Carbonaceous matter in glacier at the headwaters of the Yangtze River: Concentration, sources and fractionation during the melting process

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ABSTRACT

Carbonaceous matter has an important impact on glacial retreat in the Tibetan Plateau, further affecting the water resource supply. However, the related studies on carbonaceous matter are still scarce in Geladaindong (GLDD) region, the source of the Yangtze River. Therefore, the concentration, source and variations of carbonaceous matter at Ganglongjiama (GLJM) glacier in GLDD region were investigated during the melting period in 2017, which could deepen our understanding on carbonaceous matter contribution to glacier melting. The results showed that dissolved organic carbon (DOC) concentration of snowpit samples (283 ± 200 μg/L) was much lower than that of precipitation samples (624 ± 361 μg/L), indicating that large parts of DOC could be rapidly leached from the snowpit during the melting process. In contrast, refractory black carbon (rBC) concentration measured by Single Particle Soot Photometer of snowpit samples (4.27 ± 3.15 μg/L) was much higher than that of precipitation samples (0.97 ± 0.49 μg/L), indicating that large parts of rBC could be rapidly leached from the snowpit during the melting process. In addition, it was found that both rBC and DOC with high light-absorbing ability began to leach from the snowpit when melting process became stronger. Therefore, rBC and DOC with high light-absorbing ability exhibited similar behavior during the melting process. Based on relationship among DOC, rBC and K⁺ in...
Introduction

Carbonaceous matter has been widely investigated as an important light absorption component in the aerosols and snow/ice (Jacobson, 2001; Andreae and Gelencsér, 2006; Xu et al., 2009; Bond et al., 2013; Kang et al., 2019). It is commonly divided into organic carbon (OC) and elemental carbon (EC, the same as black carbon (BC)). In terms of solubility, OC can be divided into water soluble organic carbon (WSOC, the same as dissolved organic carbon (DOC)) and water insoluble organic carbon. In addition to BC, some components of DOC can also absorb sunlight (Andreae and Gelencsér, 2006; Chen and Bond, 2010). Carbonaceous matter deposited on the glacier surface can reduce albedo and accelerate the snow/ice melting (Jacobson, 2004; Flanner et al., 2007; Bond et al., 2013; Ming et al., 2013).

The Tibetan Plateau (TP) is covered by one of the largest snow/ice areas in the world (Yao et al., 2007). In recent decades, snow/ice in the TP experienced significant thinning and shrinkage (Kang et al., 2010b; Bolch et al., 2012; Yao et al., 2012), partly owing to the increased deposition of carbonaceous matter (Xu et al., 2009; Matthew et al., 2016). So far, numerous studies have been conducted on the albedo reduction and radiative forcing effects caused by BC in the TP glaciers (Kaspari et al., 2011; Li et al., 2016e; Zhang et al., 2017). For instance, previous studies showed that BC concentration increased from fresh snow, aged snow to bare ice, resulting in continuing reduction of albedo (Qu et al., 2014; Yang et al., 2015; Niu et al., 2017).

In addition to BC, DOC accounts for a large part of the carbonaceous matter in the TP glacierized regions (29.37%–52.94% in snowpit samples) (Li et al., 2016c). Therefore, DOC has also been investigated in precipitation and snow/ice due to its important effect on carbon cycle and glacier melting (Feng et al., 2016; Yan et al., 2016; Li et al., 2017a). For instance, the deposition and light absorption ability of precipitation DOC were studied at three remote stations in the TP (Li et al., 2017a). In addition, the radiative forcing of snowpit DOC was estimated to be 0.43 W/m² at a glacier located at northern TP (Yan et al., 2016), indicating that light-absorbing DOC also caused snow/ice melting. Furthermore, it is proposed that DOC with high light absorption ability was likely to remain in the snowpit during the melting process, leading to increased radiative forcing of DOC (Hu et al., 2018). Compared to that of DOC, most of the ions were leached from the snowpit during the melting process (Hou and Qin, 1999). Thus, although many studies made use of major ions to study the sources of carbonaceous matter of snowpit samples (Gao et al., 2015; Li et al., 2016c, 2018), which may be unsuited for those samples that have experienced melting process.

