Journal of Geophysical Research: Earth Surface

RESEARCH ARTICLE
10.1029/2017JF004333

# Importance of Mountain Glaciers as a Source of Dissolved Organic Carbon

**Xiangying Li[1,2,3], Yongjian Ding[2,4], Jianzhong Xu[2], Xiaobo He[2], Tianding Han[2], Shichang Kang[2], Qingbai Wu[3], Sillanpää Mika[5,6], Zhongbo Yu[1], and Qijiang Li[7]**

[1]College of Hydrology and Water Resources/State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China, [2]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, [3]State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, [4]University of Chinese Academy of Sciences, Beijing, China, [5]Laboratory of Green Chemistry, School of Engineering Science, Lappeenranta University of Technology, Mikkeli, Finland, [6]Department of Civil and Environmental Engineering, Florida International University, Miami, FL, USA, [7]Hydrology and Water Resource Survey Bureau of Qinghai Province, Xining, China

**Key Points:**
- Data on DOC from two Asian glaciers have been collected, and a global data set of DOC from worldwide mountain glaciers have been compiled
- Storage of DOC in Asian glaciers is 8.8 to 13.8 Tg C, and release of DOC from mountain glaciers worldwide is on the order of 0.8 Tg C/a
- Current release of DOC from mountain glaciers is far more significant than previously thought and should be considered in future evaluation of the global carbon cycle

**Supporting Information:**
- Supporting Information S1

**Correspondence to:**
Y. Ding,
dyj@lzb.ac.cn

**Citation:**
Li, X., Ding, Y., Xu, J., He, X., Han, T., Kang, S., et al. (2018). Importance of mountain glaciers as a source of dissolved organic carbon. *Journal of Geophysical Research: Earth Surface*, *123*, 2123–2134. https://doi.org/10.1029/2017JF004333

Received 24 APR 2017
Accepted 13 JUN 2018
Accepted article online 25 JUN 2018
Published online 13 SEP 2018



**Abstract** Ice sheets and glaciers have been shown to deliver large amounts of labile dissolved organic carbon (DOC) to downstream aquatic ecosystems, but recent studies may underestimate the release of DOC from mountain glaciers. To date, continuous measurements of DOC from mountain glaciers throughout entire glacier melt season are very limited. Here we present high-density data on DOC from two Asian mountain glaciers over a full melt season in 2013 and compile a global data set of DOC from 42 mountain glaciers. Based on our study and previously published DOC data, we estimate the storage and release of DOC associated with Asian mountain glaciers to be 8.8 to 13.8 Tg C and 0.19 Tg C/a, respectively. Rough extrapolation of glacier runoff to a global scale suggests that DOC release from mountain glaciers is on the order of 0.8 Tg C/a, which is 1.4 times higher than the most current estimates. The current release of DOC from mountain glaciers is therefore far more significant than previously thought and should be considered in future evaluation of the global carbon cycle.

## 1. Introduction

Glaciers and ice sheets have been recognized as unique ecosystems, with potentially significant implications for the global carbon cycle (Anesio & Laybourn-Parry, 2012; Hodson et al., 2008; Hood et al., 2015). These distinctive ecosystems accumulate organic carbon from in situ primary production in the supraglacial (Bhatia et al., 2013; Lawson et al., 2014; Musilova et al., 2017), subglacial (Bhatia et al., 2013; Lawson et al., 2014; Skidmore et al., 2000), and proglacial (Bardgett et al., 2007; Hodson et al., 1998; Hood et al., 2009) environments as well as from external terrestrial (Bhatia et al., 2010; Singer et al., 2012; Smith et al., 2017) and anthropogenic (Stubbins et al., 2012; Stibal et al., 2012; Spencer, Vermilyea, et al., 2014) sources. Microbes also break down organic carbon and generate $CO_2$, which reenters the atmosphere. The balance between these processes governs the export of organic carbon from glaciers and ice sheets. Organic carbon not consumed by microbes on site is exported into downstream aquatic ecosystems by meltwater flushing (Hood et al., 2009, 2015; Y. Liu et al., 2016). Glacially derived dissolved organic carbon (DOC) is highly biologically available, and the high bioavailability of glacial DOC may prime the metabolism of apparently stable terrestrial DOC in downstream ecosystems (Bianchi, 2011; Hood et al., 2015). It is also likely to stimulate the heterotrophic metabolism in downstream aquatic ecosystems and ultimately contribute to $CO_2$ outgassing to the atmosphere (Singer et al., 2012).

