We are very grateful for the editor and reviewers and appreciate your comments and suggestions. All responses or changes have been made below. The responses are marked blue.

Thank you very much

Kind regards,

Fangping Yan

(on behalf of the co-authors)

Reply to Anonymous Referee No.1

1. It is assumed that the strong relationship between Ca^{2+} and DOC (Fig. S3) reflects a primary source for Ca^{2+} and DOC from the same allochthonous source. Could not the DOC however be produced by later autochthonous or heterotrophic biological activity within the snowpack/ice surface, catalysed by nutrients associated with the dust? This should be at least discussed, and abstract and concluding statements adjusted accordingly.

Response: Thanks for the meaningful suggestion. Yes, DOC may also be produced by these activities. We discussed these potential sources in the section 3.2. The abstract and concluding statements were adjusted accordingly.

2. How was discharge measured? You give the discharge data in the supplementary info, but you need to either a) give details of methods used to discharge at the gauging station or b) cite a reference for this data.

Response: Thank you for your advice. The discharge measurement of LHG glacier has been discussed (Gao et al., 2014). In detail: The hydrological gauging site was setup at about 0.8 km downstream of the glacier terminus. It meets the requirements for a hydrological gauging site. Horizon walls were built on the both sides of the river, and an automatic barometric sensor (HOBO Water Level Logger, Onset, America) was installed in the wall to record water pressure every 10 minutes to calculate the water levels. There was a bridge across the river to facilitate the flow velocity measurement using propeller blade current meter (Model LS25-1, Huazheng Hydrometric Instrument Ltd). The river channel was divided into nine segments in which flow velocity and water depth were measured. Coupled with mean flow velocity, width of each segment and water depth, discharge at specific water level was obtained. By including maximum and minimum water level in a year, a discharge relationship with water levels was developed. Therefore, using the HOBO water lever record, discharge of all seasons was calculated. This part was added in the supplementary information. Below is the picture of the gauging station of the glacier.

3. Line 82–be better to give numbers of different samples individually here, not just sum of total

samples

Response: The sum of total samples has been changed to numbers of different individual samples.

4. Line 82–how was ice sampled–using an ice axe? Shallow drill? To what depth? Were they also collected in the same plastic bottles after crushing?

Response: The 0-3 cm and 3-5 cm ice was sampled using a pre-cleaned ice axe and collected in the 125 mL pre-cleaned polycarbonate bottles after crushing similar with other samples, this information was added in section 2.2.

5. Line 115–how were the plastic bottles cleaned?

Response：The plastic polycarbonate bottles were firstly cleaned by ultrapure water for three times, then soaked into 1 M HCl for 24 h (Spencer et al., 2009), after that washed for three times using ultrapure water, finally soaked into ultrapure water for over 24 h. This information was added into the method part 2.2.

6. Line 162–I'd use pre-combusted or pre-baked rather than pre-burned.

Response "Pre-burned" has been changed to "pre-combusted" through the whole text.

7. Line 164–I am unclear as to the methodology here. You state that the experimental samples are first filtered through 0.7um nominal filters, then incubated. But won't the filtration remove much of the biological activity? Plus isn't refrigerating the already filtered samples to act as controls effectively the same as the non control samples? Do you mean instead that samples were actually incubated prior to filtration, and then filtered at each time point then refrigerated? If so, please rewrite. And if so, please state the values of controls and place them on Fig 3. Note that you are unlikely to remove all microorganisms when filtering through the nominal 0.7um filters, so they shouldn't be expected to be sterile i.e. the initial samples may also have had some biological activity, hence the BDOC values should be seen as minimum values.

Response： Thanks for the suggestions. Although it might remove some part of the biological activity, this method was used in previous researches (e.g. Spencer et al., 2014). We adopted this method for the purpose of easy comparison with previous results. In detail, we filtered the samples, then started the experiment: firstly, refrigerated the two filtered original samples, other samples were put in the outside natural environment, and every 3 days 2 samples were put into the refrigerator to keep frozen till analysis. The control value was added on Figure 3. According to the other reviewer, Figure 3 was changed to Figure 4 as below.

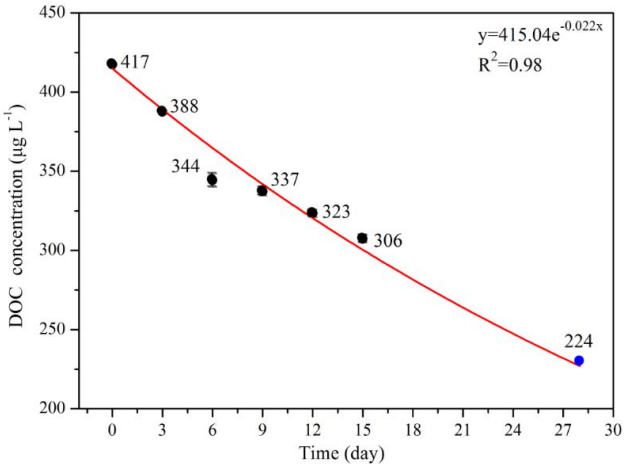


Figure 4 Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue point is calculated using equations derived from the experimental data (black point). Mean values ± standard deviations

of duplicate treated samples are presented.

8. Line 177–DOC could also be influenced by microbial activity–see point 1 above.

Response：We agree that DOC was influenced not only by the mineral dust but also the microbial activities. "Microbial activity" has been added in the sentences.

9. Line 189–again, should mention potential biological activity here

Response: We added the potential biological activity in the sentence.

10. Line 198–you estimate from extrapolation that 43.2% DOC could be re-mineralized within 28 days. How does 28 days compare with the likely residence time of supraglacial runoff and river runoff, where will the water be in this time–still in a river, or lake, could the DOC survive long enough to impact additional downstream ecosystems?

Response：Supraglacial runoff of LHG glacier No. 12 is the headwater of Xiaochangma River, which disappears as underground water at the mouth of LHG valley and appears as the spring downstream, flowing into Shule River in the place of Changma. Therefore, DOC can survive long enough to impact the downstream ecosystem.

11. Line 205–I don't think Anesio et al 2009 looked at viruses. A good additional reference for viruses would be Bellas et al 2012 'Viral impacts on bacterial communi-ties in Arctic cryoconite' Env Res Lett 8 http://iopscience.iop.org/article/10.1088/1748-9326/8/4/045021.

Response: Reference "Bellas et al., 2013" was added in the text, and the section of DOC sources was rewritten according to your point 1.

12. I found that the number of acronyms made it harder to read. For those used only a couple of times (e.g. BrC for brown carbon, WSOC for water soluble organic matter). I'd write them out in full each time simply to aid readability.

Response: These acronyms were rewritten in full name in the text.

13. There are too many decimal points e.g. in abstract 6,949.4 kg (line 27) should be rewritten as 6,950 kg; 425.8 (line 26) should be rewritten as 426. And the same throughout the main text and supplementary information.

Response: Adjusted accordingly throughout the main text and supplementary information.

14. Figures:

1) Fig. 2. Add in error bars both ways, plus put n = x under each bar for sample numbers.

Response: Adjusted accordingly.

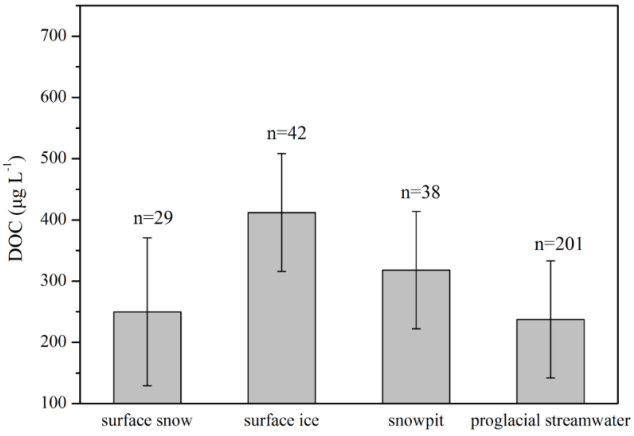


Figure 2 Average DOC concentrations of ice, snow and proglacial streamwater for LHG glacier.

2) Fig. 3. I would have thought that the relationship here could also be adequately described by a linear regression. Also, need to put control (refrigerated) values on here.

Response: The control values were added on the Figure 3. Yes, based on the data only, the linear regression could be adequate. However, according to the DOC bioavailablity, the exponential one can be more authentic (Spencer et al., 2015), because some DOC are bio-refractory, so that DOC cannot reach zero with long enough resident time. The modified figures are shown on Figure 3, and this Figure is now Figure 4 based on the other reviewer's comment as below.

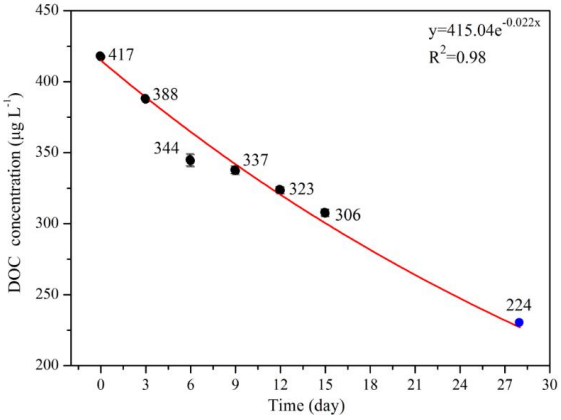


Figure 4 Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue point is calculated using equations derived from the experimental data (black point). Mean values ± standard deviations of duplicate treated samples are presented.

3) Fig. 4. Would help to put some lines as dotted/dashed (when printing in black+white)

Response: Yes, the line types have been changed in Figure 4, and the spectrum of desert sand was deleted according to the other reviewer's comment. Figure 4 is now changed to Figure 5 in the main text as below.

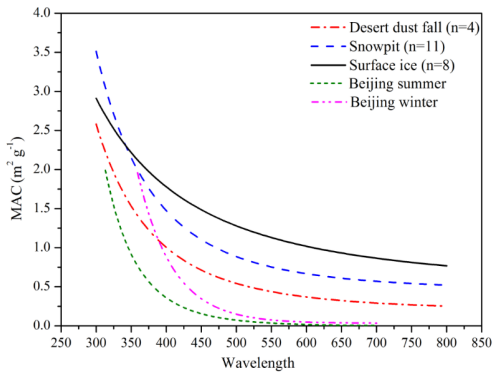


Figure 5 Absorption spectra for the DOC in snow and ice of LHG glacier and the dust and desert sand from surrounding areas.

4) Fig. 5. Again, be better to have one line dotted or dashed plus have different symbols to aid interpretation when printing in black + white.

Response: The line and symbol types have been changed, and this Figure is now changed to Figure 6 in the main text based on the other reviewer's comment.

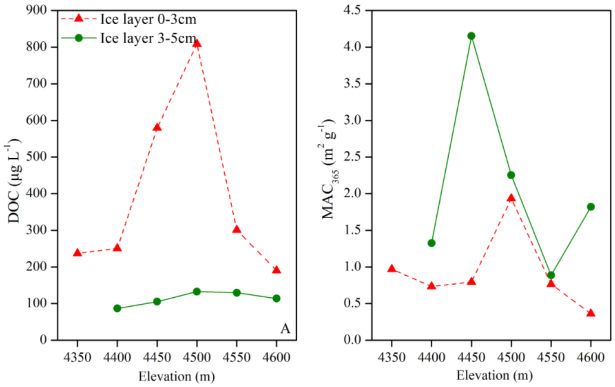


Figure 6 Comparison of DOC concentrations (A) and MAC365 (B) between surface and subsurface ice.

5) Fig. 6. How was discharge calculated and smoothed from raw data?

Response: By measuring water levels and flow velocity in different parts of the river channel in different seasons, a relationship between discharge and water levels was developed using the minimum, maximum and usual water levels. Coupled with HOBO water lever record, discharge of whole ablation period was calculated. Detained method was added in the supplementary information.

6) Fig. S2. Typo–should be elevation, not evelation

Response: Has been corrected.

7) Fig. S4–use different symbols for ice and snow to aid readability.

Response: The symbols are changed to recognize easily in Figure S4, and now it is Figure S3 based on the other reviewer's comment as below.

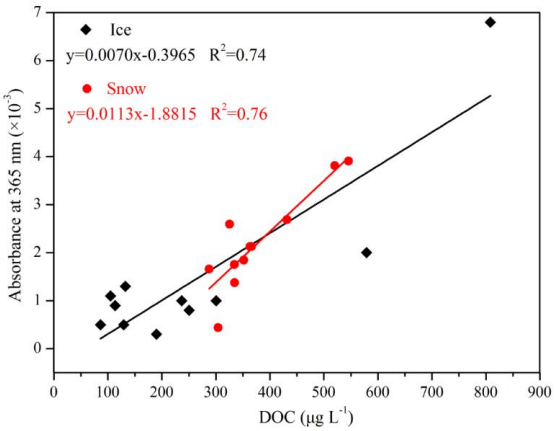


Figure S3 Relationship of the light absorbance at 365 nm and the DOC concentrations of snow and ice samples.

15. Tables:

1) Table 1. Use 3 sig figures throughout (e.g. 332.4 should be 332)

Response: Adjusted accordingly.

2) Table 2. Footnote unclear

Response: Very sorry for the mistake. The footnote was rewritten.

3) Table S1. Please clarify resolution–e.g. for snowpack I presume it is vertical resolution, for ice I presume horizontal distance on glacier, or is it calculated vertical distance?

Response: Yes, for snowpack it is vertical resolution, for surface ice and snow it is elevation interval (horizontal distance).

4) Table S2 BK2 (top line) is out of line. Plus would be better to replace BK numbers with date to show how they encompass the time of study. Could also include the mean+STDEV at bottom.

Response: BK numbers have been adjusted accordingly and the mean+STDEV was added at bottom.

References

Gao, X., Xie, X., Qin, X.: Analysis on a floor happened at the No. 12 glacier in Laohugou Valley, Qilian Mountain in June 2013, Journal of Northwest Normal University: Natural Science, 50, 88-91, 2014 (in Chinese with English abstract).

Spencer, R. G., Stubbins, A., Hernes, P. J., Baker, A., Mopper, K., Aufdenkampe, A. K., Dyda, R. Y., Mwamba, V. L., Mangangu, A. M., and Wabakanghanzi, J. N.: Photochemical degradation of dissolved organic matter and dissolved lignin phenols from the Congo River, J. Geophys. Res. Biogeosci., 114, doi:10.1002/2015GL063498, 2009.

Spencer, R. G. M., Guo, W., Raymond, P. A., Dittmar, T., Hood, E., Fellman, J., and Stubbins, A.: Source and biolability of ancient dissolved organic matter in glacier and lake ecosystems on the Tibetan Plateau, Geochim. Cosmochim. Acta, 142, 64-74, 2014.