Geladaindong (GLDD) area is one of the most remote parts of the TP with limited anthropogenic emissions activities (Kang et al., 2010a). For instance, the Hg concentration in GLDD (Kang et al., 2016) was as low as that in remote regions of Greenland (Zheng, 2015), indicating that the atmospheric environment was less affected by anthropogenic activities. Despite of that, dramatic thinning occurred at the glacier accumulation area in GLDD region (Kang et al., 2015), which was partly caused by increased carbonaceous matter deposition at this region (Matthew et al., 2016). As the headwater of the Yangtze river, the glacier retreat will reduce its glacier water reserves (Yang et al., 2003) and long-term water supply, which further causes serious damage to the ecological system of the Yangtze River Basin (Chao et al., 2017). However, there is not yet relevant study on carbonaceous matter in precipitation and snowpit at GLDD glacierized region, which limits our understanding on carbonaceous matter contribution to glacier melting. Carbonaceous matter in precipitation represents its initial state in glacier snow. In addition, exact evaluation of radiative forcing caused by carbonaceous matter was based on the knowledge of its concentration and light absorption ability changes during the melting process in the TP (Hu et al., 2018; Li et al., 2018).

Therefore, precipitation and snowpit samples were collected during two scientific explorations in Ganglongjiama (GLJM) glacier at GLDD glacierized region between June and September, 2017 to investigate (1) the basic concentration of major ions, DOC and refractory black carbon (rBC) in this remote area; (2) the variations of rBC and light absorption characteristic of DOC during the melting process; (3) the sources of carbonaceous matter during the study period.

1. Sampling and methods

1.1. Sampling site

GLJM glacier is located in the northern of Mt. GLDD (33°00′–33°50′N, 90°30′–91°41′E, 5200–6621 m) where many relevant previous studies have been carried out in snowpit and ice core samples (Kang et al., 2015; Matthew et al., 2016; Zhang et al., 2016).

1.2. Sample collection

Four snowpits were dug at an approximate elevation interval of 50 m from the altitude of 5600–5750 m in GLJM glacier in July 10, 2017 (Fig. 1). Ice layer made by meltwater was widespread in the snowpit indicating a strong melting process during the monsoon period. Two days later, two snowpits were dug at the same position in the altitude of 5650 and 5750 m, respectively, which can visually obtain the variations of major ions and carbonaceous matter during the melting process. Around two months later, another snowpit was dug in the altitude of 5750 m in September 23, 2017 (Fig. 1). Two blanks were made for every sampling process to confirm that the contamination was low. In total, 101 snowpit samples were collected (Table S1). Meanwhile, 13 precipitation
samples were collected in the glacier terminus from June 29 to July 13, 2017 (Fig. 1). Snowpit and precipitation samples were collected followed the same method of our previous study (Yan et al., 2016; Li et al., 2017a).

1.3. Laboratory analyses

1.3.1. Concentration measurements for major ions, DOC and rBC

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., 2016). The detection limit of the analyzer and precision, average DOC concentrations of the blanks were low of 15 μg/L and ±5%, 27 ± 6 μg/L, respectively, demonstrating that contamination during the pre-treatment and analysis processing of these samples was weak. The major cations (Ca2+, Mg2+, Na+, K+ and NH4+) and major anions (Cl−, NO3− and SO42−) were measured using a Dionex-6000 Ion Chromatograph and a Dionex-3000 Ion Chromatograph (Dionex, USA), respectively. The detection limit was 1 μg/L, and the standard deviation was less than 5%. The average ion concentrations of the blanks were low (Ca2+ = 2.22 μg/L, Mg2+ = 2.07 μg/L, NH4+ = 2.65 μg/L, Na+ = 1.86 μg/L, K+, SO42−, Cl− and NO3− < 1 μg/L). rBC was determined using Single Particle Soot Photometer (SP2) (DMT, USA), which is widely used to measure the rBC concentration in snowpit and ice core (Kaspari et al., 2014; Gao et al., 2015; Matthew et al., 2016). Ultra-pure water background and 10 μg/L colloidal graphite standard sample were measured to calibrate the instrument and evaluate its long-term stability. The average rBC concentrations of the blanks were very close to zero. All the reported concentrations in this study were subduced by those of the blanks.