Recently, the storage and release of DOC from glaciers and ice sheets has been quantified (e.g., Bhatia et al., 2013; Hood et al., 2015; Yan et al., 2016). At regional scales, the releases of glacially derived DOC were estimated at 130 Gg C/a (Gg = $10^9$ g) from Gulf of Alaska (Hood et al., 2009), 0.34 Gg C/a from European Alps (Singer et al., 2012), 80 Gg C/a from Greenland ice sheet (Bhatia et al., 2013), 12.7 to 13.2 Gg C/a from the Tibetan Plateau (Yan et al., 2016), and 15.4 Gg C/a from Chinese Territory (Y. Liu et al., 2016). At global scales, glacier runoff liberates 1,040 Gg C/a of DOC to the proglacial ecosystems (Hood et al., 2015), with the largest contribution from mountain glaciers (580 Gg C/a) compared to Greenland and Antarctic ice sheets (460 Gg C/a). In addition, glacier-stored DOC is 3.96 Tg C (Tg = $10^{12}$ g) in Chinese glaciers (Y. Liu et al., 2016),

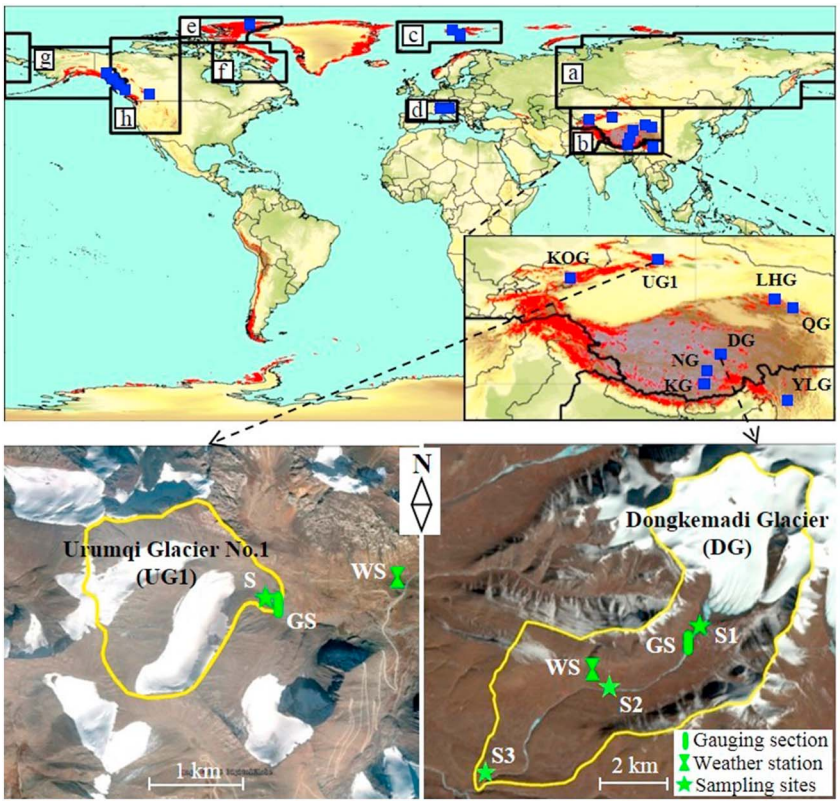


**Figure 1.** Location of Dongkemadi Glacier (DG) and Urumqi Glacier No. 1 (UG1) as well as Koxkar Glacier (KOG), Laohugou Glacier (LHG), Qiyi Glacier (QG), Yulong Glacier (YLG), Nyainqentanglha Glacier (NG), and Karola Glacier (KG) in Asia (a, b). Sampling sites (S, S1, S2, and S3), weather stations (WS) and gauging sections (GS) at DG and UG1 catchments are marked. Mountain glaciers globally are shown in red, and glacier outflow sampling sites (blue squares) are widely distributed in Asia (a, b), Svalbard and Jan Mayen (c), central Europe (d), Arctic Canada (e, f), Alaska (g), and Western Canada and the United States (h; Pfeffer et al., 2014; Bliss et al., 2014).