Spencer, R. G., Mann, P. J., Dittmar, T., Eglinton, T. I., McIntyre, C., Holmes, R. M., Zimov, N., and Stubbins, A.: Detecting the signature of permafrost thaw in Arctic rivers, Geophys. Res. Lett., 42, 2830-2835, 2015.

Reply to Anonymous Referee No.2

This study examines radiative forcing of dissolved organic carbon in snow and ice and its contribution to carbon flux returned to the atmosphere using samples collected form the Laohugou glacier No. 12 (LHG glacier)) in the north-eastern Tibetan Plateau. Radiative forcing is very small (0.1_0.1%) in comparison with black carbon in ice but constitutes about 10% of the black carbon forcing in snow although the uncertainty on this estimation is close to the estimation itself. I suggest that the authors comment on the importance of this forcing carefully given that these are not large figures. Figure 6S and text given in lines 256-258 are confusing as they suggest much higher radiative forcing of dissolved organic carbon. This should be explained more clearly. I also suggest that the two themes – radiative forcing and release of carbon from the glacier into the atmosphere should be given more distinct separation in the text and the latter given more prominence that it has now (a very short section 3.4).

Response: Thanks a lot for the suggestions. Sorry for the confusing statement about Figure 6S and lines 256-258. Figure 6S was intended to explain the relatively higher radiative forcing of snowpit compared to glacier ice. Lines 256-258 were deleted from the text. For section 3.4, we combined DOC concentration of proglacial streamwater collected previously across the TP (Table S2) to estimate the total output of DOC from glacier region of the TP. The result showed that about 12.7-13.2 Gg DOC (Gg=10^9 g) was exported from glaciers of the TP, which was higher than that of DOC deposition in the glacier region (Li et al., 2016), indicating glacier of the TP is a carbon source at present environment condition. Therefore, we extend this part of our MS to glaciers of the entire TP.

Table S2 Information of the studied glaciers and DOC concentrations (μg L^{-1}) of proglacial streamwater samples across the TP.

Glacier ID	Glacier name	Mountain range	DOC (monsoon)	DOC (non-monsoon)
LHG	Laohugou glacier No. 12	Qilian	325	394
TGL	Xiaodongkemadi glacier	Tanggula	150	212
EV	East Rongbu glacier	Middle Himalaya	139	171
ZD	Zhadang glacier	Nyainq ên tanglha	169	222
DML	Demula glacier	Eastern Himalaya	103	134
QY	Qiangyong glacier	Central Himalaya	124	167

Lines 82-83 and lines 102-107: I suggest that Supplement Table 1 should be given together with Fig. 1 in the main text. Both snow pits should be shown on Fig. 1. Or were they in the same place? If yes, clarify in the text (line 103).

Response: Yes, the two snowpits are almost in the same site and marked on Figure 1. Supplement Table 1 was moved into the main text.

Lines 82-83 and Section 2.2: How did you measure discharge? Explain

Response: Thanks a lot for this question, which was also asked by the other reviewer. In detail: The hydrological gauging site was setup at about 0.8 km downstream of the glacier terminus. It meets the requirements for a hydrological gauging site. Horizon walls were built on the both sides of the river, and an automatic barometric sensor (HOBO Water Level Logger, Onset, America) was installed in the wall to record water pressure every 10 minutes to calculate the water levels. There was a bridge across the river to facilitate the flow velocity measurement using propeller blade current meter (Model LS25-1, Huazheng Hydrometric Instrument Ltd). The river channel was divided into nine segments in which flow velocity and water depth were measured. Coupled with mean flow velocity, width of each segment and water depth, discharge at specific water level was obtained. By including maximum and minimum water level in a year, a discharge relationship with water levels was developed. Therefore, using the HOBO water lever record, discharge of all seasons was calculated. This part was added in the supplementary information.

Line 105 and Fig. 1: What is the 'eastern tributary'? Is it a tributary of the glacier or of the stream? It is not clear from Fig. 1.

Response: Sorry for the missing of the description of this glacier. "Eastern tributary" is one of the branches of LHG glacier No. 12 (Figure 1). "It is divided into two parts of western and eastern branch at the elevation of 4560 m a.s.l (Dong et al., 2014)" has been added in section 2.1.

Line 105: How did you collect ice samples? How did you store them? Crushed or melted before placing in a bottle?

Response: Surface ice (0-3 and 3-5cm) samples were collected using an ice axe directly into 125 mL pre-cleaned polycarbonate bottles after crushing. This method of sample collection was added in section 2.2.

Line 105: Were your samples collected from the surface?

Response: Yes, they were collected from the surface. "71 snow/ice samples" was changed to "29 surface snow and 42 surface ice samples".

Line 105: Please clarify how many samples of snow or ice collected. You currently give one number for all.

Response: "71 snow/ice samples" was changed to "29 surface snow and 42 surface ice samples".

Lines 110-111: 'Clean Hands –Dirty Hands' procedure: Please explain in plain English, avoiding jargon, what it is.

Response: "Clean Hands-Dirty Hands" is the sample collection protocol in which the person who takes charge of the sample collection should not touch any other things except the samples to avoid contamination, the hands are "clean hands", while the other people can take charge of other processes and these hands called "dirty hands".

Lines 115-119: Your numbers of samples from the deserts are low and sand may not make a useful comparison as it is not the material to undergo long-range transport (too large particles). Please comment on the spatial homogeneity / heterogeneity of mineral and elemental composition of desert material

Response: Data of desert sand were deleted from Figure 5. In this study, we focused on the dust in the desert sand, and the desert sands are well mixed, for instance, the 187Os/188Os ratios study showed that for Taklimakan Desert sands are close to the average of Kunlun moraines, river sediments around the Taklimakan Desert and the Tibetan soils. Therefore, the Taklimakan Desert sands are derived from moraines and river sediments around the desert or from Tibetan soils and are homogenized by aeolian activity in the desert (Hattori et al., 2003). Furthermore, because dusts loaded on the glaciers are well mixed during long distant transport from the desert region, mineral and elemental compositions of dust deposited on glacier are also homogenized (Wu et al., 2009). Therefore, "Mineral and elemental composition of desert sands of west China are homogenized by aeolian activity (Hattori et al., 2003), so that the dust samples collected in this study are representative of desert sourced dust in west China" was added into the MS.

Line 117: Is Dunhuang a desert location? Please clarify.

Response: Yes, it is a desert location. This information was added in section 2.2.

Line 147: Provide references supporting your first sentence.

Response: References "Kaspari et al., 2014", "Qu et al., 2014" and "Ming et al., 2013" were added in the sentence.

Line 161: Use 'pre-combusted' instead of 'pre-burned'.

Response: "pre-burned" in line 161 and 162 was changed to "pre-combusted".

Lines 188-189: In the text you state "Therefore, the distributions of DOC concentrations in the glacier surface snow and ice were influenced by complicated factors, such as the terrain, surface moraine and atmosphere circulation". (i) In which way does the 'terrain' (whatever it means here) influence DOC? (ii) What is the impact of atmospheric circulation? I suppose you can't make quantitative conclusions in the absence of continuous measurements but you should at least comment and refer to literature. (iii) In Section 2.2 you refer to the collection of samples from deserts so I assume that 'mineral dust' implies 'desert dust'. If this is the case, make it clear. How can you tell input of desert dust in DOC concentrations from input of material from local moraines?

Response: For question (i), 'Terrain' means different slopes and faces of the glacier, which will cause different enrichment of particles on the glacier surface, finally cause variations of DOC concentration. (ii) 'Atmospheric circulation' is deleted because it hardly influences the contribution of DOC in glacier surface ice. (iii) "Mineral dust" is "desert dust" Therefore, "mineral dust" was replaced by "desert sourced mineral dust". Research on Sr-Nd isotopic compositions (Xu et al., 2012) has shown that dust loaded on LHG glacier was mainly derived from long range transported dust rather than local moraines.

Lines 210-211: Concentrations of Ca^{2+} in desert dust. Have you compared your desert dust samples with the samples from the local moraines? What other tracers can you use? Do you have absorption spectra for material from local moraines and how is it different from those for your desert material samples?

Response: Sorry for not doing this comparison because according to previous research on Sr-Nd isotopic compositions (Xu et al., 2012), it was well constrained that dust loaded on LHG glacier was mainly transported from deserts rather than local moraines. Therefore we only check the desert sourced dust. Furthermore, according to our observation during sampling collecting process, we found local moraines belong to coarse crusted sand and stones, which should contain little organic matter and hard to be transported to the glacier surface.

Section 3.2: You should bring Supplement Figure 1 into this section and add comments on the profiles of DOC in your snow pits highlighting differences between the layers containing dust and the relatively clean layers.

Response: Supplement Figure 1 was brought into the main text as Figure 3. "Moreover, the profiles of DOC in two snowpits varied with the dust content, DOC concentration of dust layer was much higher than that of clean layers." was added in section 3.2.

Lines 256-258 and Fig. 6S: Please explain the elevation dependence of DOC relative to BOS more clearly

Response: Lines 256-258 were deleted for the misunderstanding.

Add more detailed comments on Fig. 6S.

Response: Paragraph 2 in section 3.3.3 was rewritten and changed to "The high radiative forcing ratio of snowpit samples was caused by its higher DOC/BC (0.65) than that of surface ice (0.012) (Fig. S5), and the low ratio of DOC/BC in surface ice was caused by enrichment of BC in surface glacier ice during the intensive ablation period (Xu et al., 2009)".

Equation 3 show that radiative forcing depends on concentration and Fig. 6S shows the ratios between black carbon and dissolved carbon but a couple of sentences would be required to clarify and strengthen you message.

Response: Two sentences were added into the MS. "It is obvious that the value of is closely connected with relative concentrations between DOC and BC." was added into the method part 2.3.2. Meanwhile, the expression in part 3.3.3 was modified to "The high radiative forcing ratio of snowpit samples was caused by its higher DOC/BC (0.65) than that of surface ice (0.012) (Fig. S5), and the low ratio of DOC/BC in surface ice was caused by enrichment of BC in surface glacier ice during the intensive ablation period (Xu et al., 2009)."

Section 3.3.3: Too many abbreviations (BrC, WSOC) make reading this section difficult.

Response: These abbreviations were rewritten in full name in the text.

Line 287: Provide references after ": : :the European Alps and Alaska"

Response: References "Singer et al., 2012" and "Fellman et al., 2015" were added in the sentence.

Section 3.4 is very brief. Can you expand it and give it more prominence?

Response: We measured DOC concentrations of proglacial streamwater samples at other 5 glaciers during last three years. Although only two data were achieved for each glacier, the total flux of DOC for all the glaciers of the TP was estimated and the following information was added in the section 3.4.

"When it comes to the entire TP, it is obvious that proglacial streamwater DOC concentrations (Table S2) showed similar spatial variation to that of snowpit DOC (Li et al., 2016), with high and low value appeared at north and south TP, respectively, reflecting good succession of proglacial

streamwater DOC concentration to that of snowpit samples. Therefore, it was calculated that DOC flux in proglacial streamwater of the entire TP glacier was around 12.7-13.2 Gg C (Gg = 10^9 g) based on average proglacial streamwater DOC concentration of 193 μg L^{-1} (Table S2) and annual glacial meltwater runoff in China of 66-68.2 km^3 (Xie et al., 2006), which is higher than that of DOC deposition (5.6 Gg C) at glacier region of the TP, agree well with the negative water balance of the glaciers of the TP. Therefore, the TP glaciers can be considered as a carbon source under present environment condition."

Section Conclusions (Lines 291-293) and Abstract: radiative forcing of DOC is 0.1±0.1% of BC in ice and 9.5±8.4 % for snow. So this in effect is an almost zero addition in case of ice and might be close to zero addition for snow. I suggest that you should convert this into W m^{-2} using data from literature to be more convincing.

Response: Thanks a lot for the suggestion. Since the radiative forcing ratio of surface ice is almost zero, we converted the ratio of snowpit into W m^{-2} based on the previous published data of black carbon in snowpit of LHG glacier (Ming et al., 2013). "Based on the previous published radiative forcing data of black carbon of snowpit of LHG (Ming et al., 2013), for the first time, it is estimated that the radiative forcing caused by snowpit DOC was 0.43 W m^{-2} , accounting for around 10 % of the radiative forcing caused by BC" was added into conclusions section and section abstract was adjusted accordingly.

Figures and Tables Tables 1 and 2: Why are your references in parentheses?

Response：These references were changed according to the writing standards.

Combine Fig. 1 with Table 1 in the Supplement and show both snow pits.

Response：Table 1 in supplement information was moved into the main text, the other snowit was marked on Figure 1.

Fig. 2: Show error bars both ways and add the number of samples in each category.

Response: Adjusted accordingly on Figure 2.

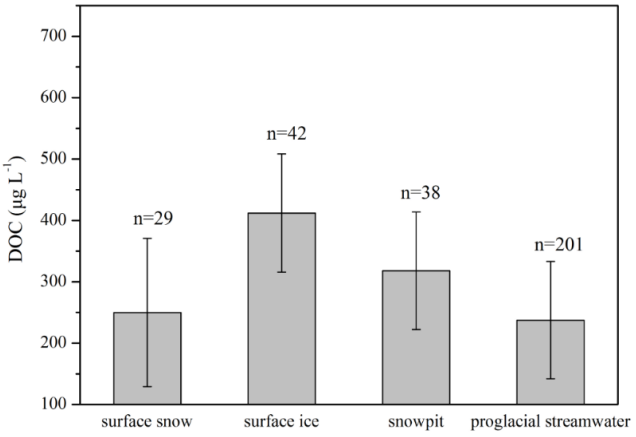


Figure 2 Average DOC concentrations of ice, snow and proglacial streamwater for LHG glacier.

Fig. 3: Why do you need exponential fit here? Linear regression describes this relationship well. Your standard deviation bars are impossible to see.

Response: Yes, based on the data only, the linear regression could be adequate. However, according to the DOC bioavailablity, the exponential one can be more authentic (Spencer et al., 2015), because some DOC are bio-refractory, so that DOC cannot reach zero with long enough resident time. The differences between the parallel samples were very small, so the standard deviation bars were very short.

Fig. 4: What is 'desert' and what is 'dust'?

Response: “Desert” was desert sand collected from the desert at Dunhuang; “Dust” was the dust fall collected during dust storm events at Dunhuang. The spectrum of desert sand was deleted because of the low numbers of the samples. Figure 4 was changed to Figure 5 based on the previous comments as below.