1.3.2. Light absorption measurements

Snowpit and precipitation samples were filtered by Teflon filters (0.45 μm) for light absorption measurement. The light absorption spectra of DOC were measured between wavelength of 200–800 nm with 5 nm precision by a UV–Visible Spectrophotometer (SpectraMax M5, USA). Each spectrum was determined relative to that of blank filter treated by the same amount of Milli-Q water. The mass absorption cross-section, usually measured at 365 nm (MAC365) (Kirillova et al., 2014; Li et al., 2016b), is an important parameter for characterizing the light absorption properties of DOC (Cheng et al., 2011). Absorption Ångström Exponent (AAE) is a measure of the spectral dependence of aerosol light absorption. The detailed information on calculation of mass absorption cross-section (MAC) and AAE of DOC (Cheng et al., 2011; Kirillova et al., 2014) are demonstrated in supporting information file.

2. Results and discussion

2.1. Concentrations of major ions

The average NH4+, Ca2+ and NO3− concentrations of precipitation samples in GLJM glacier were 328, 239 and 237 μg/L, respectively (Fig. 2), which made up 70% of the total mass of major ions. The NH4+ and NO3− were mainly influenced by biogenic emissions and anthropogenic sources (Zheng et al., 2010), indicating that remote areas in the TP
were also affected by human activities. Meanwhile, Ca²⁺ was exclusively derived from mineral dust (Kang et al., 2010a; Zheng et al., 2010). The mean concentrations of major ions of precipitation samples in this study were much lower than those of Muztagh Ata Station (Liu et al., 2015) and Nam Co region (Li et al., 2007) (Table 1), this is probably due to higher altitude and lusher vegetation of the GLDD region, while the short sampling period in this study will cause some uncertainties on the above comparison.

The average concentrations of major ions in snowpit samples were much lower than that of precipitation samples in GLJM glacier (Fig. 2) because that large part of major ions leached from the snowpit during the melting process (Hou and Qin, 1999) and higher altitude. Correspondingly, the ice layer of snowpit formed by meltwater contained high concentrations of major ions. Meanwhile, concentrations of major ions of fresh snow were usually decreased with the increase of altitude due to lower chemical components deposition and heavier precipitation at higher elevations (Liu et al., 2017; Li et al., 2016a). However, average Ca²⁺ concentration of precipitation was close to that of snowpit samples because dry deposition of mineral dust at glacier surface and dirty layer of snowpit contained large amount of Ca²⁺ (Yan et al., 2016) and Zhadang glacier (370 ± 280 μg/L) (Li et al., 2016c), lower than that of Greenland ice sheet (400–570 μg/L) (Hagler et al., 2007) indicating a clean atmospheric environment of the TP.

DOC concentration of snowpit had great space–time differences in GLJM glacier. Spatially, DOC concentration of snowpit samples was consistent with the trend of altitude change. Temporally, average DOC concentration of snowpit samples (July 12, 2017) was also slight lower than that of two days later at the same location (July 10, 2017) (Fig. 2). Furthermore, DOC concentration (132 ± 46 μg/L) of snowpit samples collected in September, 2017 was much lower than that of fresh snow collected at the same location (334 ± 37 μg/L) days later at the same location (July 10, 2017) (Fig. 2). Both of the above two phenomena indicate a mass of major ion could be effectively leached from the snowpit by the meltwater.

### 2.2. Carbonaceous matter concentrations

#### 2.2.1. DOC concentration

Mean DOC concentration of precipitation samples in this study was 624 ± 361 μg/L (Fig. 2), which was lower than those of Nam Co and Everest stations (Li et al., 2017a) due to higher altitude and remote location of GLDD region (Table 2). Meanwhile, mean DOC concentration of snowpit samples was much lower than that of precipitation samples in this study probably due to large part of DOC leached from the snowpit during the melting process (Meyer and Wania, 2008) and higher altitude of snowpit samples. Similar to those of major ions, the snowpit ice layer formed by meltwater contained high DOC concentration (520 ± 230 μg/L). The average DOC concentration of snowpit samples (283 ± 200 μg/L) in this study was compared to those of LHG glacier (330 ± 130 μg/L) (Yan et al., 2016) and Zhadang glacier (370 ± 280 μg/L) (Li et al., 2016c), lower than that of Greenland ice sheet (400–570 μg/L) (Hagler et al., 2007) indicating a clean atmospheric environment of the TP.