4,410 Tg C in ice sheets, and 70 Tg C in mountain glaciers (Hood et al., 2015). However, recent studies may underestimate the reserves and export of DOC from mountain glaciers due to the higher deposition and release efficiency of DOC from mountain glaciers in Asia (ASG; Y. Liu et al., 2016; Yan et al., 2016). Considering that the ASG are one of the main contributors to global ice volume loss (Farinotti et al., 2015; Kraaijenbrink et al., 2017; Radić et al., 2014) and stream runoff in Asia is increasing consistently due to increasing glacier melt and precipitation (Lutz et al., 2014), we contend that further evaluating the storage and release of DOC from mountain glaciers is critical for understanding how glacier volume loss is impacting the transport of DOC from terrestrial to downstream aquatic ecosystems. Significantly, recent warming has accelerated the loss of glacier volumes, and present-day glacier loss rate was estimated at 369 to 905 Gt/a (IPCC, 2013).

Although a few studies have been conducted on concentration and/or flux of DOC from mountain glaciers (e.g., Barker et al., 2006; Stibal et al., 2008; Stubbins et al., 2012; Spencer, Guo, et al., 2014, Spencer, Vermilyea, et al., 2014; Zhu et al., 2016), spatiotemporally intensive seasonal data describing the concentrations and flux of DOC from mountain glaciers are lacking. This can be attributed to challenging logistics of sampling glacier outflow over a full melt season in remote glacial catchments. However, comprehensive time series are critical given that solute concentrations from mountain glaciers have a significant seasonality as a result of the evolution of glacial drainage system and biological process therein (Hodson et al., 2010; Singer et al., 2012; Stibal et al., 2012). Here we present a comprehensive data set of concentrations and fluxes of DOC from two Asian mountain glaciers over a full melt season. These temporal and spatial data, combined with previously published data, provide a comprehensive estimate of the storage and release of DOC related to ASG. We further use previously published data to estimate DOC fluxes from mountain glaciers in other regions including Svalbard and Jan Mayen (SJG), Alaska (ALG), Western Canada and United States (CUG),

Arctic Canada (ACG), and Central Europe (CEG). We propose that the storage (8.8–13.8 Tg C in Asia) and release (0.8 Tg C/a) of labile DOC associated with mountain glaciers may be far larger than recent estimates, which could potentially influence downstream aquatic ecosystems, and should thus be considered in future evaluation of the regional and global carbon cycles in a warming climate.

## 2. Materials and Methods

### 2.1. Site Description

Dongkemadi Glacier (DG; 92°04′E, 33°04′N) is located in the Tanggula Mountains (Figure 1). It has an area of 16.4 $km^2$ and ranges in altitude from 5,275 to 6,049 m (X. Li et al., 2016). The local atmospheric circulation is dominated by the Indian monsoon and westerly jet. Urumqi Glacier No.1 (UG1; 86°49′E, 43°06′N) is located in the Tianshan Mountains (Figure 1). It has an area of 1.65 $km^2$ and ranges in altitude from 3,740 to 4,486 m (Han et al., 2015). The local atmospheric circulation is dominated by the westerly jet and polar air mass. Overall, the climate is characterized by dry-cold (January to May and October to December) and warm-wet (June to September) seasons at the DG and UG1 basins. The glacial drainage system evolves from a distributed drainage system to a channelized system (Han et al., 2015; X. Li et al., 2016), which is typical of glacial drainage system for Asian mountain glaciers, such as Koxkar Glacier (KOG) in the Tianshan Mountains (Wang et al., 2010), Qiyi Glacier (QG) in the Qilian Mountains (X. Li et al., 2013), and Dunagiri Glacier and Gangotri Glacier in the Himalaya (Deepak et al., 2014; Singh et al., 2014). Within China, mountain glaciers with an area of less than 20 $km^2$ make up 99.4% of glaciers, 48.9% of glacier volume, and 73.5% of glacier area, over 97.5% of which occurs within a range of 3,000 to 6,500 m (S. Liu et al., 2015). Thus, we contend that DG and UG1, combined with Nyainqentanglha Glacier (NG, 5,530 m), Karola Glacier (KG, 5,370 m), and Laohugou Glacier (LHG, 4,210 m; Y. Liu et al., 2016; Spencer, Guo, et al., 2014; Yan et al., 2016; Figure 1), are broadly representative of larger population of ASG, which is dominated by mountain glaciers within Chinese territory (S. Liu et al., 2015; Pfeffer et al., 2014).