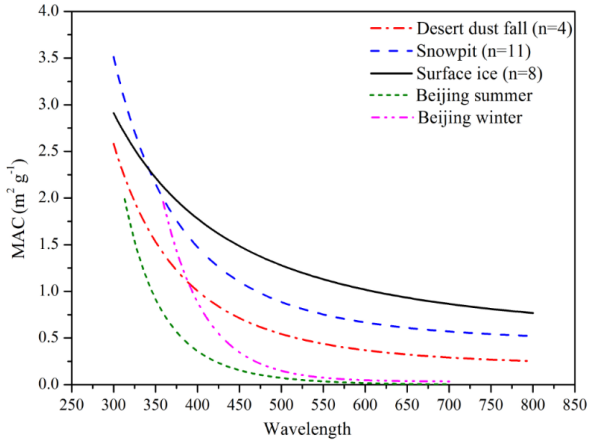


Figure 5 Absorption spectra for the DOC in snow and ice of LHG glacier and the dust and desert sand from surrounding areas.

Fig.S1: Use the same scales on X and Y axes for both profiles for an easier comparison. Move this figure to the main text.

Response: This Figure was moved to the main text as Figure 3 and the scales were adjusted accordingly.

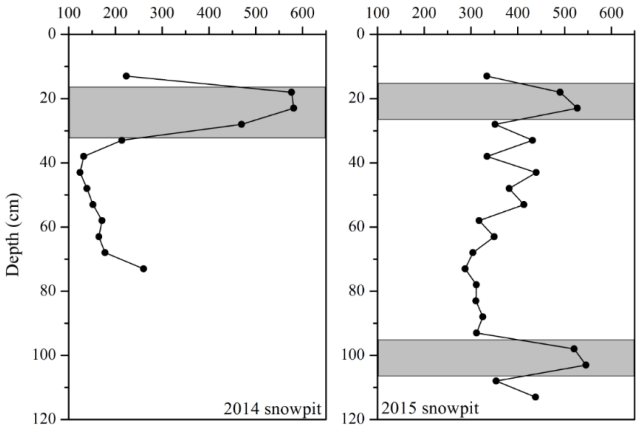


Figure 3 Variation in DOC concentrations in profiles of studied snowpits. The gray rectangles are dirty layers.

Fig. 6S: Are these average ratios for all samples?

Response: They were average DOC and BC ratios of snowpits and surface ice, respectively, “snow” was changed to “snowpit”, “ice” was changed to “surface ice” on this figure, and “6S” was changed to “5S”.

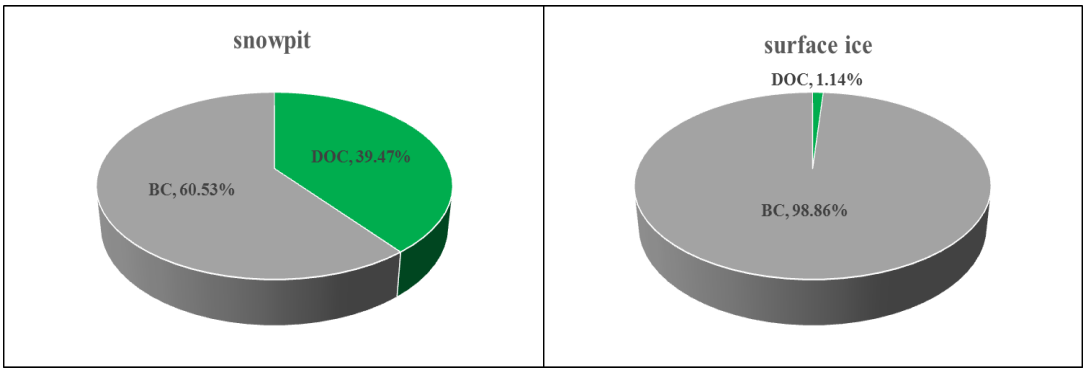


Figure 5S The DOC/BC ratios of snow and ice of LHG glacier.

References

Dong, Z., Qin, D., Chen, J., Qin, X., Ren, J., Cui, X., Du, Z., and Kang, S.: Physicochemical impacts of dust particles on alpine glacier meltwater at the Laohugou Glacier basin in western Qilian Mountains, China, Sci. Total Environ., 493, 930-942, 2014.

Dong, Z., Kang, S., Qin, D., Li, Y., Wang, X., Ren, J., Li, X., Yang, J., Qin, X.: Provenance of cryoconite deposited on the glaciers of the Tibetan Plateau: New insights from Nd-Sr isotopic composition and size distribution, J. Geophys. Res. Atmos., 121, doi: 10.1002/ 2016JD024944, 2016.

Hattori, Y., Suzuki, K., Honda, M., and Shimizu, H.: Re-Os isotope systematics of the Taklimakan Desert sands, moraines and river sediments around the Taklimakan Desert, and of Tibetan soils, Geochim. Cosmochim. Acta, 67, 1203-1213, 2003.

Hood, E. and Scott, D.: Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage, Nat. Geosci., 1, 583-587, 2008.

Li, C., Chen, P., Kang, S., Yan, F., Li, X., Qu, B., and Sillanp ää, M.: Carbonaceous matter deposition in the high glacial regions of the Tibetan Plateau, Atmos. Environ., 141, 203-208, 2016.

Ming, J., Xiao, C., Du, Z., and Yang, X.: An overview of black carbon deposition in High Asia glaciers and its impacts on radiation balance, Adv. Water Resour., 55, 80-87, 2013.

Spencer, R. G., Stubbins, A., Hernes, P. J., Baker, A., Mopper, K., Aufdenkampe, A. K., Dyda, R. Y., Mwamba, V. L., Mangangu, A. M., and Wabakanghanzi, J. N.: Photochemical degradation of dissolved organic matter and dissolved lignin phenols from the Congo River, J. Geophys. Res. Biogeosci., 114, doi: 10.1002/2015GL063498, 2009.

Spencer, R. G., Mann, P. J., Dittmar, T., Eglinton, T. I., McIntyre, C., Holmes, R. M., Zimov, N., and Stubbins, A.: Detecting the signature of permafrost thaw in Arctic rivers, Geophys. Res. Lett., 42, 2830-2835, 2015.

Wu, G., Zhang, C., Gao, S., Yao, T., Tian, L., and Xia, D.: Element composition of dust from a shallow Dunde ice core, Northern China, Global Planet. Change, 67, 186-192, 2009.

Xie, Z., Wang, X., Kang, E., Feng, Q., Li, Q., and Cheng, L.: Glacial runoff in China: an evaluation and prediction for the future 50 years, Journal of Glaciology and Geocryology, 28, 457-466, 2006.

Xu, B., Cao, J., Hansen, J., Yao, T., Joswia, D. R., Wang, N., Wu, G., Wang, M., Zhao, H., and Yang, W.: Black soot and the survival of Tibetan glaciers, PNAS, 106, 22114-22118, 2009.

Xu, J., Yu, G., Kang, S., Hou, S., Zhang, Q., Ren, J., and Qin, D.: Sr–Nd isotope evidence for modern aeolian dust sources in mountain glaciers of western China, Journal of Glaciology, 58, 859-865, 2012.

Other relevant changes are made as follow:

Line 29: “43.2%” was changed to “46.3%”.

Line 33-36: “The radiative forcing of DOC relative to black carbon (BC) was calculated to be 9.5 ± 8.4 % in snow and 0.1±0.1 % in ice, respectively, implying the necessity of accounting for DOC in future radiative forcing investigations in the glacierized region on the TP, especially when these areas are covered by fresh snow” was changed to “Meanwhile, autotrophic or heterotrophic biological activities and autochthonous carbon could also contribute to glacier DOC. The radiative forcing of snowpit DOC was considered to be 0.43 W m^{-2}, implying the necessity of accounting DOC of snow for accelerating melt of glaciers on the TP”.

Line 197: “glacier” was changed to “Xiaodongkemadi glacier”; “Dong Rongbuk” was changed to “East Rongbu”.

Line 223: “43.2%” was changed to “46.3%”.

Line 360-361: “the number of glacial rivers across the entire TP and surrounding areas may be large due to the glacial area of approximately 100,000 km^2 (Yao et al. 2012). These factors need to be comprehensively studied in the future” was changed to “when it comes to the entire TP DOC flux from glaciers of the entire TP was around 12.7-13.2 Gg C”.

References: All the references were changed according to the manuscript preparation guidelines.

Concentration, sources and light absorption characteristics of dissolved organic carbon on a typical glacier, the northern Tibetan Plateau

F. Yan[1,4,5], S. Kang[1,3]*, C. Li[2, 3]*, Y. Zhang[1], X. Qin[1], Y. Li[2,4], X. Zhang[1,4], Z. Hu[1,4], P. Chen[2], X. Li[1], B. Qu[5], M. Sillanpää[5,6]

[1]Qilian Station for Glaciology and Ecological Environment, State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

[2]Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[3]CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China

[4]University of Chinese Academy of Sciences, Beijing 100049, China

[5]Laboratory of Green Chemistry, Lappeenranta University of Technology, Sammonkatu 12, FIN-50130 Mikkeli, Finland

[6]Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174, USA

Abstract. Light-absorbing dissolved organic carbon (DOC) constitutes a major part of the organic carbon in glacierized regions. It has important influences on the carbon cycle and radiative forcing of glaciers. However, currently, few data are available in the glacierized regions of the Tibetan Plateau (TP). In this study, DOC characteristics of a typical glacier (Laohugou glacier No. 12 (LHG glacier)) in the northern TP were investigated. Generally, DOC concentrations on LHG glacier were comparable to those in other regions around the world. DOC concentrations in snowpits and surface snow were 332~~.4~~ ± 132~~.3~~ μg L^{-1} and 229~~.3~~ ± 104~~.4~~ μg L^{-1}, respectively, which were slightly higher than those of the Greenland ice sheet. DOC concentration of surface ice (superimposed ice) was 42~~5.86~~ ± 2~~69.970~~ μg L^{-1}, comparable to that of the Antarctic ice sheet. The average discharge-weighted DOC of proglacial streamwater was 23~~7.58~~ ± 9~~5.66~~ μg L^{-1}, which is lower than that of Mendenhall glacier, Alaska. The annual DOC flux released from this glacier was estimated to be 6,949~~.4~~ kg C yr^{-1}, of which 4~~63~~.2 % of

DOC was bioavailable and could be decomposed into CO_2 within one month of its release. The mass absorption cross section (MAC) of DOC at 365 nm was 1.4 ± 0.4 $m^2 g^{-1}$ in snow and 1.3 ± 0.7 $m^2 g^{-1}$ in ice, similar to the values of dust transported from adjacent deserts. Based on this finding and the significant relationship between DOC and Ca^{2+}, the main source of DOC ~~was~~ might be desert mineral dust. Meanwhile, ~~autochthonous,~~ autotrophic or heterotrophic biological activities and autochthonous carbon could also contribute to glacier DOC. The radiative forcing of snowpit DOC ~~relative to black carbon (BC)~~ was considered to be 0.43 W m^{-2} ~~9.5 ± 8.4 % in snow and 0.1 ± 0.1 % in ice~~, implying the necessity of accounting ~~for~~ DOC of snow for accelerating melt of glaciers ~~in future radiative forcing investigations in the glacierized regions~~ on the TP~~, especially when these areas are covered by fresh snow~~.

Key words: dissolved organic carbon, ~~concentration,~~ light absorption, LHG glacier, the Tibetan Plateau

1 Introduction

Ice sheets and mountain glaciers cover 11 % of the land surface of the Earth and store approximately 6 Pg (1 Pg = 10^{15} g) of organic carbon, the majority of which (77 %) is in the form of dissolved organic carbon (DOC) (Hood et al., 2015). The annual global DOC release through glacial runoff is approximately 1.04 ± 0.18 Tg C (1 Tg = 10^{12} g) (Hood et al., 2015). Therefore, glaciers not only play an important role in the hydrological cycle by contributing to sea-level rise (Rignot et al., 2003; Jacob et al., 2012) but also potentially influence the global carbon cycle (Anesio and Laybourn-Parry, 2012; Hood et al., 2015) in the context of accelerated glacial ice loss rates. In addition, a large portion of glacier-released DOC has proven to be highly bioavailable, influencing the balance of downstream ecosystems (Hood et al., 2009; Singer et al., 2012; Spencer et al., 2014).

Although DOC storage in ice sheets is much larger than that of mountain glaciers, the annual mountain glacier-derived DOC dominates the global DOC release (Hood et al., 2015). Currently, many studies on the concentration, age, composition, storage and release of DOC have been conducted around the world (Hood et al., 2009; Stubbins et al., 2012; May et al., 2013; Bhatia et al., 2013; Lawson et al., 2014; Fellman et al., 2015; Hood et al., 2015). The sources of glacier-derived DOC were found to be diverse (Bhatia et al., 2010; Stubbins et al., 2012; Singer et al., 2012; Spencer et al., 2014), with large variations in concentrations and ages (Hood et al., 2009; Singer et al., 2012; Hood et al., 2015). For example, a study on the Greenland ice sheet showed that the concentration of exported DOC exhibited slight temporal variations during the melting period, with subtly higher values in early May than in late May and July (Bhatia et al., 2013). Additionally, the concentration of total organic carbon in snow across the East Antarctic ice sheets exhibited remarkable spatial variations due to the marine source of organic carbon (Antony et al., 2011). Studies on both radiocarbon isotopic compositions and biodegradable DOC (BDOC) have proposed that ancient organic carbon from glaciers was much easier for microbes to utilize in glacier-fed rivers and oceans, implying that large amounts of this DOC will return to the atmosphere quickly as CO_2 and participate in the global carbon cycle, thereby producing a positive feedback in the global warming process (Hood et al., 2009; Singer et al., 2012; Spencer et al., 2014). In addition to black carbon (BC), another DOC fraction known as water-soluble brown carbon ~~(WS-BrC)~~ has also been considered a warming component in the climate system (Andreae and Gelencsér, 2006; Chen and Bond, 2010). This type of DOC exhibits strong light-absorbing properties in the ultraviolet wavelengths (Andreae and Gelencsér, 2006; Chen and Bond, 2010; Cheng et al., 2011).

The relative radiative forcing caused by water-soluble organic carbon (~~WSOC,~~ the same as DOC) relative to BC in aerosols was estimated to account for 2-10 % and approximately 1 % in a typical pollution area of North China (Kirillova et al., 2013) and a remote island in the Indian Ocean (Bosch et al., 2014), respectively. Unfortunately, so far, few direct evaluations have been conducted in the glacierized regions around the world, including the Tibetan Plateau (TP), where DOC accounts for a large part of the carbonaceous matter (Legrand et al., 2013; May et al., 2013) and potentially contributes to the radiative forcing in the glacierized region.