#### 2.2.2. rBC concentration

Mean rBC concentration of precipitation samples was 0.97 ± 0.49 μg/L during the monsoon period (Fig. 2), which was compared with that of snowpit samples in high Himalaya (1 μg/L, 6400 m a.s.l) (Kaspari et al., 2014) indicating a clean atmospheric environment in GLDD region. Meanwhile, the mean rBC concentration (4.27 ± 3.15 μg/L) of snowpit samples was much higher than those of precipitation samples in this study and in the Greenland (1.9 ± 0.8 μg/L) (Lim et al., 2014), suggesting that rBC was likely to be enriched in the snowpit during the melting process, as shown in many samples collected in July 12, 2017 were also lower than that of the same location in July 10, 2017 (Fig. 2). Both of the above two phenomena indicate a mass of major ion could be effectively leached from the snowpit by the meltwater.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sample type</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>NO₃⁻</th>
<th>Na⁺</th>
<th>NH₄⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Ca²⁺</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLJM glacier</td>
<td>Precipitation</td>
<td>101.02</td>
<td>93.30</td>
<td>236.65</td>
<td>110.75</td>
<td>328.62</td>
<td>39.15</td>
<td>17.51</td>
<td>238.58</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>Snowpit</td>
<td>28.36</td>
<td>16.93</td>
<td>39.04</td>
<td>27.53</td>
<td>122.12</td>
<td>5.36</td>
<td>9.45</td>
<td>223.60</td>
<td></td>
</tr>
<tr>
<td>Zhadang glacier</td>
<td>Snowpit</td>
<td>26.34</td>
<td>44.75</td>
<td>66.70</td>
<td>62.95</td>
<td>98.80</td>
<td>10.68</td>
<td>29.45</td>
<td>307.08</td>
<td>Li et al. (2018)</td>
</tr>
<tr>
<td>Mt. Everest</td>
<td>Precipitation</td>
<td>36.21</td>
<td>69.12</td>
<td>20.52</td>
<td>9.43</td>
<td>6.12</td>
<td>5.85</td>
<td>5.52</td>
<td>68.4</td>
<td>Kang et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Snowpit</td>
<td>45.80</td>
<td>34.75</td>
<td>66.70</td>
<td>62.95</td>
<td>98.80</td>
<td>10.68</td>
<td>29.45</td>
<td>307.08</td>
<td></td>
</tr>
<tr>
<td>Nam Co station</td>
<td>Precipitation</td>
<td>699.35</td>
<td>448.8</td>
<td>642.9</td>
<td>355.1</td>
<td>326.3</td>
<td>565.1</td>
<td>178.3</td>
<td>2623.2</td>
<td>Li et al. (2007)</td>
</tr>
</tbody>
</table>
previous studies (Xu et al., 2012; Qu et al., 2014; Li et al., 2017b).

The detailed variations of snowpit rBC were a little complex. Firstly, rBC was abundant in the snowpit (Fig. 3a). The snowpit depth at the altitude of 5650 m (50 cm) was much lower than that of 5750 m (95 cm) indicating a stronger ablation condition in lower altitude. As the melting condition became stronger, the ice layer of snowpit also contained high concentration of rBC, indicating that rBC also began to leach from the snowpit with meltwater (Fig. 3b) (Niu et al., 2017). Correspondingly, rBC showed a significant positive relationship with DOC ($R^2 = 0.52$, $N = 18$, $p < 0.05$) for samples from two snowpits at the altitude of 5650 m (Fig. S1), indicating that rBC also could be leached from the snowpit by the meltwater (Conway et al., 1996), which increases our understanding on rBC contribution to glacier melting.

