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Carbonaceous matter deposition in the high glacial regions of the Tibetan Plateau

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HIGHLIGHTS

- DOC at glacial region of the TP is low and mainly contributed by natural dust.
- DOC at glacial region is significantly related to that of IPC for all the TP.
- DOC flux is 0.11 ± 0.05 g-C m^{-2} yr^{-1} at glacial region of the TP.

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ABSTRACT

Carbonaceous matter at glacial region plays important role in river ecosystems fed by glacier and albedo reduction of glacier surface. However, currently, limited knowledge are available on the carbonaceous matter within the glacial region of the Tibetan Plateau (TP). In this study, the data from six snowpits in the glacial region across the TP were reported. The results showed that dissolved organic carbon (DOC) concentrations of snowpit samples of the TP were comparable to those of European Alps and the Arctic. The ratio of DOC to carbonaceous matter (40.25 ± 8.98%) was lower than that of Alpine glaciers, thus indicating greater particulate carbon content in the TP glacial region. In addition, the DOC was significantly correlated with insoluble particulate carbon (IPC), indicating that IPC and DOC likely came from the same sources. Spatially, the DOC concentration decreased from the north (0.42 ± 0.29 mg-C L^{-1}) to the south TP (0.15 ± 0.06 mg-C L^{-1}), which was consistent with variations in the distribution of dust storm on the TP. Principal component analysis of major ions and DOC showed that mineral dust contributed the major part of DOC, followed by biogenic sources such as agriculture and livestock. Finally, based on DOC concentrations and precipitation amounts at different periods, the mean annul flux of DOC in the glacial region of the TP was calculated to be 0.11 ± 0.05 g-C m^{-2} yr^{-1}.

1. Introduction

Glaciers represent a unique ecosystem that exhibits potential implications for the biotic systems near glacial outflow (Anesio and Laybourn-Parry, 2012; Hood et al., 2009, 2015) and sea level variations (Jacob et al., 2012). Glaciers contain an important store of carbonaceous matter, which includes dissolved organic carbon (DOC) and insoluble particulate carbon (IPC). IPC can be further divided into water insoluble organic carbon (WIOC) and black carbon (BC). DOC has been proposed to dominate carbonaceous matter in glaciers and may play a key role in glacial environments (Hood et al., 2015; Legrand et al., 2013a; May et al., 2013) because it is one of the most active components in these ecosystems (Battin et al., 2008). For example, a significant fraction of glacier-derived

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DOC is bioavailable compared with that of terrestrially derived DOC (Hood et al., 2009; Singer et al., 2012), which influences the stability of terrestrial DOC in downstream ecosystems (Bianchi, 2011). In addition, the characteristics of DOC also reflect the atmospheric environment so that it is an important proxy of studying historical anthropogenic impact on the atmospheric load of organic species at the glacial region (Legrand et al., 2007, 2013a). Although IPC is stable relative to DOC, it is also an indispensable component of the carbonaceous matter (Hood et al., 2015). Moreover, DOC and IPC both play important roles in the albedo reduction of glacier surface (Flanner et al., 2007; Wang et al., 2015). IPC is well known of reducing albedo of glacier by absorbing sunlight (Flanner et al., 2007; Wang et al., 2015). Some part of DOC has also been proven of absorbing sunlight at ultraviolet range. This part of DOC is generally called as water soluble brown carbon (Andreae and Gelencser, 2006).

Although mountain glaciers account for only a small portion of the global ice storage compared with polar ice sheets, they are proposed as dominating the release of DOC from glaciers around the world (Hood et al., 2015). Studies on the concentrations, compositions, age and historical variations of DOC have been conducted at glaciers in the Antarctic(Lyons et al., 2007), Arctic (Hood et al., 2009; Stubbins et al., 2012) and European Alps (May et al., 2013; Singer et al., 2012). However, few related data are available on the Tibetan Plateau (TP) (Spencer et al., 2014; Yan et al., 2015), which is the so called “the third pole” of the world and holds the largest number of glaciers at middle latitudes. Carbonaceous matter in air and on the glacier surface has caused changes in climate (Lau et al., 2010) and retreat of large numbers glaciers of the TP (Wang et al., 2015), especially those around the Himalayas, causing an increase in the export of carbonaceous matter out of the glacial watershed, which impacts their downstream ecosystems. Therefore, the characteristics of the carbonaceous matter of TP glaciers is an important research direction, and the source and deposition of carbonaceous matter are two key components. Therefore, the concentration, source and deposition of DOC in the glacial regions spanning the Himalayans from the south TP to the Qilian Mountain in the north TP were investigated in this study to better understand carbonaceous matter of the TP glacial region. The relationship between the DOC and IPC was also investigated.

