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

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Abstract. Light-absorbing dissolved organic carbon (DOC) constitutes a major part of the organic carbon in the glacierized region. It has important influences on the carbon cycle and radiative forcing of glaciers. However, currently, few data are available in the glacierized region of the Tibetan Plateau (TP). In this study, DOC characteristics of a typical glacier (Laohugou glacier No. 12 (LHG glacier)) in the Northeastern TP were investigated. Generally, DOC concentrations on LHG glacier were comparable to other glacierized regions around the world. The average DOC concentrations in snowpits, surface snow, surface ice (superimposed ice) and proglacial streamwater were 332.4±132.3 μg L^{-1}, 229.3±104.4 μg L^{-}

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[1], 425.8±269.9 μg L^{-1}, and 237.5±95.6 μg L^{-1}, respectively. It was estimated that the annual DOC flux released from this glacier was 6,949.4 kg C yr^{-1}, of which 43.2% DOC was bioavailable and could be decomposed into CO_2 within 28 days 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 those of dust transported from adjacent deserts. Based on this finding and the significant relationship between DOC and Ca^{2+}, it was proven that the main source of DOC of this glacier was mineral dust. 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.

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

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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 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).

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 (Stubbins et al., 2012; Bhatia et al., 2013; Lawson et al., 2014 ; 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), with large variations in concentrations and ages (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 late May and July (Bhatia et al., 2013). Additionally, 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 these 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). 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). 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

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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 region 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 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; Kang et al., 2015) and anthropogenic carbonaceous particle deposition (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 region on the TP, despite some investigations of concentrations and sources (Spencer et al., 2014; Yan et al., 2015). The primary results of these studies have showed that DOC concentrations in snowpits in the northeastern TP were higher than those in the southern TP (Yan et al., 2015). In addition, a large fraction of the ancient DOC in the glacier 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, ice and proglacial streamwater samples (n=310) (Table S1, Fig. 1) were collected from a typical glacier in the northeastern TP (Laohugou glacier No. 12 (LHG glacier)) based on the preliminary research of snowpit samples (Yan et al., 2015). 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 characteristics and carbon dynamics in this glacieried 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

LHG glacier is the largest mountain glacier (9.85 km, 20.4 km^2) in the Qilian Mountains located on the northeastern edge of the TP (39°05'-40'N, 96°07'-97°04'E 4260-5481 m) (Du et al., 2008; 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).

The LHG glacier features typical continental and arid climate characteristics (Li et al., 2012; Zhang

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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 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, 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 S1). The concentrations of glacier DOC have been observed to be very low and prone to contamination, causing an overestimation of DOC concentration (Legrand et al., 2013). Therefore, during the whole sampling procedure, samples were collected according to the "Clean hands-Dirty Hands" principle to prevent any contamination (Fitzgerald, 1999). Meanwhile, at least one blank was made for every sampling process to confirm that the contamination was low (Table S2). Moreover, 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) and these results will be presented in another article.

All the collected samples were stored in 125 mL pre-cleaned polycarbonate bottles, 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 samples from Dunhuang (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 characteristic of dust-sourced DOC to those of the snowpit and ice samples.

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 31.9 ±7.4 μg L^{-1}, demonstrating that contamination can be ignored

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126 during the pre-treatment and analysis processing of these samples (Table S2). The major cations (Ca^{2+},
127 Mg^{2+}, Na^{+}, K^{+} and NH_4^{+}) and major anions (Cl^{-}, NO_3^{-} and SO_4^{2-}) were measured using a Dionex-6000 Ion
128 Chromatograph and a Dionex-3000 Ion Chromatograph (Dionex, USA), respectively. The detection limit
129 was 1 μg L^{-1}, and the standard deviation was less than 5 % (Li et al., 2007; Li et al., 2010). The average
130 ion concentrations of the blank were very low and could be ignored (Na^{+}, K^{+}, Mg^{2+}, F^{+}, SO_4^{2-}, Cl^{-}, NO_3^{-} <
131 1 μg L^{-1}; NH_4^{+}=1.4 μg L^{-1}; Ca^{2+}=1.2 μg L^{-1}).

