 6

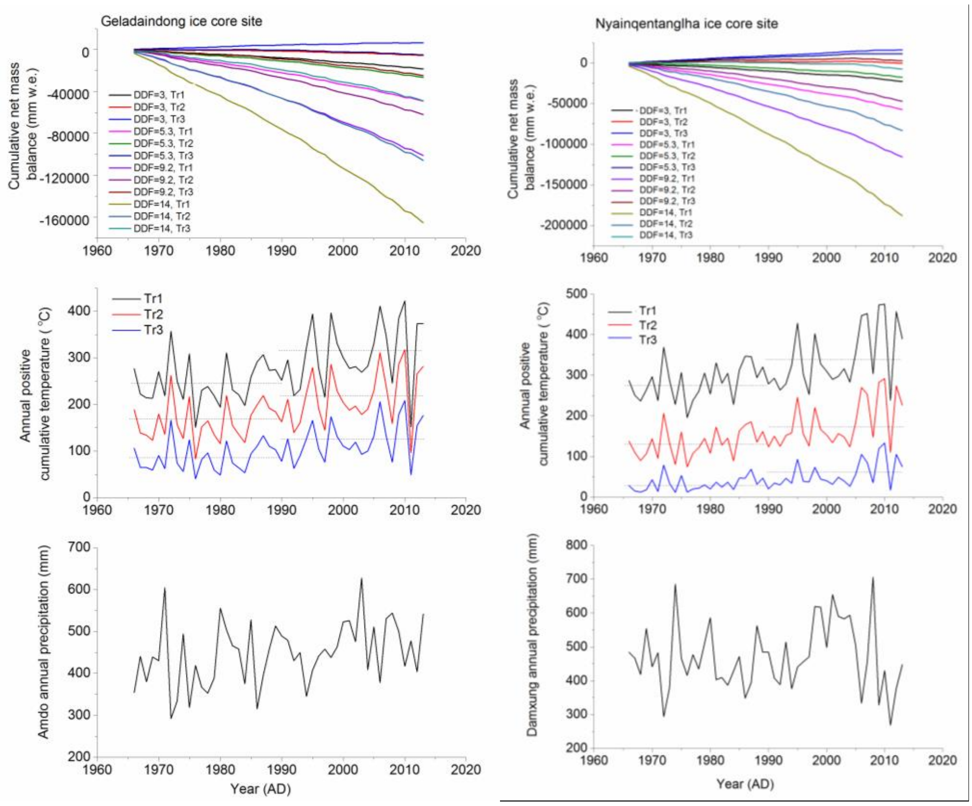


Xiaodongkemadi
Cumulative mass balance (mm w.e.)
Annual mass balance (mm w.e.)
Year
2000
0
-2000
-4000
-6000
-8000
500
0
-500
-1000
-1500
1990
1995
2000
2005
2010



Zhadang
Cumulative mass balance (mm w.e.)
Annual mass balance (mm w.e.)
Year
2000
0
-2000
-4000
-6000
-8000
-10000
1000
0
-1000
-2000
-3000
1990
1995
2000
2005
2010

Figure 7



Geladaindong ice core site
Nyainqentanglha ice core site
Cumulative net mass balance (mm w.e.)
DDF=3, Tr1
DDF=3, Tr2
DDF=3, Tr3
DDF=5.3, Tr1
DDF=5.3, Tr2
DDF=5.3, Tr3
DDF=9.2, Tr1
DDF=9.2, Tr2
DDF=9.2, Tr3
DDF=14, Tr1
DDF=14, Tr2
DDF=14, Tr3
Annual positive cumulative temperature (°C)
Tr1
Tr2
Tr3
Amdo annual precipitation (mm)
Damxung annual precipitation (mm)
Year (AD)