2. Sampling and analyses

Sixty two snowpit samples from 6 glaciers were collected across the TP in 2013 and 2014 (Fig. 1, Table S1). In addition, 35 fresh snow samples were collected during the monsoon period to calculate the carbonaceous matter flux of the glacial region. The DOC concentration was determined by a TOC-5000A analyzer (Shimadzu Corp, Kyoto, Japan) (Stubbins and Dittmar, 2012; Yan et al., 2015), major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and NH_4^{+}) and major anions (Cl^{-}, $NO_3^{-}$and SO_4^{2-}) were measured by ion chromatograph (Li et al., 2007). IPC was measured by TOT carbon analyzer (Sunset Laboratory, Tigard, OR) (Chen et al., 2013). For IPC measurement, snow samples were collected with 5 L Whirl-Pak® bags and transported to the laboratory frozen and then transferred into PTFE bags. These samples thawed at room temperature, subjected to an ultrasonic treatment and filtered twice through a pre-combusted quartz fiber filter (Whatman, 47 mm in diameter) to collect the IPC (Xu et al., 2009b), which was then measured by a TOT carbon analyzer using the NIOSH method 5040 (Chen et al., 2013). In brief, the filters were acidified by fumigation in open glass petri dishes held in a desiccator over 37% HCl acid for 24 h to remove carbonates and subsequently dried at 60 °C for 1 h to drive the HCl acid out of the filter. A 1 cm^2 piece of acid-treated filter was cut out and analyzed. To evaluate the capture efficiency of the quartz filter, IPC collected by not adding and adding coagulant ($NH_4H_2PO_4$) for 16 snowpit samples were tested (Kuchiki et al., 2015; Torres et al., 2014). In detail, each melted snow sample was divided into two equal parts, $NH_4H_2PO_4$ (1.5 g per 100 mL of melted snow sample) was added to one of the subsamples, and the mixture was magnetically stirred and sonicated for 20 min. Then, two subsamples with and without $NH_4H_2PO_4$ were filtered through quartz filters in parallel. The collected particles were also treated by HCl acid before being measured. IPC collected on quartz filter for samples that were treated and not treated by $NH_4H_2PO_4$ were much close (Fig. S1), which was similar to result of previous study (Kuchiki et al., 2015) and implied filter process in this study collected most IPC.

3. Results and discussion

3.1. Concentration of snowpit DOC

Mean DOC concentrations of snowpit, monsoon period and the whole year were 0.28 ± 0.10 mg-C L^{-1}, 0.15 ± 0.04 mg-C L^{-1} and 0.18 ± 0.05 mg-C L^{-1}, respectively (Table 1 and Table S2). High DOC concentrations were observed in the snowpit at north TP glaciers (LH: 0.42 ± 0.29 mg-C L^{-1}), and low DOC concentrations were observed in the snowpit of the south and southeast TP glaciers (EV: 0.15 ± 0.06 mg-C L^{-1}) (Fig. 1). This spatial distribution was similar to that of other components, such as mercury (Zhang et al., 2012) and black carbon (BC) (Ming et al., 2013), both of which were closely connected to dust concentration. Several large deserts are distributed around the north fringe of the TP (Fig. 1), and dust storms occur more frequently in the north than in the south TP (Wang et al., 2005). Therefore, the natural mineral dust deposited in the north TP is relatively heavy, causing a high DOC concentration in this region, whereas the mineral dust deposited in the south TP is relatively minor and heavier precipitation is occurred, resulting in a lower DOC concentration in this region. Thus, despite the serious air pollution in the regions of East Asia and South Asia that surround the TP (Kurokawa et al., 2013), the distributions of DOC within the TP glaciers are still primarily influenced by natural processes rather than anthropogenic pollutants transported over long distances. One special case is the mean DOC concentration of ZD, which is slightly higher than that of TG because ZD is a relative small glacier received a massive deposit of dust from the western TP. Meanwhile, ZD is close to zone of local residents so that influence of anthropogenic emissions is high for this glacier (Ming et al., 2009).

Compared with other glacial regions in the world (Table 1), the snowpit DOC concentration in the TP (0.28 ± 0.10 mg-C L^{-1}) was close to the normalized surface values of the Greenland ice sheet (GIS) (0.20 mg-C L^{-1}) but lower than values for the Antarctic ice sheet (AIS) (0.46 mg-C L^{-1}) and mountain glaciers (MGL) (0.49 mg-C L^{-1}) (Hood et al., 2015) (Table 1). The high surface values obtained for the AIS and MGL might be caused by the contribution from moraines that accumulated at the surface of glaciers. In addition, the mean DOC concentration of the TP snowpits was slightly higher than that of the Alaskan (0.19 mg-C L^{-1}) (Stubbins et al., 2012) and European Alpine glacier (0.14 mg-C L^{-1}) (Singer et al., 2012). Because of the light mineral dust load, the monsoon DOC concentration of the TP was lower than that of the non-monsoon period (Table 1 and Table S2), which was inconsistent with the results from European Alpine glaciers, where high DOC concentrations were observed in the summer primarily because of contributions from the living biosphere (Legrand et al., 2013b) (Table 1).

3.2. Sources of DOC

Sources of atmospheric DOC are complex, including primary