The TP has the largest number of glaciers at moderate elevations. Most of the glaciers on the TP are experiencing intensive retreat because of increases in temperature (Kang et al., 2010; Yao et al., 2012; Yao, 2004a; Kang et al., 2015; Zhang et al., 2015) and anthropogenic carbonaceous particle deposition (Ming et al., 2008; Xu et al., 2009; Qu et al., 2014; Kaspari et al., 2014). However, to date, no study has quantitatively evaluated the light absorption characteristics of DOC in the glacierized regions on the TP, despite some investigations of concentrations and sources of DOC (Spencer et al., 2014; Yan et al., 2015). The primary results of these studies have shown that DOC concentrations in snowpits in the northern TP are higher than those in the southern TP (Yan et al., 2015). In addition, a large fraction of the ancient DOC in the glaciers in the southern TP has high bioavailability characteristics (Spencer et al., 2014). However, knowledge of DOC in TP glaciers remains lacking due to the large area and diverse environments of the TP and the relatively limited samples and studies. Therefore, numerous snow (n=67), ice (n=42) and proglacial streamwater samples (n=201)~~(n=310)~~ were collected from a typical glacier in the northeastern TP (Laohugou glacier No. 12) based on the preliminary research of snowpit samples (Yan et al., 2015) (Table ~~S~~1, Fig. 1). The concentrations of DOC and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, Cl^{-}, NO_3^{-} and SO_4^{2-}) and DOC light absorbance were measured to comprehensively investigate the sources, light absorption properties and carbon dynamics in this glacierized region to provide a basis for the study of DOC across the TP and other regions in the future.

2 Methodology

2.1 Study area and sampling site

Laohugou glacier No. 12 (LHG glacier) (39 °05'-40'N, 96 °07'-97 °04'E 4260-5481 m) is the largest mountain glacier (9.85 km, 20.4 km^2) in the Qilian Mountains located on the northeastern edge of the TP (Du et al., 2008; Dong et al., 2014a). It is divided into two part of western and eastern branch at the

elevation of 4560 m a.s.l (Dong et al., 2014a). This glacier is surrounded by large arid and semi-arid regions (sandy deserts and the Gobi desert) (Fig. 1). The area of the glacier covers approximately 53.6 % of the entire LHG glacier basin (Du et al., 2008; Li et al., 2012).

LHG glacier features typical continental and arid climate characteristics (Li et al., 2012; Zhang et al., 2012b). Precipitation occurs mainly from May to September, accounting for over 70 % of the total annual precipitation (Zhang et al., 2012b). The monthly mean air temperatures in the ablation zone of the glacier range from -18.4 ℃ in December to 3.4 ℃ in July (Li et al., 2012). Like other glaciers on the TP, LHG glacier has been experiencing significant thinning and shrinkage at an accelerated rate since the mid-1990s (Du et al., 2008; Zhang et al., 2012b).

2.2 Sample collection

Two snowpits were dug in 2014 and 2015 almost in the same site in the accumulation zone of LHG glacier. In total, 15 and 23 snow samples were collected in 2014 and 2015, respectively, at a vertical resolution of 5 cm for each snowpit. Moreover, 29 surface snow and 42 surface ice ~~71 snow/ice~~ samples were collected along the eastern tributary at an approximate elevation interval of 50 or 100 m from the terminus to the accumulation zone, and 201 proglacial streamwater samples were collected at the gauge station during the melting period (Fig. 1, Table ~~S~~1). The concentrations of glacier DOC have been observed to be very low and prone to contamination, causing an overestimation of DOC concentrations (Legrand et al., 2013). Therefore, before sample collection, polycarbonate bottles were firstly cleaned by ultrapure water for three times, then soaked into 1 M HCl for 24 h (Spencer et al., 2009), and rinsed three times using ultrapure water, finally soaked into ultrapure water for over 24 h; during the whole sampling procedure, snow samples were collected directly into 125-mL pre-cleaned bottles, surface ice (0-3 cm and 3-5 cm) samples were collected using an ice axe directly into polycarbonate bottles after crushing, while proglacial streamwater samples were filtered immediately after collection before putting into bottles. All ice and snow sample were filtered as soon as possible after they were melted~~samples were collected according to the "Clean hands Dirty Hands" principle to prevent any contamination~~ . During all the processes, the person who takes charge of sample collection should not touch any other things to avoid contamination. Meanwhile, at least one blank was made for every sampling process to confirm that the contamination was low (Table S1~~2~~). Meanwhile, another batch of samples were also collected for BC concentration measurement following the protocol discussed in detail in our earlier work (Qu et al., 2014); these results will be presented in another article.

In order to evaluate DOC release ~~on~~of the ~~total~~entire TP, DOC concentrations of proglacial streamwater samples of other five glaciers in monsoon and non-monsoon seasons were measured, respectively (Fig. 1, Table S2).

All the collected samples ~~were stored in 125 mL pre-cleaned polycarbonate bottles and~~ were kept frozen and in the dark in the field, during transportation and in the laboratory until analysis. In addition, ~~two sand samples from the desert and~~ four dust fall samples from Dunhuang, a desert location (39°53'-41°35'N, 92°13'-93°30'E) – ~~a~~ potential source region of the dust deposited on LHG glacier – were collected to compare the light absorption characteristics of dust-sourced DOC to those of the snowpit and ice samples. Mineral and elemental composition of desert sands of west China are homogenized by aeolian activity (Hattori et al., 2003), so that the dust samples collected in this study are representative of desert sourced dust in west China.

2.3 Laboratory analyses

2.3.1 Concentration measurements of DOC and major ions

DOC concentrations were determined using a TOC-5000A analyzer (Shimadzu Corp, Kyoto, Japan) after the collected samples were filtered through a PTFE membrane filter with 0.45-μm pore size (Macherey–Nagel) (Yan et al., 2015). The detection limit of the analyzer was 15 μg L^{-1}, and the average DOC concentration of the blanks was 3~~1.9~~2 ± 7~~.4~~ μg L^{-1}, demonstrating that contamination can be ignored during the pre-treatment and analysis processing of these samples (Table S1~~2~~). The major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and NH_4^{+}) and major anions (Cl^{-}, NO_3^{-} and SO_4^{2-}) were measured using a Dionex-6000 Ion Chromatograph and a Dionex-3000 Ion Chromatograph (Dionex, USA), respectively. The detection limit was 1 μg L^{-1}, and the standard deviation was less than 5 % (Li et al., 2007; Li et al., 2010). The average ion concentrations of the blank were very low and could be ignored (Na^{+}, K^{+}, Mg^{2+}, F^{+}, SO_4^{2-}, Cl^{-}, NO_3^{-} < 1 μg L^{-1}; NH_4^{+} = 1.4~~2~~ μg L^{-1}; Ca^{2+} = 1.2~~4~~ μg L^{-1}).

2.3.2 Light absorption measurements

The light absorption spectra of DOC ~~was~~ were measured using an ultraviolet-visible absorption spectrophotometer (SpectraMax M5, USA), scanning wavelengths from 200-800 nm at a precision of 5 nm. The mass absorption cross section (MAC) was calculated based on the Lambert-Beer Law (Bosch et al., 2014; Kirillova et al., 2014a; Kirillova et al., 2014b):

$$MAC_{DOC} = \frac{-\ln|\frac{I}{I_0}|}{C.L} = \frac{A}{C.L} \times \ln(10) \quad (1)$$

where I_0 and I are the light intensities of the transmitted light and incident light, respectively; A is the absorbance derived directly from the spectrophotometer; C is the concentration of DOC; and L is the absorbing path length (1 cm).

In order to investigate the wavelength dependence of DOC light absorption characteristics, the Absorption Ångström Exponent (AAE) was fitted by the following equation (Kirillova et al., 2014b;Kirillova et al., 2014a):

$$\frac{A(\lambda_1)}{A(\lambda_2)} = (\frac{\lambda_2}{\lambda_1})^{AAE} \quad (2)$$

AAE values were fitted from the wavelengths of 330 to 400 nm; within this wavelength range, light absorption by other inorganic compounds can be avoided (such as nitrate) (Cheng et al., 2011).The radiative forcing caused by BC has been widely studied (Kaspari et al., 2014; Qu et al., 2014; Ming et al., 2013). Therefore, in this study, using a simplistic model (the following algorithm), the amount of solar radiation absorbed by DOC compared to BC was estimated:

$$f = \frac{\int_{300}^{2500} I_0(\lambda) \cdot \left\{1 - e^{-(MAC_{365}(\frac{365}{\lambda})^{AAE_{DOC}} \cdot C_{DOC} \cdot h_{ABL})}\right\} d\lambda}{\int_{300}^{2500} I_0(\lambda) \cdot \left\{1 - e^{-(MAC_{550}(\frac{550}{\lambda})^{AAE_{BC}} \cdot C_{EC} \cdot h_{ABL})}\right\} d\lambda} \quad (3)$$

where λ is the wavelength; $I_0(\lambda)$ is the clear sky solar emission spectrum determined using the Air Mass 1 Global Horizontal (AM1GH) irradiance model (Levinson et al., 2010); MAC_{365} and MAC_{550} are the mass absorption cross section of DOC at 365 nm and mass absorption cross section of BC at 550 nm, respectively; h_{ABL} is the vertical height of the atmospheric boundary layer; and AAE_{DOC} and AAE_{BC} are the Absorption Ångström Exponents (AAEs) of DOC and BC. In this simplistic model, following a previous study, we used $MAC_{550} = 7.5 \pm 1.2$ $m^2 g^{-1}$ (Bond and Bergstrom, 2006), and AAE for BC was set as 1, while h_{ABL} was set to 1000 m, which has little influence on the integration from the wavelengths of 300 - 2500 nm (Kirillova et al., 2013; Bosch et al., 2014; Kirillova et al., 2014a; Kirillova et al., 2014b). It is obvious that the value of "f" is closely connected with relative concentrations between DOC and BC.

2.3.3 *In situ* DOC bioavailability experiment

The bioavailability experiment was conducted from August 17th to 31st, 2015, at the glacier terminus during fieldwork. In brief, surface ice samples were collected in ~~pre-burned~~ pre-combusted (550 ℃, 6 h) aluminum basins and melted in the field. The melted samples were filtered through ~~pre-burned~~ pre-combusted glass fiber filters (GF/F 0.7 μm) into 12 pre-cleaned 125-mL polycarbonate bottles and wrapped with three layers of aluminum foil to avoid solar irradiation. Two samples were refrigerated immediately after filtering to obtain initial DOC concentrations; the others were placed outside at the terminus of the glacier, and 2 samples were refrigerated every 3 days to get corresponding DOC values. The BDOC was calculated based on the discrepancies between the initial and treated samples.

3 Results and discussion

3.1 DOC concentrations and bioavailability

3.1.1 Snowpits

LHG glacier is surrounded by arid and semi-arid regions and frequently influenced by strong dust storms (Dong et al., 2014b) (Fig. 1). Therefore, heavy desert sourced mineral dust deposition contributes to high DOC concentrations on LHG glacier. The average DOC concentration of the snowpit samples was 332~~.4~~ ± 132~~.3~~ μg L^{-1} (Fig. 2), with values ranging from 124~~.4~~ μg L^{-1} to 581~~.0~~ μg L^{-1} (Fig. ~~S1~~3). The highest values appeared in the dirty layers (Fig. ~~S1~~3), similar to the pattern observed in the Greenland summit (Hagler et al., 2007) and glaciers in the southern TP (Xu et al., 2013), indicating that DOC concentrations were mainly influenced by dust deposition in this region in addition to the potential microbial activities (Anesio et al., 2009). Spatially, our results were higher than those of Xiaodongkemadi glacier on Mountain Tanggula ~~glacier~~ (TGL) in the middle TP and ~~Dong~~East Rongbu~~k~~ glacier on Mount Everest (EV) in the southern TP (Fig. 1) (Yan et al., 2015) but similar to the mercury distribution on the TP (Zhang et al., 2012a). Moreover, the DOC concentrations on LHG glacier were also higher than those of Alaskan glaciers (Stubbins et al., 2012) and the Greenland summit (Hagler et al., 2007) (Table 2~~1~~).

3.1.2 Surface snow and ice

The average DOC concentration in LHG glacier surface snow was significantly lower than that in surface ice because more impurities are present in the latter (Fig. 2). Like those of the snowpits, DOC concentrations in the glacier surface ice (Fig. 2) were higher than those in the southern TP (Nyainqentanglha glacier) (Spencer et al., 2014) and subsurface ice (0.5 m beneath the glacier surface)

in a European Alpine glacier (Singer et al., 2012) (Table 2) but comparable to that in the surface ice of the Antarctic ice sheet (Hood et al., 2015). However, the DOC concentrations in surface snow (~~Fig. 2~~Table 2) were higher than those in the Greenland ice sheet (Hagler et al., 2007), mainly due to the heavy dust load of LHG glacier ~~(Table 2)~~. No significant relationship was found between DOC concentration and elevation for either the surface snow or ice (Fig. S1~~2~~), suggesting no "altitude effect" on DOC in this glacier. This finding is similar to the mercury distribution pattern in surface snow of this glacier (Huang et al., 2014). Therefore, the distributions of DOC concentrations in the glacier surface snow and ice were influenced by complicated factors, such as ~~the terrain~~different slopes (Hood and Scott, 2008) and ~~surface~~ cryoconite holes~~moraineand atmosphere circulation~~. Furthermore, DOC concentrations of snow and ice of this glacier were within the range of previously reported values for glacieried regions outside the TP.

3.1.3 DOC bioavailability

Previous studies conducted under controlled conditions (stable temperature) have shown that glacier-derived DOC is more bioavailable than terrestrial-derived DOC (Hood et al., 2009; Fellman et al., 2010; Spencer et al., 2014). Our results showed that the amount of DOC being consumed decreased exponentially over time (R^2 = 0.98) (Fig. 4~~3~~), with approximately 26.7 % (from 41~~6.9~~ 7μg L^{-1} to 30~~5.6~~6 μg L^{-1}) degraded within 15 days during the experiment (average temperature: 3.~~77~~ 8 ± 3.~~65~~ 7 ℃; range: -4.~~77~~8-11.~~36~~ 4 ℃). The BDOC reached 4~~3.2~~6.3~~2~~ % if the experiment duration was extended to 28 days, according to the equation derived from the 15-day experiment (Fig. 4~~3~~). Despite different incubation conditions, this finding agrees well with the reports of BDOC from a glacier in the southern TP (28-day dark incubation at 20 ℃, 46-69 % BDOC）(Spencer et al., 2014) and European Alpine glaciers (50-day dark incubation at 4 ℃, 59±20 % BDOC) (Singer et al., 2012). Therefore, the previous results obtained in the laboratory closely reflect the real situation and can be used to estimate the bioavailability of glacier-derived DOC.