### 2.2. Sample Collection

Field sampling was performed in proglacial streams over a full melt season in 2013 (Figure 1). For DG, glacial outflow was sampled at three sites located 0.5 km (S1, with an altitude of 5,250 m and a drainage area of 27.96 $km^2$), 4.8 km (S2, 5,160 m and 38.33 $km^2$), and 9.8 km (S3, 5,030 m and 52.75 $km^2$) from the glacier terminus over 29 May to 30 September. Samples were collected bihourly at even times at S1. At S2 and S3 samples were collected simultaneously bi-hourly at even times from 12:00 to 10:00 hr the following day over four diurnal cycles (7 to 8 June [D1], 5 to 6 July [D2], 5 to 6 August [D3], and 22 to 23 September [D4]). For UG1, glacial outflow was sampled at site S (3,659 m and 3.34 $km^2$) located 0.5 km from the glacier terminus over 29 May to 4 October. Samples were collected twice daily at approximately minimum (9:00 hr) and maximum (17:00 hr) flows. After sampling, all samples were immediately filtered through precombusted Whatman glass fiber membranes (pore size 0.7 μm) in a designated lab tent. In detail, 150-ml water samples were first filtered to rinse the filtration apparatus, and then the residual samples were filtered and collected in the acid-washed HDPE bottles. Blank samples were prepared using MilliQ ultrapure water (X. Li et al., 2016). Field samples were kept in a refrigerator and then transported to the State Key Laboratory of Cryospheric Science (SKLCS) of Chinese Academy of Sciences and kept frozen until laboratory analysis.

### 2.3. Laboratory Analysis

Concentrations of DOC in four samples each day (04:00, 10:00, 16:00 and 22:00 hr) at site S1 and in all samples at sites S2, S3 and S were determined by a Vario EL TOC/TNb analyzer (Elementar, Hanau, Germany) in the SKLCS of CAS. The system was calibrated using a potassium hydrogen phthalate standards for DOC. The detection limits were 30 μg/L for DOC defined as three times the standard deviation of low concentration samples. The reproducibility (the relative deviation from the mean value) was better than 5%. Mean concentration of DOC in blank samples was 76 μg/L, and all data reported here are corrected for this.

### 2.4. Water and DOC Fluxes

Water fluxes from DG and UG1 were calculated by measuring discharge at gauging stations located ~1.0 km downstream of the glacier terminus (Figure 1). Water stages were logged by self-recording pressure transducers every 30 min, and discharge was measured regularly using current meters at river cross sections immediately below gauging stations. Water stage measurements were converted to glacial discharge using the

**Table 1**
*Summary Statistics for DOC Concentrations (mg/L) in Proglacial Stream Water Draining From Dongkemadi Glacier (DG), Urumqi Glacier No. 1 (UG1), Nyainqentanglha Glacier (NG), Karola Glacier (KG), and Laohugou Glacier (LHG) in Asia (AS), As Well As Four Mountain Glaciers in Alaska (AL), Two Mountain Glaciers in Western Canada and United States (CU), One Mountain Glacier in Arctic Canada North (AC), Two Mountain Glaciers in Svalbard and Jan Mayen (SJ), and 28 Mountain Glaciers in Central Europe (CE)*