132 **2.3.2 Light absorption measurements**

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

137 $$\mathrm{MAC_{DOC}} = \frac{-\ln|\frac{I}{I_0}|}{C.L} = \frac{A}{C.L} \times \ln(10) \quad (1)$$

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

141 In order to investigate the wavelength dependence of DOC light absorption characteristics, the
142 Absorption Ångström Exponent (AAE) was fitted by the following equation (Kirillova et al.,
143 2014a;Kirillova et al., 2014b):

144 $$\frac{A(\lambda_1)}{A(\lambda_2)} = (\frac{\lambda_2}{\lambda_1})^{AAE} \quad (2)$$

145 AAE values were fitted from the wavelength of 330 to 400 nm, within this wavelength range, light
146 absorption by other inorganic compounds can be avoided (Cheng et al., 2011).

147 The radiative forcing caused by BC has been widely studied. Therefore, in this study, using a
148 simplistic model (the following algorithm) the amount of solar radiation absorbed by DOC compared to
149 BC was estimated:

150 $$f = \frac{\int_{300}^{2500} I_0(\lambda) \cdot \left\{1 - e^{-(MAC_{365}(\frac{365}{\lambda})^{AAE_{DOC}} \cdot C_{DOC} \cdot h_{ABL})}\right\} d\lambda}{\int_{300}^{2500} I_0(\lambda) \cdot \left\{1 - e^{-(MAC_{550}(\frac{550}{\lambda})^{AAE_{BC}} \cdot C_{EC} \cdot h_{ABL})}\right\} d\lambda} \quad (3)$$

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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 $MAC_{550}=7.5\pm1.2$ 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).

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 (550 ℃, 6 h) aluminum basins and melted in the field. The melted samples were filtered through pre-burned 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. The BDOC was calculated based on the discrepancies between 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 mineral dust deposition contributes to high DOC concentrations in LHG glacier. 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). The highest values appeared in the dirty layers (Fig. S1), similar to the pattern observed in the Greenland summit snowpit (Hagler et al., 2007) and glaciers in the southern TP (Xu et al., 2013), indicating DOC concentrations were mainly influenced by dust deposition in this region. Spatially, our results were higher than those of Tanggula glacier (TGL) in the middle TP and Rongbuk glacier on Mount Everest (EV) in the southern TP (Fig. 1) (Table 1) (Yan et al., 2015), which was similar to the distributions of mercury and particle on the TP

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180 (Zhang et al., 2012a).

181 **3.1.2 Surface snow and ice**

182 Average DOC concentration in LHG glacier surface snow was significantly lower than that in
183 surface ice because more impurities were presented in the latter (Fig. 2). Like those of the snowpits, DOC
184 concentrations in the glacier surface ice (Fig. 2) were higher than those in glacier of the southern TP
185 (Nyainqentanglha glacier) (Spencer et al., 2014) (Table 1) mainly due to heavy dust load of LHG glacier.
186 No significant relationship was found between DOC concentration and elevation for either the surface
187 snow or ice (Fig. S2), suggesting no "altitude effect" of DOC in this glacier. Therefore, the distributions
188 of DOC concentrations in the glacier surface snow and ice were influenced by complicated factors, such
189 as the terrain, surface moraine and atmosphere circulation. Furthermore, DOC concentrations of snow
190 and ice of this glacier were within the range of previously reported values for glacieried regions outside
191 the TP (Table 1).

192 **3.1.3 DOC bioavailability**

193 Previous studies conducted under controlled conditions (stable temperature) have shown that
194 glacier-derived DOC was more bioavailable than those of terrestrial-derived DOC (Hood et al., 2009;
195 Fellman et al., 2010). Our results showed that the amount of DOC being consumed decreased
196 exponentially over time (R^2=0.98) (Fig. 3), with approximately 26.7% (from 416.9 μg L^{-1} to 305.6 μg L^{-1})
197 degraded within 15 days during the experiment (average temperature: 3.8±3.7 ℃; range: -4.8-11.4 ℃).
198 BDOC reached 43.2% if the experiment duration was extended to 28 days, according to the equation
199 derived from the 15-day experiment (Fig. 3). Despite different incubation conditions, this finding agreed
200 well with the reports of BDOC from a glacier in the southern TP (28-day dark incubation at 20 ℃, 46-
201 69% BDOC) (Spencer et al., 2014) and European Alpine glaciers (50-day dark incubation at 4 ℃,
202 59±20% BDOC) (Singer et al., 2012). Therefore, the previous results obtained in the laboratory are close
203 to the reality and can be used to estimate the bioavailability of glacier-derived DOC.