3.2 Sources of snowpit DOC

The sources of glacier DOC are diverse and include ~~microbial~~ autochthonous or *in situ* biological activities~~y (viruses, bacteria and algae) in subglacial systems~~ (Anesio et al., 2009; Bellas et al., 2013), allochthonous carbon derived from overridden soils and vegetation in subglacial systems (Bhatia et al., 2010); terrestrial inputs (DOC deposition from vascular plants and dust) (Singer et al., 2012) and

anthropogenic sources (fossil fuel and biomass combustion) (Stubbins et al., 2012; Spencer et al., 2014)~~(Anesio et al., 2009; Hood et al., 2009; Bhatia et al., 2010; Stubbins et al., 2012; Singer et al., 2012; Spencer et al., 2014; Antony et al., 2014)~~. Research on glacier microbial activity suggests that globally only cryoconite holes can potentially fix about 64 Gg ~~carbon~~C per year (Anesio et al., 2009). Moreover, viral induced mortality at the cost of heterotrophic bacterial community plays a dominant role in carbon cycle and other nutrients transformation in supraglacier ecosystems (Bellas et al., 2013). In this study, major ions were adopted as indicators to investigate the potential sources of snowpit DOC, because the sources of major ions in snowpit samples from Tibetan glaciers have been investigated in detail (Kang et al., 2002; Kang et al., 2008; Wu et al., 2011; Yan et al., 2015). Moreover, the profiles of DOC in two snowpits varied with the dust content, DOC concentration of dust layer was much higher than that of clean layers. Furthermore,~~I~~ it was found that DOC and Ca^{2+} (a typical indicator of mineral dust (Yao, 2004b)) were significantly related (R^2 = 0.84, Fig. S2~~3~~), suggesting that the major source of DOC was desert sourced mineral dust, which is consistent with the previous DOC source investigations of snowpits on this glacier (Yan et al., 2015). In addition, the combined study of geochemistry and backward trajectories for LHG glacier showed that the dust particles on the glacier were mainly derived from the deserts to the west and north of the study area (Dong et al., 2014a; Dong et al., 2014b).

3.3 Light absorption characteristics of DOC

3.3.1 AAE

The Absorption Ångström Exponent (AAE) is generally used to characterize the spectral dependence of the light absorption of DOC, which is important input data for radiative forcing calculations ~~(supporting information)~~. The fitted $AAE_{330\text{-}400}$ values ~~(supporting information)~~ ranged from 1.2 to 15.2 (5.0 ±5.9) for snow samples and from 0.3 to 8.4 (3.4 ±2.7) for ice samples (Fig. S4~~5~~). The relatively low $AAE_{330\text{-}400}$ values of the ice indicated that the DOC experienced strong photobleaching due to long-duration exposure to solar irradiation. Previous studies have found that the AAE values of brown carbon ~~(BrC)~~in aged aerosols (Zhao et al., 2015) and secondary organic aerosols (SOAs) (Lambe et al., 2013) were much lower compared to that of the primary values. Therefore, the large divergence in AAE values might suggest different chemical compositions of DOC due to multiple possibilities, such as different sources and photobleaching processes. Regardless, the average AAE value of the snow samples was comparable to that of atmospheric aerosols in urban areas in South Asia (New Delhi, India) (Kirillova et al., 2014b) (Table 2). In general, the $AAE_{330\text{-}400}$ values had a negative

relationship with MAC_{365}, especially in the ice samples (Fig. S45), suggesting that stronger absorbing DOC might contribute to lower AAE values, which was also found in other aerosol studies (Chen and Bond, 2010; Bosch et al., 2014; Kirillova et al., 2014b).

3.3.2 MAC_{365}

The mass absorption cross section at 365 nm (MAC_{365}) for DOC is another input data point for the radiative forcing calculation. The light absorption ability at 365 nm is selected to avoid interferences of non-organic compounds (such as nitrate) and to be consistent with previous investigations (Hecobian et al., 2010; Cheng et al., 2011). The MAC_{365} was 1.4 ± 0.4 m^2 g^{-1} in snow and 1.3 ± 0.7 m^2 g^{-1} in glacier ice (Fig. S45), both of which were higher than those of water soluble organic carbon ~~WSOC~~ in outflow in northern China (Kirillova et al., 2014a) and a receptor island in the Indian Ocean (Bosch et al., 2014). Meanwhile, the values were comparable to DOC concentrations in typical urban aerosols associated with biomass combustion in winter in Beijing, China (Cheng et al., 2011) and in New Delhi, India (Kirillova et al., 2014b) (Table 32). The MAC values for DOC from different sources vary widely. Normally, the MAC_{365} of DOC derived from biomass combustion can be as high as 5 m^2 g^{-1} (Kirchstetter, 2004) (Table 32). Correspondingly, the values for SOAs can be as low as 0.001-0.088 m^2 g^{-1} (Lambe et al., 2013). Due to the remote location of LHG glacier, it was considered that the snowpit DOC should be SOAs with low MAC_{365} values; however, the high MAC_{365} value of the snowpit DOC indicated that DOC may not be entirely derived from SOAs. Here, it was proposed that mineral dust-sourced DOC caused the high MAC_{365} values in the snowpit samples. For instance, the light absorption characteristics of DOC from both snowpit and ice showed similar patterns to those of water soluble organic carbon ~~WSOC~~ in dust from the adjacent deserts, further indicating that LHG glacier DOC was transported via desert sourced mineral dust and shared similar light absorption characteristics (Fig. 54). Moreover, the difference in light absorption characteristics (especially for wavelengths larger than 400 nm) between snow/ice samples and aerosols in Beijing, China, also indicated different sources (Fig. 54). Light absorbance was significantly correlated with DOC concentrations in both snow and ice samples (Fig. S34), indicating that DOC was one of the absorption factors. Nevertheless, the MAC_{365} values of surface ice (0-3 cm) were lower than those of subsurface layers (3-5 cm), despite its higher DOC concentrations (Fig. 65), reflecting stronger DOC photobleaching in the surface ice due to the direct exposure to solar irradiation.

3.3.3 Radiative forcing of DOC relative to BC

The radiative forcing contributed by water soluble organic carbon ~~WSOC~~ relative to BC in aerosols has been proposed to be as high as 2-10 % (Kirillova et al., 2013; Kirillova et al., 2014a). Furthermore, it was estimated that brown carbon ~~BrC~~ accounts for a higher ratio of 20 % of the direct radiative forcing of aerosols at the top of the atmosphere because BC concentrations decrease faster than brown carbon ~~BrC~~ in the high-altitude atmosphere (Liu et al., 2014). ~~Because the studied glacier is located at high elevations near the top of the troposphere and features relatively high DOC/BC ratios in the snowpit samples (Fig. S6), the radiative forcing caused by DOC relative to BC should also be high.~~

Our results showed that the relative radiative forcing caused by DOC relative to BC ranged from 2.1 % to 30.4 % (9.5 ± 8.4 %) for snowpit samples and from 0.01 % to 0.5 % (0.1 ± 0.1%) for surface ice samples (Fig. S4~~5~~).~~,~~ The high radiative forcing ratio of snowpit samples was caused by its higher DOC/BC (0.65) than that of surface ice (0.012) (Fig. S5), and the low ratio of DOC/BC in surface ice was caused by enrichment of BC in surface glacier ice during the intensive ablation period (Xu et al., 2009)~~mainly because of the higher DOC/BC ratio (0.65) in the snowpit samples than in the ice samples (0.012) (Fig. S6). The value in ice was much lower due to the enrichment of BC in surface glacier ice during the intensive ablation period (Xu et al., 2009).Therefore, the relative radiative forcing contribution of DOC relative to BC in snowpit samples on LHG glacier was comparable with those of aerosols in urban areas of New Delhi, India (Kirillova et al., 2014b). The value in ice was much lower due to the enrichment of BC in surface glacier ice during the intensive ablation period (Xu et al., 2009).~~ Snowpit samples can be approximately considered to be fresh snow; thus, it is concluded that radiative forcing caused by DOC is a non-ignorable contributor in addition to BC in reducing the albedo of a glacier when the glacier is covered by fresh snow.

3.4 DOC export during the melt season

The two-year average discharge-weighted DOC concentration was 23~~7.5~~8 ± 9~~5.6~~6 μg L^{-1} during the melting period, comparable with the proglacial streamwater of Mount Nyainqentanglha glacier in the southern TP (Spencer et al., 2014). Seasonally, high DOC concentrations appeared during the low discharge periods (May to July and September to October) (Fig. 7~~6~~), suggesting that DOC concentrations were slightly enriched to some extent. However, there were no clear diurnal variations in the DOC concentrations with the discharge, suggesting that the discharge from different parts of the glacier was well mixed at the glacier terminus (Fig. S6~~7~~).

The seasonal variations in DOC flux were similar to those of the discharge (Fig. 7~~6~~), indicating

that discharge (rather than DOC concentrations) played a dominant role in the DOC mass flux. Hence, the majority of the glacier DOC export occurred during the summer melting season. Over the whole melting season, the annual flux of DOC from LHG glacier was 192~~.0~~ kg km^{-2} yr^{-1}, with peak DOC fluxes from mid-late July to late August (70 % of the annual flux). Combined with the value of BDOC determined above, at least ~~3,001.5~~3211 kg C yr^{-1} was ready to be decomposed and returned to the atmosphere as CO_2 within one month of its release, producing positive feedback in the global warming process.

When it comes to the entire TP, it is obvious that proglacial streamwater DOC concentrations (Table S2) showed similar spatial variation to that of snowpit DOC (Li et al., 2016), with high and low value appeared at north and south TP, respectively, reflecting good succession of proglacial streamwater DOC concentration to that of snowpit samples. Therefore, it was calculated that DOC flux in proglacial streamwater of the total TP glacier was around 12.7-13.2 Gg C (Gg = 10^9 g) based on average proglacial streamwater DOC concentration of 193 μg L^{-1} (Table S2) and annual glacial meltwater runoff in China of 66-68.2 km^3 (Xie et al., 2006), which is higher than that of DOC deposition (5.6 Gg C) at glacial region of the TP (Li et al., 2016), agree well with the negative water balance of the glaciers of the TP. Therefore, the TP glaciers can be considered as a carbon source under present environment condition.

4 Conclusions and implications

The concentrations and light absorption characteristics of DOC on a typical glacier in the northern TP were reported in this study. The mean DOC concentrations of snowpit samples, fresh snow, surface ice and proglacial streamwater were 332~~.4~~ ± 132~~.3~~ μg L^{-1}, 229~~.3~~ ± 104~~.4~~ μg L^{-1}, 42~~5.8~~6 ± 2~~69.9~~70 μg L^{-1} and 23~~7.5~~8 ± 9~~5.6~~6 μg L^{-1}, respectively. These values were slightly higher or comparable to those of other regions, such as the European Alps and Alaska (Singer et al., 2012; Fellman et al., 2015). DOC in the snowpit samples was significantly correlated with Ca^{2+}, a typical cation in mineral dust, indicating that mineral dust transported from adjacent arid regions made important contributions to DOC of the studied glacierized regions except autochthonous or *in situ* biological activities. In addition, the light absorption profile of the snowpit DOC was similar to that of dust from potential source deserts, providing further evidence of the influence of desert sourced mineral dust on snowpit DOC. Based on the previous published radiative forcing data of black carbon in snowpit of LHG (Ming et al., 2013), ~~For~~ for the first time, it is estimated that the radiative forcing caused by snowpit DOC was 0.43 W

m^{-2}~~accounts for 9.5 ± 8.4 % and 0.1 ± 0.1 % relative to that of BC in the snowpit samples and surface ice, respectively~~, accounting for around 10 % of the radiative forcing caused by BC. Therefore, in addition to BC, DOC is also an important agent in terms of absorbing solar radiation in glacierized regions, especially when the glacier is covered by fresh snow~~, which contains high DOC/BC ratios.~~ It has also been proven that water-insoluble organic carbon has ~~a~~ stronger light absorption ability (Chen and Bond, 2010). Therefore, the total contribution of OC to light absorption in glacierized regions should be higher, which requires further study in the future. Wet deposition is the most effective way of removing carbonaceous matter from the atmosphere (Vignati et al., 2010), and the removal ratio of OC in remote areas is almost the same as that of BC after long-range transport from source regions (Garrett et al., 2011). Because snowpit samples directly reflect the wet and dry deposition of carbonaceous matter, it is assumed that the contribution of radiative forcing for water soluble organic carbon ~~WSOC~~ relative to BC in the atmosphere in glacierized regions should be close to that of the snowpit samples in this study.

Because proglacial streamwater from different parts of the glacier is well mixed, no clear diurnal variations in DOC concentrations have been found. Combined with discharge and the corresponding DOC concentration, it was calculated that approximate 192.0 kg km^{-2} yr^{-1} of DOC was released from LHG glacier. It was also calculated that approximately 4~~6~~3.3~~2~~ % of the DOC could be decomposed within 28 days; thus, 3,~~001.5~~211 kg C yr^{-1} would return to the atmosphere as CO_2, producing positive feedback in the warming process. Although the flux of DOC from the studied glacier is small, when it comes to the entire TP ~~he number of glacial rivers across the entire TP and surrounding areas may be large due to the glacial area of approximately 100,000 km^2 (Yao et al. 2012). These factors need to be comprehensively studied in the future.~~DOC flux from glaciers of the total TP was around 12.7-13.2 Gg C.

Acknowledgements. This study was supported by the National Nature Science Foundation of China (41225002, 41271015, 41121001), State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2015-10 and SKLCS-OP-2014-05) and the Academy of Finland (decision number 268170). The authors acknowledge the staff of the Qilian Shan Station of Glaciology and Ecological Environment, Chinese Academy of Science.

References

Andreae, M. and Gelencsér, A.: Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols, Atmos. Chem. Phys., ~~Atmospheric Chemistry and Physics,~~6, 3131-3148, 2006.

Anesio, A. M., Hodson, A. J., Fritz, A., Psenner, R., and Sattler, B.: High microbial activity on glaciers: importance to the global carbon cycle, Global Change Biol.,~~Global Change Biology~~ 15, 955-960, 2009.

Anesio, A. M. and Laybourn-Parry, J.: Glaciers and ice sheets as a biome, Trends Ecol. Evol.~~Trends in Ecology & Evolution~~, 27, 219-225, 2012.

Antony, R., Grannas, A. M., Willoughby, A. S., Sleighter, R. L., Thamban, M., and Hatcher, P. G.: Origin and sources of dissolved organic matter in snow on the East Antarctic ice sheet, Environ. Sci. Technol., ~~Environmental science & technology,~~ 48, 6151-6159, 2014.

Antony, R., Mahalinganathan, K., Thamban, M., and Nair, S.: Organic Carbon in Antarctic Snow: Spatial Trends and Possible Sources, Environ. Sci. Technol.,~~Environmental Science & Technology,~~ 45, 9944-9950, 2011.

Bhatia, M. P., Das, S. B., Longnecker, K., Charette, M. A., and Kujawinski, E. B.: Molecular characterization of dissolved organic matter associated with the Greenland ice sheet, Geochim. Cosmochim. Acta., ~~Geochimica et Cosmochimica Acta,~~74, 3768-3784, 2010.