### 2.3. MAC$_{365}$ value

The mean MAC$_{365}$ values of precipitation and snowpit samples were 0.41 ± 0.36 and 2.17 ± 2.13 m$^2$/g, respectively. The average MAC$_{365}$ value of precipitation samples in this study was similar to that of Nam Co station (0.48 ± 0.47 m$^2$/g) (Li et al., 2017a), much lower than that of biomass burning and vehicle emission sourced aerosols (Hu et al., 2017) (Table 2) because precipitation DOC contains a mass of lower light absorption components such as secondary organic aerosols (SOAs) and volatile organic compounds (VOCs) (Li et al., 2017a). In addition, the mean MAC$_{365}$ value of snowpits samples was much higher than those of precipitation, ice layer (1.02 ± 0.96 m$^2$/g) samples in this study and aerosols in Everest and Lulang station (Li et al., 2016a) (Table 2), indicating that DOC with high light-absorbing ability was easier to be kept in the snowpit during the melting process (Hu et al., 2018). Meanwhile, the MAC$_{365}$ value of snowpit in this study was lower than that of LHG glacier (4.73 ± 2.25 m$^2$/g) because DOC with high light absorption ability in local dust contributed larger to that of snowpit in LHG glacier (Hu et al., 2018).

The MAC$_{365}$ values showed a negative correlation with their AAE$_{330-440}$ ($R^2 = 0.50$, $N = 101$, $p < 0.01$) (Fig. 4), suggesting that DOC of higher MAC$_{365}$ values also had lower wavelength dependence.

### Table 2 – Average DOC concentrations and MAC$_{365}$ values of precipitation, snowpit and aerosols samples in this study and previous studies.

<table>
<thead>
<tr>
<th>Site/Source</th>
<th>Sample types</th>
<th>DOC ($\mu$g/L)</th>
<th>MAC$_{365}$ (m$^2$/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLJM glacier</td>
<td>Precipitation</td>
<td>624 ± 361</td>
<td>0.41 ± 0.36</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>Snowpit</td>
<td>283 ± 200</td>
<td>2.17 ± 2.13</td>
<td>Hu et al. (2018)</td>
</tr>
<tr>
<td>Laohugou glacier</td>
<td>Precipitation</td>
<td>380 ± 60</td>
<td>0.65 ± 0.16</td>
<td>Hu et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>Snowpit</td>
<td>220 ± 110</td>
<td>4.73 ± 2.25</td>
<td>Li et al. (2017a)</td>
</tr>
<tr>
<td>Lulang station</td>
<td>Precipitation</td>
<td>830 ± 850</td>
<td>0.25 ± 0.15</td>
<td>Li et al. (2017a)</td>
</tr>
<tr>
<td>Everest station</td>
<td>Precipitation</td>
<td>860 ± 910</td>
<td>0.64 ± 0.49</td>
<td>Li et al. (2017b)</td>
</tr>
<tr>
<td>Xiaodongkemadi glacier</td>
<td>Snowpit</td>
<td>250 ± 230</td>
<td>–</td>
<td>Li et al. (2016c)</td>
</tr>
<tr>
<td>Mount Everest</td>
<td>Snowpit</td>
<td>150 ± 60</td>
<td>–</td>
<td>Li et al. (2017c)</td>
</tr>
<tr>
<td>Mendenhall Glacier</td>
<td>Snowpit</td>
<td>190 ± 110</td>
<td>–</td>
<td>Li et al. (2017b)</td>
</tr>
<tr>
<td>Nam Co station</td>
<td>Biomass burning</td>
<td>–</td>
<td>0.91 ± 0.18</td>
<td>Hu et al. (2017)</td>
</tr>
<tr>
<td>Beijing</td>
<td>Summer</td>
<td>–</td>
<td>0.51</td>
<td>Du et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>–</td>
<td>1.26</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 3 – Evolution of rBC, DOC and MAC$_{365}$ values across snowpit profile at the altitude of 5750 m (a) and 5650 m (b) collected in the 10th July, 2017 at the GLJM glacier.](image-url)
An interesting finding was that MAC365 values of snowpit DOC showed a significant positive relationship with rBC ($R^2 = 0.54$, $N = 19$, $p < 0.05$) (Fig. S2) at the altitude of 5750 m (Fig. 3a), indicating that both DOC with high light-absorbing ability and rBC were likely to enrich in the snowpit during the melting process. However, mean MAC365 value of snowpit samples at the altitude of 5650 m was much lower than that of 5750 m due to the hydrophobic DOC with high light-absorbing ability (Hu et al., 2018) leached from the snowpit during stronger melting process (Meyer and Wania, 2008). Above all, the DOC with high light-absorbing ability and rBC measured by SP2 exhibited similar behavior during the melting process.