204 **3.2 Sources of snowpit DOC**

205 The sources of glacier DOC are diverse and include microbial activities (viruses, bacteria and algae)
206 (Anesio et al., 2009), terrestrial inputs (DOC deposition from vascular plants and dust) (Singer et al.,
207 2012) and anthropogenic sources (fossil fuel and biomass combustion) (Stubbins et al., 2012). In this
208 study, major ions were adopted as indicators to investigate the potential sources of snowpit DOC, because

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the sources of major ions in snowpit samples from Tibetan glaciers have been investigated in detail (Kang et al., 2002; Kang et al., 2008). It was found that DOC and Ca^{2+} (a typical indicator of mineral dust) were significantly related (R^2=0.84, Fig. S3), suggesting that the major source of DOC was 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).

3.3 Light absorption characteristics of DOC

3.3.1 AAE

AAE is generally used to characterize the spectral dependence of the light absorption of DOC, which is important input data for radiative forcing calculations. The fitted $AAE_{330\text{-}400}$ values 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. S5). The relatively low $AAE_{330\text{-}400}$ values of ice indicated that the DOC experienced strong photo-bleaching due to long-duration exposure to solar irradiation. Previous studies have found that the AAE 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 photo-bleaching processes. In general, $AAE_{330\text{-}400}$ had a negative relationship with MAC_{365}, especially in the ice samples (Fig. S5), 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}

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} of DOC was 1.4±0.4 m^2 g^{-1} in snow and 1.3±0.7 m^2 g^{-1} in glacier ice (Fig. S5). The MAC values for DOC from different sources varied widely. Normally, the MAC_{365} of DOC derived from biomass combustion was as high as 5 m^2 g^{-1} (Kirchstetter, 2004). Correspondingly, the value for SOAs was as low as 0.001-0.088 m^2 g^{-1} (Lambe et al., 2013) and humic like substances (HULIS) in Arctic snow was 2.6±1.1 at 250 nm (Voisin et al., 2012) (Table 2). Due to the remote location of LHG glacier, it was

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239 considered that the snowpit DOC should be SOAs with low MAC_{365} values, however, the high MAC_{365}
240 value of the snowpit DOC indicated that these DOC may not be entirely derived from SOAs. Therefore,
241 it was proposed that mineral dust-sourced DOC caused high MAC_{365} values in the snowpit samples. The
242 light absorption characteristics of DOC from both snowpit and ice showed similar patterns to those of
243 WSOC in dust from the adjacent deserts, further indicating that LHG glacier DOC was transported via
244 mineral dust and shared similar light absorption characteristics (Fig. 4). Moreover, the difference in light
245 absorption characteristics (especially for wavelengths larger than 400 nm) between snow/ice samples
246 and aerosols in Beijing, China, also indicated different sources (Fig. 4) (Table 2). Light absorbance was
247 significantly correlated with DOC concentrations in both snow and ice samples (Fig. S4), suggesting that
248 DOC was one of the absorption factors. Nevertheless, MAC_{365} values of surface ice (0-3 cm) were lower
249 than those of subsurface layers (3-5 cm), despite its higher DOC concentrations (Fig. 5), reflecting
250 stronger DOC photo-bleaching in the surface ice due to the direct exposure to solar irradiation.

251 **3.3.3 Radiative forcing of DOC relative to BC**

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

259 Our results showed that the relative radiative forcing caused by DOC relative to BC ranged from
260 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
261 samples (Fig. S5), mainly because of the higher DOC/BC ratio (0.65) in the snowpit samples than in the
262 ice samples (0.012) (Fig. S6). The value in ice was much lower due to the enrichment of BC in surface
263 glacier ice during the intensive ablation period (Xu et al., 2009). Because snowpit samples can be
264 approximately considered to be fresh snow; thus, radiative forcing caused by DOC is a non-ignorable
265 contributor in addition to BC in reducing the albedo of a glacier when the glacier is covered by fresh
266 snow.