Bhatia, M. P., Das, S. B., Xu, L., Charette, M. A., Wadham, J. L., and Kujawinski, E. B.: Organic carbon export from the Greenland ice sheet, Geochim. Cosmochim. Acta.,~~Geochimica et Cosmochimica Acta,~~ 109, 329-344, 2013.

Bond, T. C., and Bergstrom, R. W.: Light Absorption by Carbonaceous Particles: An Investigative Review, Aerosol Sci. Technol., 40, 27-67, 10.1080/02786820500421521, 2006.

Bosch, C., Andersson, A., Kirillova, E. N., Budhavant, K., Tiwari, S., Praveen, P., Russell, L. M., Beres, N. D., Ramanathan, V., and Gustafsson, Ö.: Source - diagnostic dual - isotope composition and optical properties of water - soluble organic carbon and elemental carbon in the South Asian outflow intercepted over the Indian Ocean, J. Geophys. Res. Atmos.,~~Journal of Geophysical Research: Atmospheres,~~ 119, 11,743-711,759, 2014.

Chen, Y. and Bond, T. C.: Light absorption by organic carbon from wood combustion, Atmos. Chem. Phys.,~~Atmospheric Chemistry and Physics~~ 10, 1773-1787, 2010.

Cheng, Y., He, K. B., Zheng, M., Duan, F. K., Du, Z. Y., Ma, Y. L., Tan, J. H., Yang, F. M., Liu, J. M., Zhang, X. L., Weber, R. J., Bergin, M. H., and Russell, A. G.: Mass absorption efficiency of elemental carbon and water-soluble organic carbon in Beijing, China, Atmos. Chem. Phys.,~~Atmospheric Chemistry and Physics~~ 11, 11497-11510, 2011.

Dong, Z., Qin, D., Chen, J., Qin, X., Ren, J., Cui, X., Du, Z., and Kang, S.: Physicochemical impacts of dust particles on alpine glacier meltwater at the Laohugou Glacier basin in western Qilian Mountains, China, Sci. Total Environ.~~The Science of the total environment~~, 493, 930-942, 2014a.

Dong, Z., Qin, D., Kang, S., Ren, J., Chen, J., Cui, X., Du, Z., and Qin, X.: Physicochemical characteristics and sources of atmospheric dust deposition in snow packs on the glaciers of western Qilian Mountains, China, Tellus B, 66, 2014b.

Du, W., Qin, X., Liu, Y. S., and Wang, X. F.: Variation of Laohugou Glacier No. 12 in Qilian Mountains, Journal of Glaciology and Geocryology, 30, 373-379, 2008 (in Chinese with English abstract).

Fellman, J. B., Hood, E., Raymond, P. A., Stubbins, A., and Spencer, R. G. M.: Spatial Variation in the Origin of Dissolved Organic Carbon in Snow on the Juneau Icefield, Southeast Alaska, Environ. Sci. Technol.,~~Environmental Science & Technology,~~ doi: 10.1021/acs.est.5b02685, 2015. ~~2015.~~

Fellman, J. B., Spencer, R. G. M., Hernes, P. J., Edwards, R. T., D'Amore, D. V., and Hood, E.: The impact of glacier runoff on the biodegradability and biochemical composition of terrigenous dissolved organic matter in near-shore marine ecosystems, Mar. Chem.,~~Marine Chemistry,~~ 121, 112-122, 2010.

~~Fitzgerald, W. F.: Clean hands, dirty hands: Clair Patterson and the aquatic biogeochemistry of mercury, Clean Hands: Clair Patterson's Crusade Against Environmental Lead Contamination, 1999. 119-137, 1999.~~

Garrett, T. J., Brattström, S., Sharma, S., Worthy, D. E. J., and Novelli, P.: The role of scavenging in the seasonal transport of black carbon and sulfate to the Arctic, Geophys. Res. Lett.,~~Geophysical Research Letters,~~ 38, L16805, doi:10.1029/2011GL048221~~n/a-n/a~~, 2011.

Hagler, G. S. W., Bergin, M. H., Smith, E. A., Dibb, J. E., Anderson, C., and Steig, E. J.: Particulate and water-soluble carbon measured in recent snow at Summit, Greenland, Geophys. Res. Lett.,~~Geophysical Research Letters,~~ 34, L16505, doi:10.1029/2007GL030110~~n/a-n/a~~, 2007.

Hattori, Y., Suzuki, K., Honda, M., and Shimizu, H.: Re-Os isotope systematics of the Taklimakan Desert sands, moraines and river sediments around the Taklimakan Desert, and of Tibetan soils, Geochim. Cosmochim. Acta., 67, 1203-1213, 2003.

Hecobian, A., Zhang, X., Zheng, M., Frank, N., Edgerton, E. S., and Weber, R. J.: Water-Soluble Organic Aerosol material and the light-absorption characteristics of aqueous extracts measured over the Southeastern United States, Atmos. Chem. Phys.~~Atmospheric Chemistry and Physics~~, 10, 5965-5977, 2010.

Hood, E., Battin, T. J., Fellman, J., O'Neel, S., and Spencer, R. G. M.: Storage and release of organic carbon from glaciers and ice sheets, Nat. Geosci.~~Nature Geoscience~~, 8, 91-96, 2015.

Hood, E., Fellman, J., Spencer, R. G., Hernes, P. J., Edwards, R., D'Amore, D., and Scott, D.: Glaciers as a source of ancient and labile organic matter to the marine environment, Nature, 462, 1044-1047, 2009.

Hood, E. and Scott, D.: Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage, Nat. Geosci~~Nature Geoscience~~, 1, 583-587, 2008.

Huang, J., Kang, S., Guo, J., Sillanpää, M., Zhang, Q., Qin, X., Du, W., and Tripathee, L.: Mercury distribution and variation on a high-elevation mountain glacier on the northern boundary of the Tibetan Plateau, Atmos. Environ.~~Atmospheric Environment~~, 96, 27-36, 2014.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482, 514-518, 2012.

Kang, S., Mayewski, P. A., Qin, D., Yan, Y., Hou, S., Zhang, D., Ren, J., and Kruetz, K.: Glaciochemical records from a Mt. Everest ice core: relationship to atmospheric circulation over Asia, Atmos. Environ.,~~Atmospheric Environment,~~ 36, 3351-3361, 2002.

Kang, S., Wang, F., Morgenstern, U., Zhang, Y., Grigholm, B., Kaspari, S., Schwikowski, M., Ren, J., Yao, T., Qin, D., and Mayewski, P. A.: Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records, The Cryosphere, 9, 1213-1222, 2015.

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

Kang, S. C., Huang, J., and Xu, Y. W.: Changes in ionic concentrations and δ18O in the snowpack of Zhadang glacier, Nyainqentanglha mountain, southern Tibetan Plateau, Ann. Glaciol.~~Annals of Glaciology~~, 49, 127-134, 2008.

Kaspari, S., Painter, T. H., Gysel, M., Skiles, S. M., and Schwikowski, M.: Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings, Atmos. Chem. Phys.~~Atmospheric Chemistry and Physics~~, 14, 8089-8103, 2014.

Kirchstetter, T. W.: Evidence that the spectral dependence of light absorption by aerosols is affected by organic carbon, J. Geophys. Res.~~Journal of Geophysical Research~~, 109, D21208, doi:10.1029/2004JD004999, 2004.

Kirillova, E. N., Andersson, A., Han, J., Lee, M., and Gustafsson, Ö.: Sources and light absorption of water-soluble brown carbon aerosols in the outflow from northern China, Atmos. Chem. Phys. Discuss.~~Atmospheric~~

~~Chemistry and Physics Discussions~~, 13, 19625-19648, 2013.

Kirillova, E. N., Andersson, A., Han, J., Lee, M., and Gustafsson, Ö.: Sources and light absorption of water-soluble organic carbon aerosols in the outflow from northern China, Atmos. Chem. Phys.~~Atmospheric Chemistry and Physics~~, 14, 1413-1422, 2014a.

Kirillova, E. N., Andersson, A., Tiwari, S., Srivastava, A. K., Bisht, D. S., and Gustafsson, Ö.: Water-soluble organic carbon aerosols during a full New Delhi winter: Isotope-based source apportionment and optical properties, J. Geophys. Res. Atmos.,~~Journal of Geophysical Research: Atmospheres,~~ 119, 3476-3485, 2014b.

Lambe, A. T., Cappa, C. D., Massoli, P., Onasch, T. B., Forestieri, S. D., Martin, A. T., Cummings, M. J., Croasdale, D. R., Brune, W. H., and Worsnop, D. R.: Relationship between oxidation level and optical properties of secondary organic aerosol, Environ. Sci. Technol.~~Environmental science & technology~~, 47, 6349-6357, 2013.

Lawson, E. C., Wadham, J. L., Tranter, M., Stibal, M., Lis, G. P., Butler, C. E. H., Laybourn-Parry, J., Nienow, P., Chandler, D., and Dewsbury, P.: Greenland Ice Sheet exports labile organic carbon to the Arctic oceans, Biogeosci.~~Biogeosciences~~, 11, 4015-4028, 2014.

Legrand, M., Preunkert, S., Jourdain, B., Guilhermet, J., Fain, X., Alekhina, I., and Petit, J. R.: Water-soluble organic carbon in snow and ice deposited at Alpine, Greenland, and Antarctic sites: a critical review of available data and their atmospheric relevance, Clim. Past Discuss.~~Climate of the Past Discussions~~, 9, 2357-2399, 2013.

Levinson, R., Akbari, H., and Berdahl, P.: Measuring solar reflectance—Part I: Defining a metric that accurately predicts solar heat gain, Sol. Energy, 84, 1717-1744, 2010.

Li, C., Kang, S., Zhang, Q., and Kaspari, S.: Major ionic composition of precipitation in the Nam Co region, Central Tibetan Plateau, Atmos. Res.~~Atmospheric Research~~, 85, 351-360, 2007.

Li, C., Chen, P., Kang, S., Yan, F., Li, X., Qu, B., and Sillanp ää, M.: Carbonaceous matter deposition in the high glacial regions of the Tibetan Plateau, Atmos. Environ., 141, 203-208, 2016.

Li, J., Qin, X., Sun, W., zhang, M., and Yang, J.: Analysis on Micrometerological Characteristic in the Surface Layer of Laohugou Glacier No.12 Qilian Mountains, Plateau Meteorology, 31, 370-379, 2012.

Li, Z., Li, H., Dong, Z., and Zhang, M.: Chemical characteristics and environmental significance of fresh snow deposition on Urumqi Glacier No. 1 of Tianshan Mountains, China, Chinese Geographical Science, 20, 389-397, 2010.

Liu, J., Scheuer, E., Dibb, J., Ziemba, L. D., Thornhill, K., Anderson, B. E., Wisthaler, A., Mikoviny, T., Devi, J. J., and Bergin, M.: Brown carbon in the continental troposphere, Geophys. Res. Lett.~~Geophysical Research Letters~~, 41, 2191-2195, 2014.

May, B., Wagenbach, D., Hoffmann, H., Legrand, M., Preunkert, S., and Steier, P.: Constraints on the major sources of dissolved organic carbon in Alpine ice cores from radiocarbon analysis over the bomb - peak period, J. Geophys. Res. Atmos.~~Journal of Geophysical Research: Atmospheres~~, 118, 3319-3327, 2013.

Ming, J., Cachier, H., Xiao, C., Qin, D., Kang, S., Hou, S., and Xu, J.: Black carbon record based on a shallow Himalayan ice core and its climatic implications, Atmos. Chem. Phys.~~Atmospheric Chemistry and Physics~~, 8, 1343-1352, 2008.

Ming, J., Xiao, C., Du, Z., and Yang, X.: An overview of black carbon deposition in High Asia glaciers and its impacts on radiation balance, Adv. Water Resour., 55, 80-87, 2013.

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

Singer, G. A., Fasching, C., Wilhelm, L., Niggemann, J., Steier, P., Dittmar, T., and Battin, T. J.: Biogeochemically diverse organic matter in Alpine glaciers and its downstream fate, Nat. Geosci.~~Nature Geoscience~~, 5, 710-714, 2012.

Spencer, R. G., Stubbins, A., Hernes, P. J., Baker, A., Mopper, K., Aufdenkampe, A. K., Dyda, R. Y., Mwamba, V. L., Mangangu, A. M., and Wabakanghanzi, J. N.: Photochemical degradation of dissolved organic matter and dissolved lignin phenols from the Congo River, J. Geophys. Res. Biogeosci., 114, 2009.

Spencer, R. G. M., Guo, W., Raymond, P. A., Dittmar, T., Hood, E., Fellman, J., and Stubbins, A.: Source and biolability of ancient dissolved organic matter in glacier and lake ecosystems on the Tibetan Plateau, Geochim. Cosmochim. Acta~~Geochimica et Cosmochimica Acta~~, 142, 64-74, 2014.

Stubbins, A., Hood, E., Raymond, P. A., Aiken, G. R., Sleighter, R. L., Hernes, P. J., Butman, D., Hatcher, P. G., Striegl, R. G., Schuster, P., Abdulla, H. A. N., Vermilyea, A. W., Scott, D. T., and Spencer, R. G. M.: Anthropogenic aerosols as a source of ancient dissolved organic matter in glaciers, Nat. Geosci.~~Nature Geoscience~~, 5, 198-201, 2012.

Vignati, E., Karl, M., Krol, M., Wilson, J., Stier, P., and Cavalli, F.: Sources of uncertainties in modelling black carbon at the global scale, Atmos. Chem. Phys.~~Atmospheric chemistry and physics~~, 10, 2595-2611, 2010.

Wu, X., LI, Q., Wang, L., Pu, J., He, J., and Zhang, C.: Regional characteristics of ion concentration in glacial snowpits over the Tibetan Plateau and source analysis, Environment Science, 32, 971-975, 2011 (in Chinese with English abstract).

Xie, Z., Wang, X., Kang, E., Feng, Q., Li, Q., and Cheng, L.: Glacial runoff in China: an evaluation and prediction for the future 50 years, Journal of Glaciology and Geocryology, 28, 457-466, 2006.

Xu, B., Cao, J., Hansen, J., Yao, T., Joswia, D. R., Wang, N., Wu, G., Wang, M., Zhao, H., and Yang, W.: Black soot and the survival of Tibetan glaciers, PNAS~~Proceedings of the National Academy of Sciences~~, 106, 22114-22118, 2009.

Xu, J., Zhang, Q., Li, X., Ge, X., Xiao, C., Ren, J., and Qin, D.: Dissolved organic matter and inorganic ions in a central Himalayan glacier--insights into chemical composition and atmospheric sources, Environ Sci Technol, 47, 6181-6188, 2013.

Xu, J. Z., Zhang, Q., Wang, Z. B., Yu, G. M., Ge, X. L., and Qin, X.: Chemical composition and size distribution of summertime $PM_{2.5}$ at a high altitude remote location in the northeast of the Qinghai–Xizang (Tibet) Plateau: insights into aerosol sources and processing in free troposphere, Atmos. Chem. Phys., 15, 5069-5081, 2015.