| Mountain glaciers | Distance from glacier terminus (km) | Sampling period | Mean (±SE) | Range | Sample size | Source |
|---|---|---|---|---|---|---|
| Glacier No.1 (AS) | 1.0 | 26 May to 4 October 2013 | 0.35 (0.09) | 0.20–0.72 | 78 | This study |
| Dongkemadi Glacier (AS) | 0.5 | 29 May to 30 September 2013 | 1.17 (0.34) | 0.45–2.16 | 374 | This study |
| Nyainqentanglha Glacier (AS) | Snout | August 2011 | 0.42 [a] (N/A) | N/A | 1 | Spencer, Guo, et al. (2014) |
| Karola Glacier (AS) | Snout | August 2011 | 0.44 [a] (N/A) | N/A | 1 | Spencer, Guo, et al. (2014) |
| Laohugou Glacier (AS) | 1.0 | 20 May to 9 October 2015 | 0.34 (0.14) | 0.15–0.84 | 184 | Yan et al. (2016) |
| North Dawes Glacier (AL) | <5.0 | July, September, and November 1967/1968 | 0.38 (0.18) | 0.15–0.53 | 5 | Loder and Hood (1972) |
| Carroll Glacier (AL) | <1.0 | September 1968 | 0.14 (N/A) | N/A | 1 | Loder and Hood (1972) |
| Mendenhall Glacier (AL) | Snout | August 2009 | 0.38 (0.02) | 0.37–0.39 | 2 | Stubbins et al. (2012) |
| | Snout | May to October 2011 | 0.32 (0.08) | 0.18–0.53 | 25 | Spencer, Vermilyea, et al. (2014) |
| Herbert Glacier (AL) | Snout | May to October 2012 | 0.23 (0.09) | 0.13–0.39 | 12 | Fellman et al. (2014) |
| | Snout | August 2009 | 0.28 (N/A) | N/A | 1 | Stubbins et al. (2012) |
| Bow Glacier (CU) | <3.0 | May to August 1998–2000 | 0.40 (0.13) | 0.15–0.77 | 61 | Lafrenière and Sharp (2004) |
| Outre Glacier (CU) | Snout | July to August, 2002 | 0.10 (0.08) | 0.06–0.18 | 72 | Barker et al. (2006) and Skidmore et al. (2005) |
| John Evans Glacier (AC) | Snout | June to July, 2001 | 0.23 (0.08) | 0.12–0.43 | 48 | Barker et al. (2006) |
| | <0.1 | June to August 2002 | 0.80 (0.78) | 0.20–3.70 | 9 | Bhatia et al. (2006) |
| Werenskioldbreen Glacier (SJ) | N/A | Summer 2006 | 3.40 (3.50) | N/A | 27 | Stibal et al. (2008) |
| Austre Brøggerbreen Glacier (SJ) | 3.3 | August 2012 | 0.88 (0.37) | 0.25–1.18 | 5 | Zhu et al. (2016) |
| Tschierva/Roseg Glaciers (CE) | 0.5 | July to September 1997 | 0.30 (0.20) | N/A | 11 | Tockner et al. (2002) |
| Rotmoos stream (CE) | <3.0 | August to October 1999 | 0.35 (0.10) | 0.24–0.57 | 15 | Battin et al. (2001) |
| Austrian 26 glaciers (CE) | Snout | July to August 2010 | 0.27 (0.36) | N/A | 26 | Singer et al. (2012) |

*Note.* N/A denotes no available data.
[a]Values that are corrected by the ratio (0.62) of monthly (August) to seasonal mean concentrations from adjacent Dongkemadi Glacier (DG) over a full melt season of 2013 due to significant seasonality of DOC concentrations in glacial meltwater.

rating curves based on discharge measurements at a wide range of water levels. Glacier runoff from ASG, SJG, ALG, CUG, ACG, and CEG were assumed to be equivalent to annual mean runoff during 2003 to 2020, taken from a recent study that quantified glacier runoff (defined as all melt and rain water that runs off the glaciated area without refreezing) using an elevation-dependent glacier mass balance model with the temperature and precipitation scenarios from 14 global climate models (Bliss et al., 2014). Thus, glacier runoff from ASG, SJG, ALG, CUG, ACG, and CEG glacial regions are 359, 73, 338, 62, 212, and 9 Gt/a, respectively.

To calculate the first-order estimates of DOC fluxes from ASG, SJG, ALG, CUG, ACG, and CEG glacial regions, we use glacier runoff multiplied by mean DOC concentrations from DG, UG1, NG, KG, and LHG (in Asia); Tschierva/Roseg Glaciers, Rotmoos stream, and Austrian 26 glaciers (in central Europe), Werenskioldbreen Glacier, and Austre Brøggerbreen Glacier (in Svalbard and Jan Mayen); John Evans Glacier (in Arctic Canada); Bow Glacier and Outre Glacier (in Western Canada and United States), and North Dawes Glacier, Carroll Glacier, Mendenhall Glacier, and Herbert Glacier (in Alaska; Table 1). The errors in DOC budgets were defined as the standard deviations of DOC concentrations multiplied by glacier runoff. This method has been adopted in recent estimates (e.g., Bhatia et al., 2013; Hood et al., 2015; Y. Liu et al., 2016).