267 **3.4 DOC export during the melt season**

268 The two-year average discharge-weighted DOC concentration was 237.5±95.6 μg L^{-1} during the

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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. 6), suggesting that DOC concentrations were slightly enriched to some extent. However, there were no clear diurnal variations in DOC concentrations with the discharge, indicating that the discharge from different parts of the glacier was well mixed at the glacier terminus (Fig. S7).

The seasonal variations in DOC flux were similar to those of the discharge (Fig. 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 340.7 kg km^{-2} yr^{-1}, with peak DOC fluxes from mid-late July to late August (70% of annual flux). Combined with the value of BDOC determined above, at least 3,001.5 kg C yr^{-1} was ready to be decomposed and returned to the atmosphere as CO_2 within 28 days of its release, producing a positive feedback in the global warming process.

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 in snowpit sample, fresh snow, surface ice and proglacial streamwater were 332.4±132.3 μg L^{-1}, 229.3±104.4 μg L^{-1}, 425.8±269.9 μg L^{-1} and 237.5±95.6 μg L^{-1}, respectively. These values were slightly higher or comparable to those of other regions, such as the European Alps and Alaska. DOC in 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 region. In addition, the light absorption profile of snowpit DOC was similar to that of dust from potential source deserts, providing further evidence of the influence of mineral dust on snowpit DOC. For the first time, it is estimated that the radiative forcing caused by DOC accounted for 9.5±8.4 % and 0.1±0.1 % relative to that of BC, in the snowpit samples and surface ice, respectively. Therefore, in addition to BC, DOC is also an important agent in terms of absorbing solar irradiation in the glacierized region, 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 the glacierized region should be higher, which requires further study. Wet deposition is the most effective way of removing carbonaceous matter from the atmosphere (Vignati et al., 2010), and the

299 removal ratio of OC in remote areas is almost the same as that of BC after long-range transport from
300 source regions (Garrett et al., 2011). Because snowpit samples directly reflect the wet and dry depositions
301 of carbonaceous matter, it is assumed that the contribution of radiative forcing for WSOC relative to BC
302 in the atmosphere in glacierized regions should be close to that of the snowpit samples in this study.
303 Because proglacial streamwater from different parts of the glacier is well mixed, no clear diurnal
304 variations in DOC concentrations have been found. Combined with discharge and the corresponding
305 DOC concentration, it was calculated that approximately 340.7 kg km^{-2} yr^{-1} of DOC was released from
306 LHG glacier. It was also calculated that approximately 43.2% of the DOC could be decomposed within
307 28 days; thus, 3,001.5 kg C yr^{-1} would return to the atmosphere as CO_2, producing positive feedback in
308 the warming process. Although the flux of DOC from the studied glacier is small, the number of glacial
309 rivers across the entire TP and surrounding areas may be large due to the glacial area of approximately
310 100,000 km^2 (Yao et al. 2012). These factors need to be comprehensively studied in the future.
311
312
313 *Author contributions.* S. Kang was the lead scientist of the entire project. F. Yan wrote the first draft of the manuscript
314 with the significant help of C. Li. F. Yan did DOC and ions measurement. Y. Li and Y. Zhang helped with the sample
315 collection. X. Qin and X. Zhang provided the discharge data. M. Sillanp ää, B. Qu, P. Chen, Z. Hu and X. Li improved
316 the manuscript. S. Kang and C. Li conceived and designed the experiments.
317
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461 **Table 1**. Comparison of DOC concentrations in snow and ice from the glacier in this study and 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)	216.9±142.8	Snowpit	(Yan et al., 2015)
Mount Everest (EV)	152.5±56.1	Snowpit	
Mendenhall Glacier, Alaska	190	snowpit	(Stubbins et al., 2012)
Greenland ice sheet	40.3-56.9	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)	425.8±269.9	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)	237.5±95.6	Proglacial streamwater	This study
Mount Nyainqentanglha Glacier	261.6	Proglacial streamwater	(Spencer et al., 2014)
Mendenhall Glacier, Alaska	380±20	Proglacial streamwater	(Stubbins et al., 2012)

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

Site/Source	MAC (m^2 g^{-1})	AAE	λ	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, 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)

466 [a] AAE 的波长范围为 300-550 nm

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

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

470 Figure 3. Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue point

471 is calculated using equations derived from the experimental data (black point).