~~Yan, F., Kang, S., Chen, P., LI, Y., Hu, Z., and Li, C.: Concentration and Source of dissolved organic carbon in snowpits of the Tibetan Plateau, Environmental Science, 8, 2827-2832, 2015.~~

Yao, T.: Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China, Sci. China Ser. D~~Science in China Series D~~, 47, 1065-1075, 2004a.

Yao, T.: Relationship between calcium and atmospheric dust recorded in Guliya ice core, Chin. Sci. Bull.~~Chinese Science Bulletin~~, 49, 706-710, 2004b.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Change~~Nature Climate Change~~, doi: 10.1038/nclimate1580, 2012.~~2012.~~

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.~~Environmental science & technology~~, 46, 5404-5413, 2012a.

Zhang, Q., Kang, S., Gabrielli, P., Loewen, M., and Schwikowski, M.: Vanishing High Mountain Glacial Archives: Challenges and Perspectives, Environ Sci Technol, 49, 9499-9500, 2015.

Zhang, Y., Liu, S., Shangguan, D., Li, J., and Zhao, J.: Thinning and shrinkage of Laohugou No. 12 glacier in the Western Qilian Mountains, China, from 1957 to 2007, Journal of Mountain Science, 9, 343-350, 2012b.

Zhao, R., Lee, A. K. Y., Huang, L., Li, X., Yang, F., and Abbatt, J. P. D.: Photochemical processing of aqueous atmospheric brown carbon, Atmos. Chem. Phys. Discuss.~~Atmospheric Chemistry and Physics Discussions~~, 15,

983 2957-2996, 2015.
984

985 **Table 1**. Sampling information for snow, ice and proglacial streamwater in this study.

Sample type	Sampling time	Resolution※	Sampling site	Number (n)	Index
Snowpit	30th July, 2014	5 cm	4989 m	15	DOC, absorbance, ions
Snowpit	25th August, 2015	5 cm	5050 m	23	DOC, absorbance, ions
Surface fresh snow	4th August, 2014	100 m	4450-4900 m	18	DOC
Surface ice	6th August, 2014	100 m	4350-4900 m	20	DOC
Surface snow	16th July, 2015	50 m	4350-4850 m	11	DOC
Surface ice	15th August, 2015	50 m	4350-4850 m	11	DOC
Surface ice	25th August, 2015	50 m	4350-4600 m	6	DOC, absorbance
Subsurface ice	25th August, 2015	50 m	4350-4600 m	5	DOC, absorbance
Proglacial streamwater	29th-30th July, 2014	2h (day),4h (night)	4210 m	17	DOC
Proglacial streamwater	20th May-9th October, 2015	Every day	4210 m	184	DOC

986 ※ for snowpit it is vertical resolution, for surface ice and snow it is horizontal distance.

987

988

Table 2~~1~~. Comparison of DOC concentrations in snow ~~and,~~ ice and proglacial streamwater from the glacier in this study and glaciers in other regions.

Sites	DOC concentration ($\mu g\ L^{-1}$)	Sample types	References
Laohugou glacier (LHG)	332~~.4~~ ±132~~.3~~	Snowpit	This study
Tanggula glacier (TGL)	21~~6.9~~7 ±14~~2.8~~3	Snowpit	~~(~~Yan et al. ~~(,~~ 2015)
Mount Everest (EV)	15~~2.5~~3 ±56~~.1~~1	Snowpit	
Mendenhall Glacier, Alaska	190	snowpit	~~(~~Stubbins et al.~~,~~ (2012)
Greenland ice sheet	40~~.3~~1 - 5~~6.9~~7	Snowpit	~~(~~Hagler et al.~~,~~ (2007)
Laohugou glacier (LHG)	229~~.3~~ ±104~~.4~~	Surface snow	This study
Greenland ice sheet	111~~.2~~	Surface snow	~~(~~Hagler et al.~~,~~ (2007)
Juneau Icefield, Southeast Alaska	100 - 300	Fresh snow/snowpits	~~(~~Fellman et al. ~~,~~(2015)
Laohugou glacier (LHG)	42~~5.8~~6 ±2~~69.9~~70	Surface ice	This study
Mount Nyainqentanglha Glacier	212~~.4~~	Glacier ice	~~(~~Spencer et al.~~,~~ (2014)
Antarctic ice sheet	460 ±120	Surface ice	~~(~~Hood et al.~~,~~ (2015)
Alpine glacier	138 ±96	Subsurface ice	~~(~~Singer et al.~~,~~ (2012)
Laohugou glacier (LHG)	23~~7.5~~8 ±9~~5.6~~6	Proglacial streamwater	This study
Mount Nyainqentanglha Glacier	26~~1.6~~2	Proglacial streamwater	~~(~~Spencer et al. ~~,~~(2014)
Mendenhall Glacier, Alaska	380 ±20	Proglacial streamwater	~~(~~Stubbins et al.~~,~~ (2012)

Table 3~~2~~. Mass absorption cross section (MAC) and Absorption Ångström Exponent ($AAE_{330-400}$) of ice and snow from LHG glacier and aerosols from other regions.

Site/Source	MAC (m^2 g^{-1})	$AAE_{330-400}$	λ (MAC)	References
LHG glacier	1.4 ±0.4 (snow) 1.3 ±0.7 (ice)	5.0 ±5.9 (snow) 3.4 ±2.7 (ice)	365	This study
Biomass smoke	5.0	4.8	350	(Kirchstetter~~,~~et al. (2004)
Secondary organic aerosols	0.001 - 0.088	5.2 - 8.8	405	(Lambe et al.~~,~~ (2013)
Wood smoke	0.13 - 1.1	8.6 - 17.8	400	(Chen and Bond~~,~~ (2010)
HULIS, Arctic snow	2.6 ±1.1	6.1※a	250	(Voisin et al. ~~,~~(2012)
Beijing, China (winter)	1.79 ±0.24	7.5	365	(Cheng et al.~~,~~ (2011)
Beijing, China (summer)	0.71 ±0.20	7.1	365	(Cheng et al.~~,~~ (2011)

~~a~~※ the wavelength range for AAE of this study is 的波长范围为 300 - 550 nm

Figure 1. Location map of LHG glacier No. 12.

Figure 2. Average DOC concentrations of ice, snow and proglacial streamwater for LHG glacier.

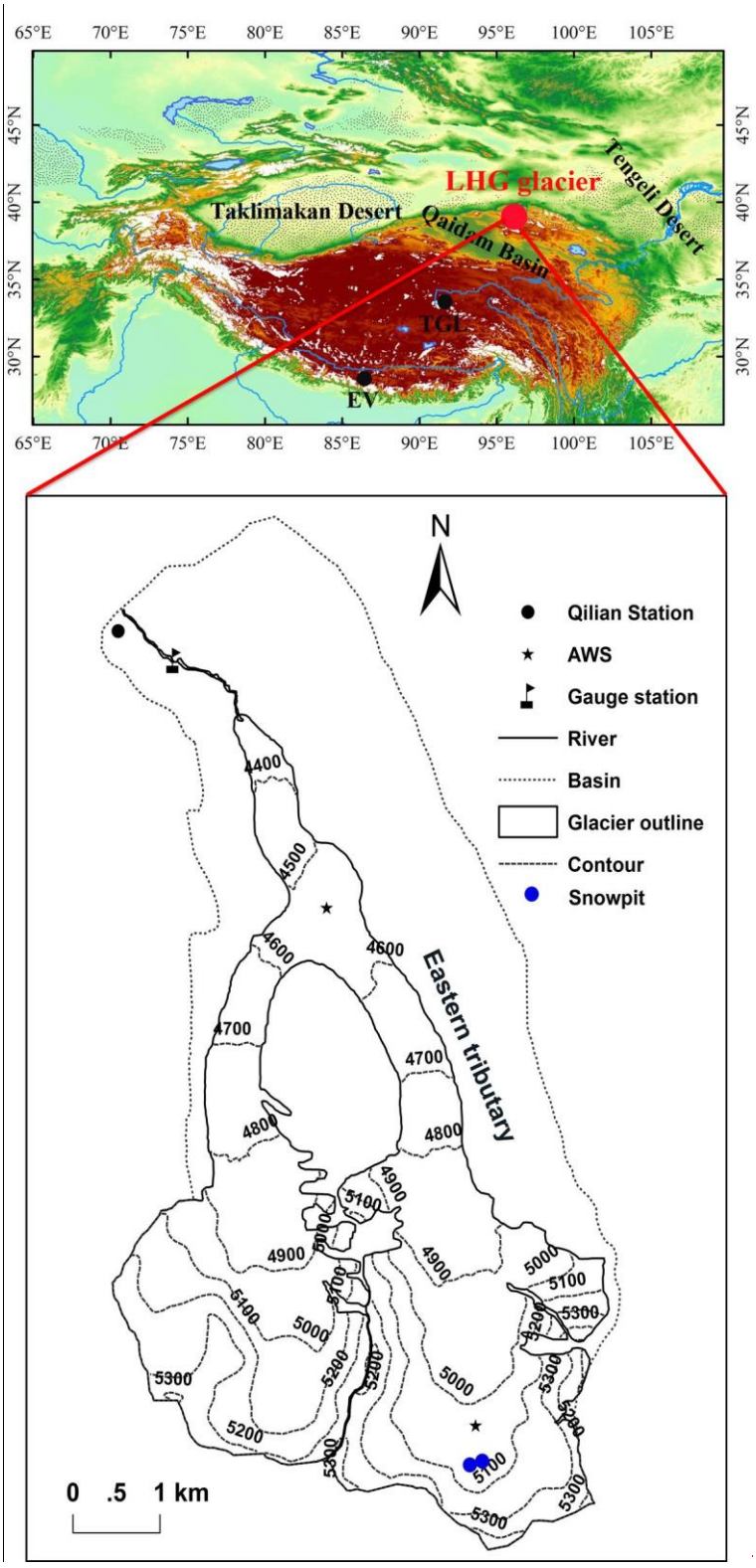
Figure 3. Variation in DOC concentrations in profiles of studied snowpits. The gray rectangles are dirty layers.

Figure ~~3~~4. Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue point is calculated using equations derived from the experimental data (black point).

Figure ~~4~~5. Absorption spectra for DOC in snow and ice of LHG glacier and the dust ~~and desert sand~~ from surrounding areas.

Figure ~~6~~5. Comparison of DOC concentrations (A) and MAC_{365} (B) between surface and subsurface ice.

Figure ~~7~~6. The discharge, DOC concentrations and fluxes exported from LHG glacier. Note: The concentrations with error bars include more than one sample on that day.



1010

1011

1012

1013

1014

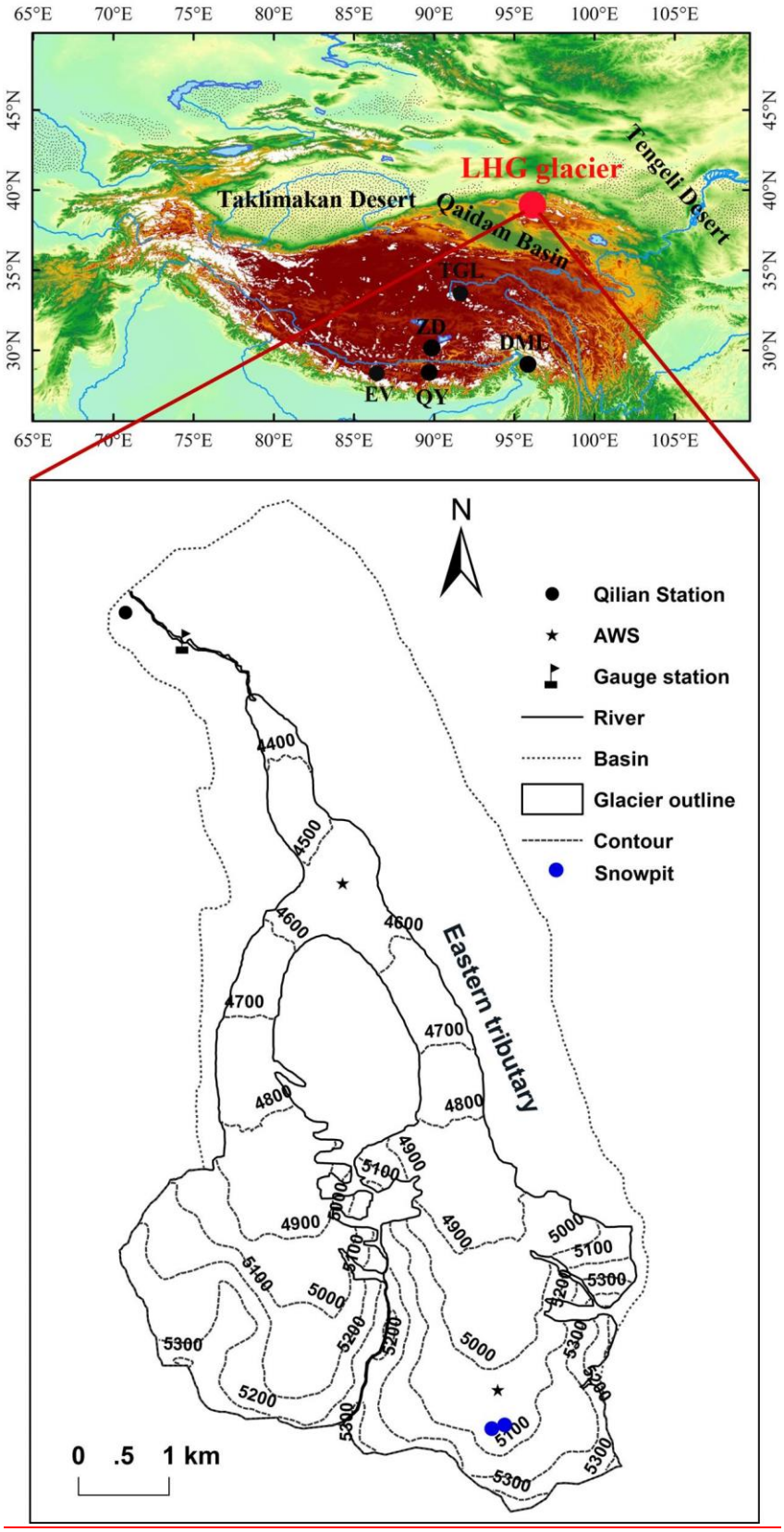


Figure 1. Location map of Laohugou glacier No. 12.