In general, compared with those of rBC, DOC has much lower MAC value and higher AAE value (Andreae and Gelencsér, 2006; Cheng et al., 2011). However, DOC with weak light-absorbing ability could be rapidly leached from the snowpit during the melting process, causing increased MAC365 and decreased AAE values of DOC (Hu et al., 2018). Consequently, MAC and AAE values of DOC for some snowpit samples could even be similar to that of rBC (Bond and Bergstrom, 2006; Hu et al., 2018). Because compositions of DOC are complex and light-absorbing abilities of DOC change from low value to as high as that of rBC, it is proposed that light absorbing of DOC and rBC have continuous absorption spectra, which improves our understanding on the light absorption characteristic of carbonaceous matter.

2.4. Source of carbonaceous matter

DOC originates from multiple sources, such as mineral dust, combustion emission, SOAs and VOCs (May et al., 2013; Li et al., 2017a), while rBC is exclusively derived from incomplete combustion of biomass and fossil fuels (Bond et al., 2013). Compared to that of snowpit, major ions of precipitation have not experienced the melting process, so it can be used for source investigation of carbonaceous matter (Santos et al., 2014; Li et al., 2016d, 2017a). Therefore, sources of major ions have been widely investigated in previous study. For instance, $\text{Ca}^{2+}$ is exclusively derived from mineral dust (Kang et al., 2010a) and $\text{K}^+$ is a typical biomass burning tracer (Szidat et al., 2006). Precipitation DOC showed a significant positive relationship with rBC ($R^2 = 0.92$, $N = 13$, $p < 0.01$) (Fig. S3), indicating that precipitation DOC was also mainly derived from combustion activities. Meanwhile, DOC ($R^2 = 0.78$, $N = 13$, $p < 0.01$) (Fig. 5a) and rBC ($R^2 = 0.70$, $N = 13$, $p < 0.01$) (Fig. 5b) both had significant positive relationships with $\text{K}^+$, suggesting that the main source of carbonaceous matter in GLJM glacier was biomass burning. It was consistent with the high proportion of biomass-sourced rBC in Zhadang glacier (Li et al., 2016a).

However, major ions of snowpit in the monsoon period are probably unsuited to study the sources of carbonaceous matter due to major ions leached from the snowpit samples during the melting process. Correspondingly, both DOC and rBC had no significant relationship with $\text{K}^+$ of snowpit samples in this study (Fig. S4). Therefore, the error result may be obtained when the major ions of snowpit samples in the monsoon period are used to study the source of carbonaceous matter.

3. Conclusions

The concentration, source and variations of carbonaceous matter at GLJM glacier in GLDD region during the melting
period were reported in this study. Concentrations of major ions and DOC of snowpit samples were much lower than those of precipitation samples, suggesting that water soluble components can be effectively leached from the snowpit during the melting process. However, rBC concentrations of snowpit (4.27 ± 3.15 μg/L) and precipitation (0.97 ± 0.49 μg/L) samples showed the opposite trend because rBC was likely to enrich in snowpit during the melting process. Meanwhile, DOC with high light-absorbing ability was also likely to be kept in snowpit during the melting process. Interestingly, at first, MAC$_{365}$ values of snowpit DOC showed a significant positive relationship with rBC concentrations at the altitude of 5750 m, indicating that rBC and DOC with high light-absorbing ability were likely to enrich in the snowpit. However, they also began to leach from the snowpit during stronger melting process. Furthermore, the light-absorbing ability of DOC for some snowpit samples could even be comparable to that of rBC. Therefore, rBC and DOC with high light-absorbing ability exhibited similar behavior during the melting process and also had continuous absorption spectra, which improves our understanding on the light absorption characteristic of carbonaceous matter.

Precipitation DOC and rBC both had significant positive relationships with K$^+$, indicating that the main source of carbonaceous matter in GLJM glacier was biomass burning. However, no significant relationships were found among DOC, rBC and K$^+$ of studied snowpit samples due to different behaviors between major ions and carbonaceous matter during the melting process. Therefore, the inappropriate conclusion may be obtained when the major ions of snowpit samples are used to investigate the source of carbonaceous matter during the monsoon period.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jes.2019.08.001.

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