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

473 areas.

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

475 Figure 6. The discharge, DOC concentrations and fluxes exported from LHG glacier. Note: The concentrations with

476 error bars include more than one sample on that day.

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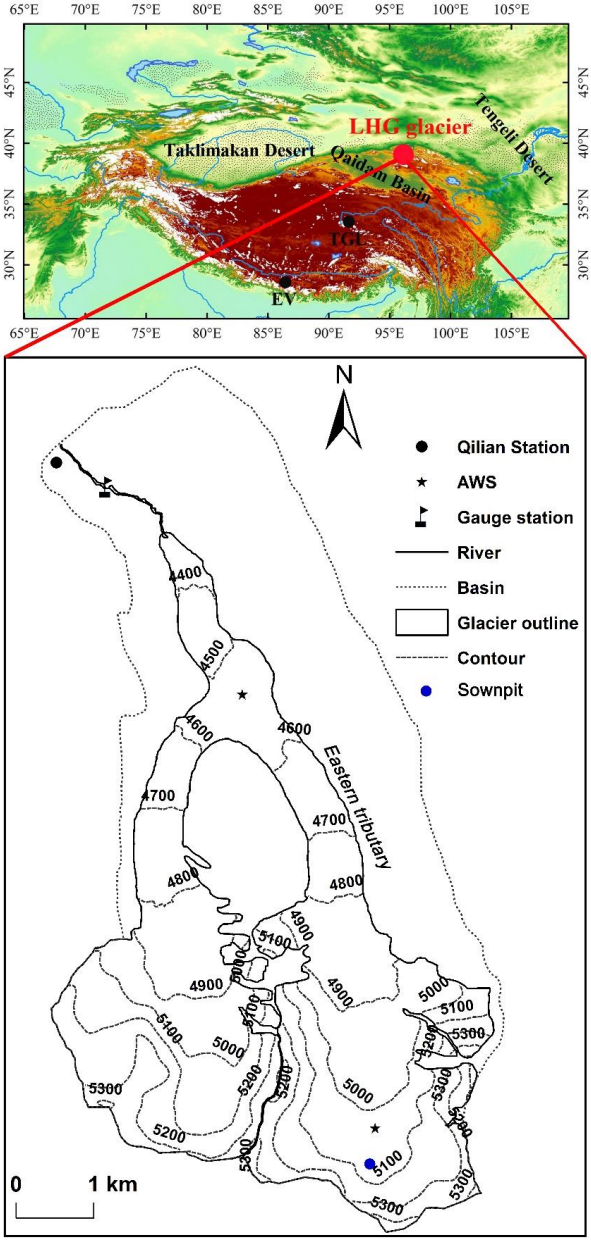

Figure 1. Location map of Laohugou glacier No. 12.

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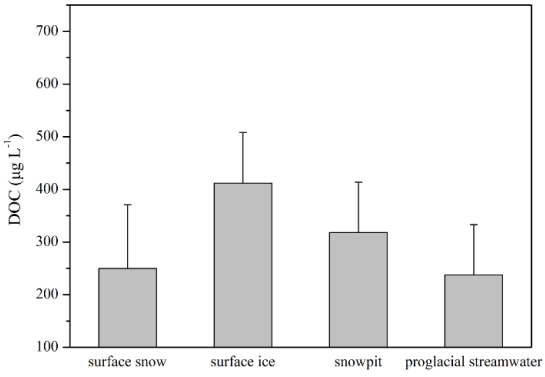

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485 **Figure 2**. Average DOC concentrations of ice, snow and proglacial streamwater of LHG glacier.