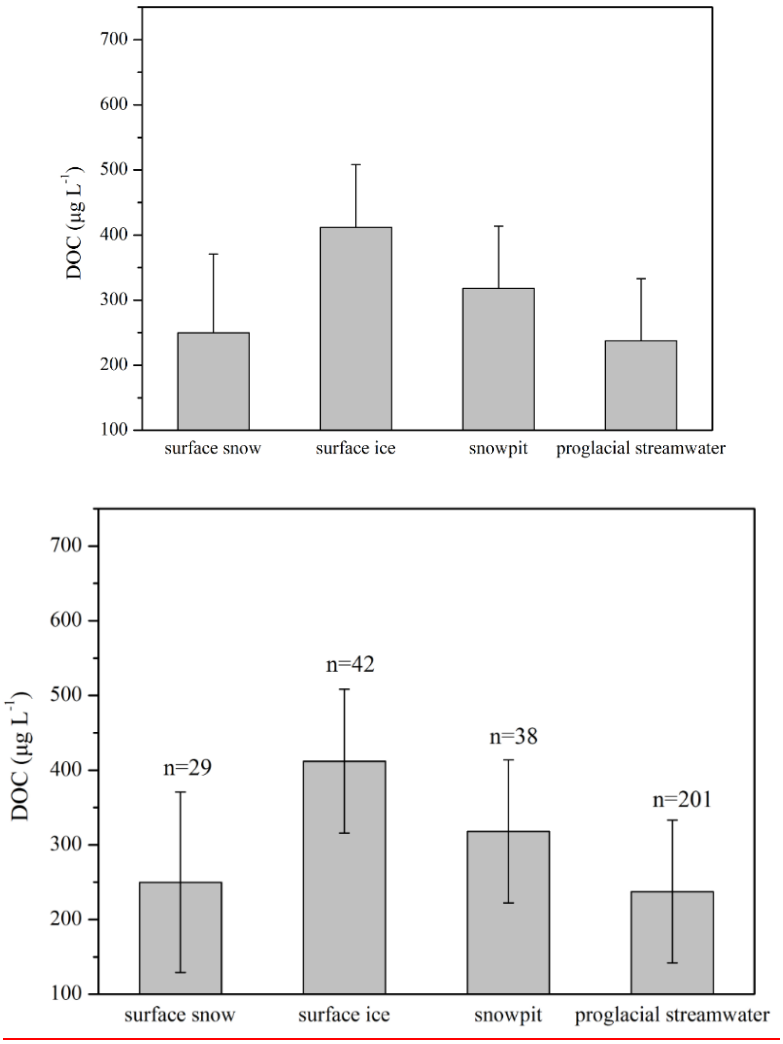


Figure 2. Average DOC concentrations of ice, snow and proglacial streamwater for LHG glacier.

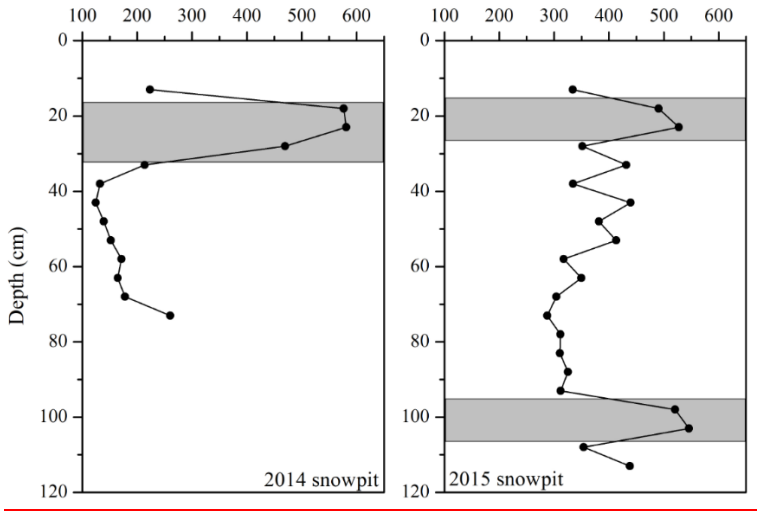


Figure 3. Variation in DOC concentrations in profiles of studied snowpits. The gray rectangles are dirty layers.

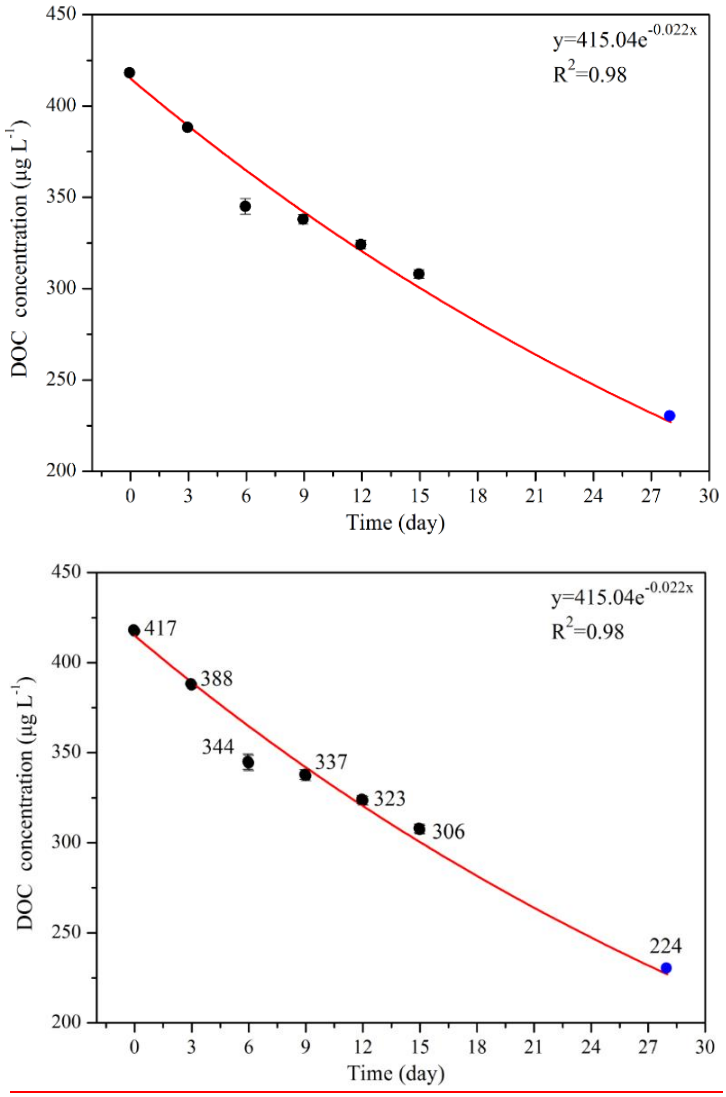


Figure 43. Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue point is calculated using equations derived from the experimental data (black point). Mean values ± standard deviations of duplicate treated samples are presented.

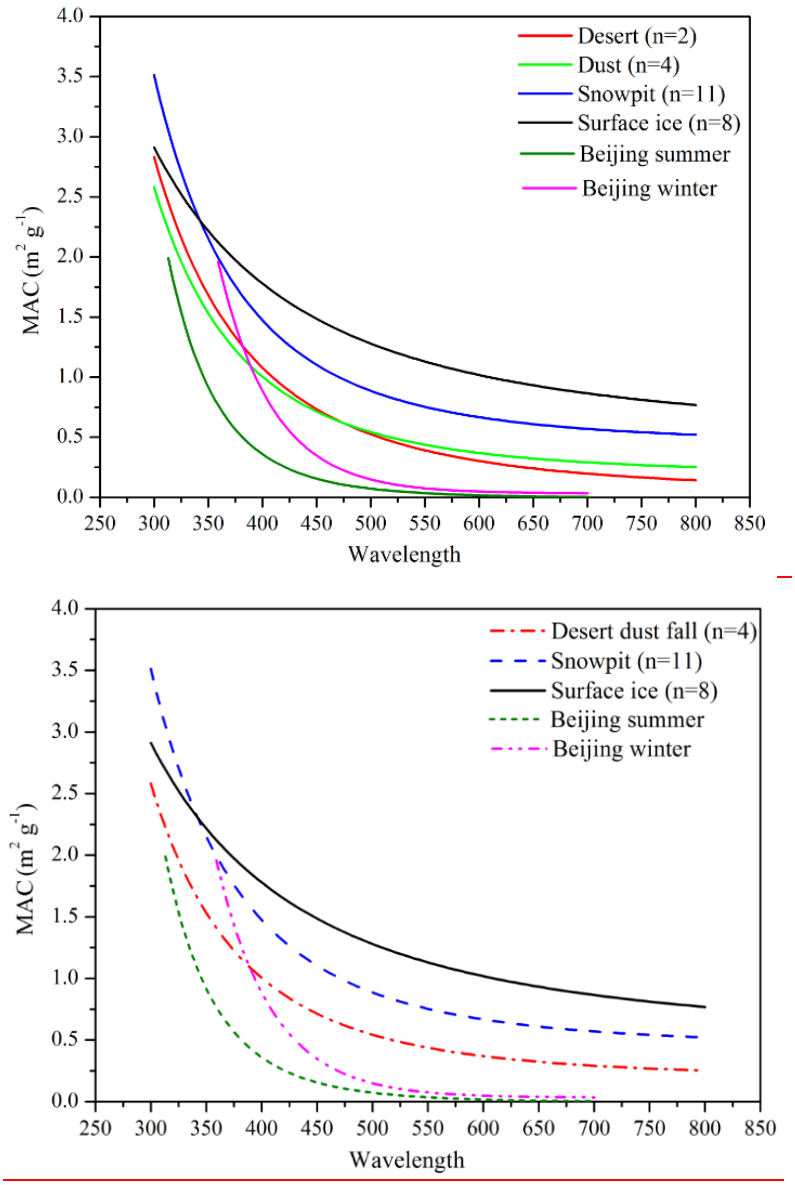


Figure 5~~4~~. Absorption spectra for ~~the~~ DOC in snow and ice of LHG glacier and the dust ~~and desert sand~~ from surrounding areas.

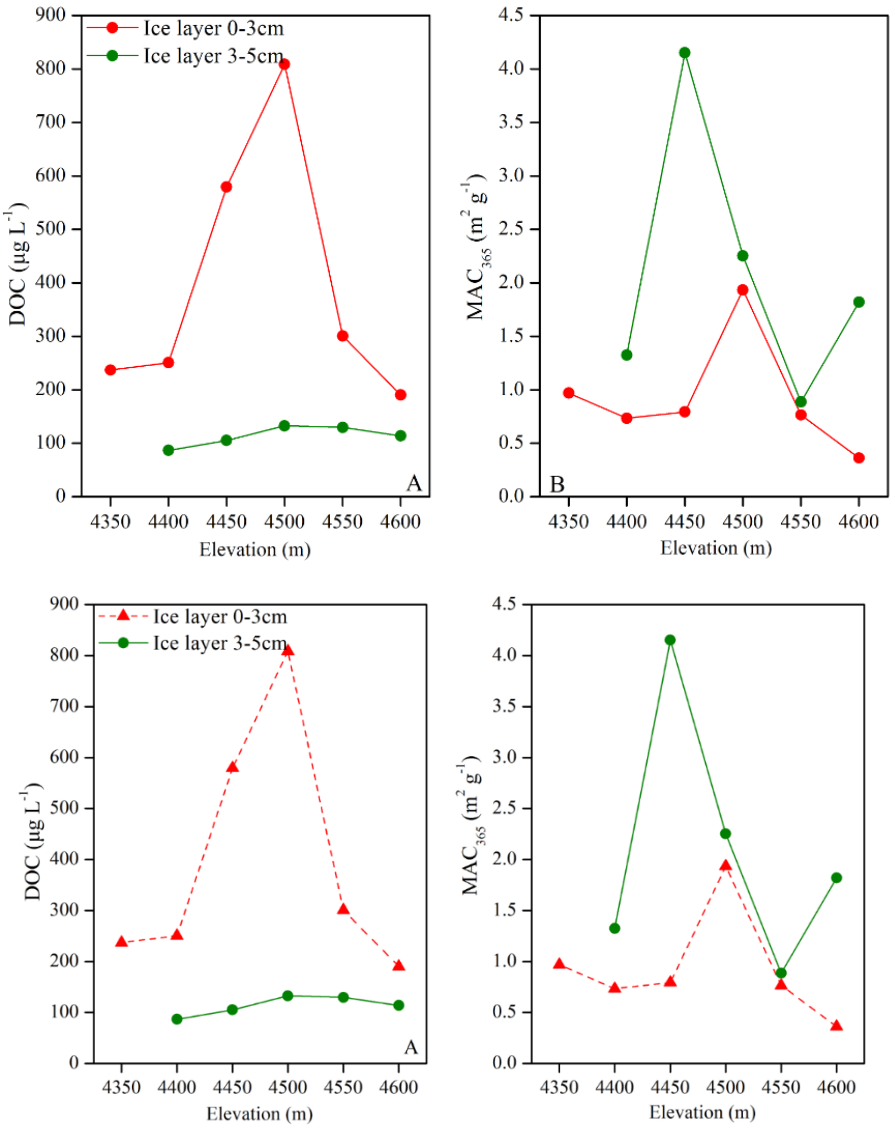


Figure 6~~5~~. Comparison of DOC concentrations (A) and MAC_{365} (B) between surface and subsurface ice.

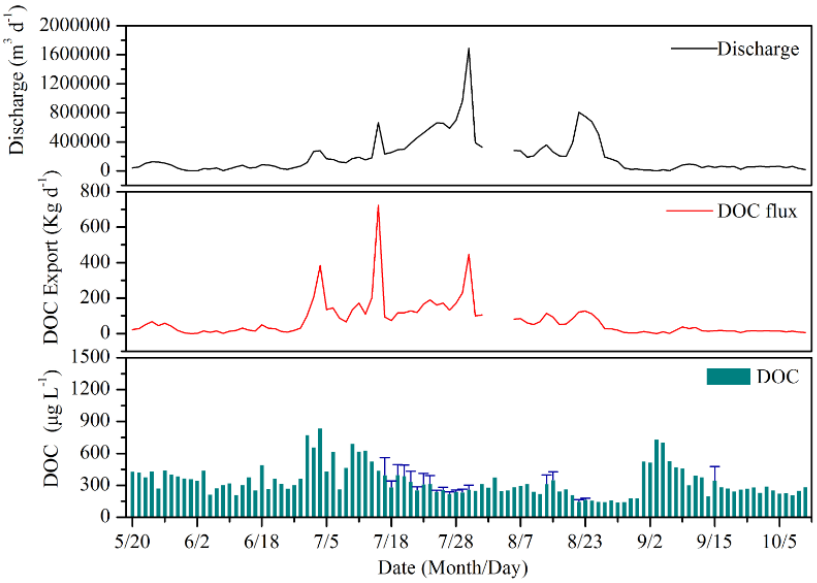


Figure 7~~6~~. The discharge, DOC concentrations and fluxes exported from LHG glacier. Note: The concentrations with error bars include more than one sample on that day.