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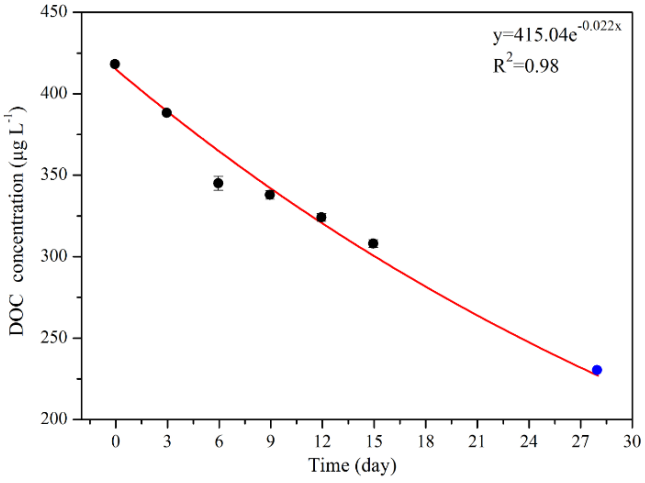

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488 **Figure 3**. Exponential deceases in DOC concentrations during the biodegradation experiment. Note: The blue

489 point is calculated using equations derived from the experimental data (black point). Mean values ± standard

490 deviation of duplicate treated samples are presented.

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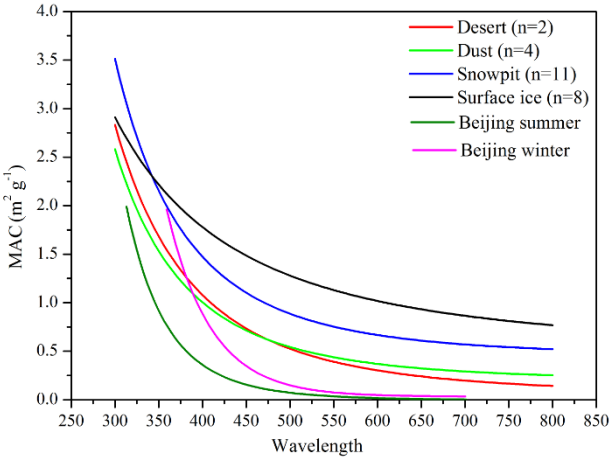

Figure 4. Absorption spectra for DOC in snow and ice of LHG glacier and the dust and desert sand from surrounding areas.

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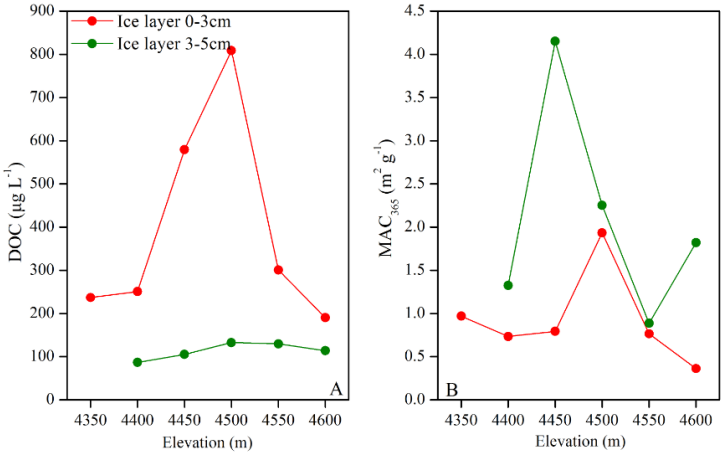

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500 **Figure 5**. Comparison of DOC concentrations (A) and MAC_{365} (B) between surface and subsurface ice.

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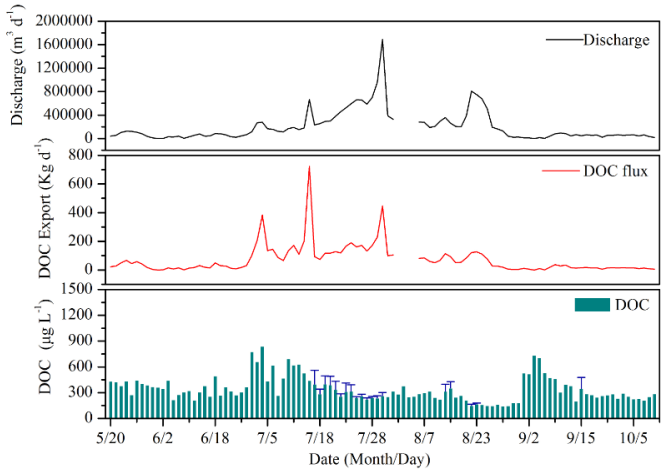

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504 **Figure 6**. The discharge, DOC concentrations and fluxes exported from LHG glacier. Note: The concentrations
505 with error bars include more than one sample on that day.

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