## 3. Results

Concentrations of DOC from DG and UG1 spanned an order of magnitude, ranging from 0.20 (UG1) to 2.16 mg/L (DG; Table 1). DOC concentrations exhibited a pronounced seasonality, with higher values during late May to July and lower values during August (Figures 2a and 2b). During September to early October, DOC presented different patterns, with higher values for DG and lower values for UG1. At diurnal timescales (D1 to D4) for DG, DOC concentrations displayed a relatively complex variation. During the low flow season on either side of glacier melt season (D1 and D4), higher values generally occurred in afternoon hours (12:00–16:00 hr) with lower values in morning hours (04:00–10:00 hr; Figures 3a–3c). During glacier melt season (D2 and D3),

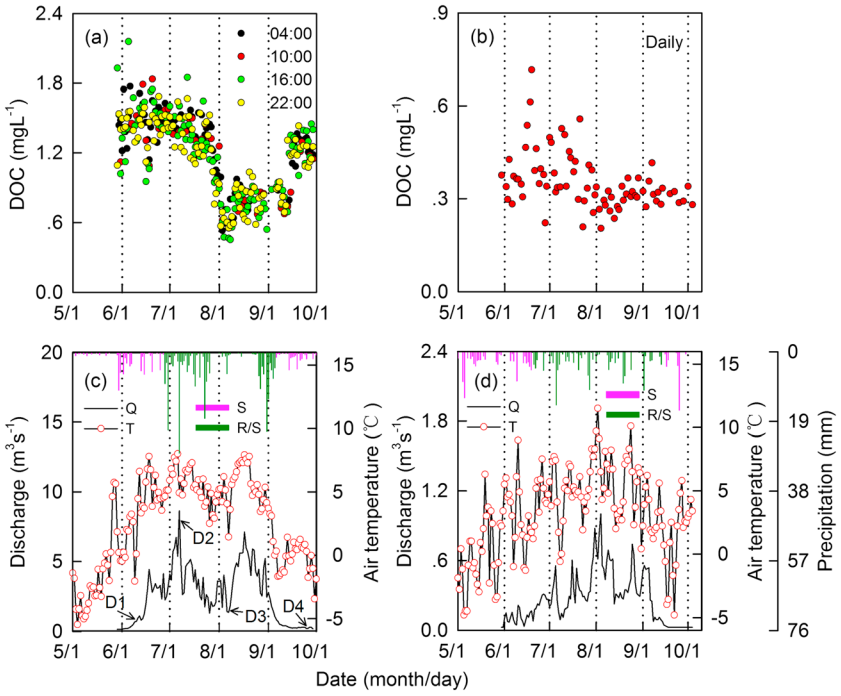


**Figure 2.** Hydrology, climate, and hydrochemistry from Dongkemadi Glacier (DG; a, c) and Urumqi Glacier No.1 (UG1; b, d) proglacial streams at sampling site S1 for DG and at site S for UG1: (a, b) hourly and daily concentrations of DOC, and (c, d) daily discharge (*Q*), air temperature (*T*), and precipitation (snowfall S, rainfall and/or snowfall, R/S) at the seasonal timescales over a full melt season during late May to early October in 2013.

DOC concentrations were variable and showed no discernable diurnal trend (Figures 2a–2d). Precipitation was dominated by snowfall during May–June and September–October compared with rainfall and/or snowfall during July–August. Snow cover usually lasted for a few days in proglacial areas, but a large snowfall occurred in late May and snow cover persisted more than a week at DG (Figures 2c and 2d).

Daily fluxes of DOC from DG and UG1 were estimated by daily mean DOC concentrations multiplied by daily mean discharge. DOC fluxes were positively related to glacial discharge, and the cumulative discharge and fluxes increased sharply during peak runoff from early July through August for DG and from late July through early September for UG1, with the largest daily fluxes (1,138 kg for DG and 23.6 kg for UG1) occurring during July and the smallest daily fluxes taking place during May for UG1 (0.6 kg) and during September for DG (13.2 kg; Figure 4). Total seasonal discharges in 2013 were $27.5 \times 10^6$ $m^3$ for DG and $2.94 \times 10^6$ $m^3$ for UG1, which transported an estimated 30,665 kg of DOC from DG and 986 kg of DOC from UG1. This equated to melt season area weighted DOC yields (DOC flux divided by the contributing area) of 1,097 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for DG and 295 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for UG1.

The range of concentrations of DOC from DG and UG1 overlapped with those in the majority of previously published studies for mountain glaciers (Table 1). We scaled up our high-resolution data from DG and UG1 in combination with published data from three mountain glaciers (NG, KG, and LHG) in Asia to estimate a regional DOC flux at 194 Gg C/a of DOC from ASG (Table 2). Similarly, other regional DOC fluxes were estimated at 156 Gg C/a from SJG, 98 Gg C/a from ALG, 16 Gg C/a from CUG, 110 Gg C/a from ACG, and 2.8 Gg C/a from CEG. This equated to glaciated area weighted DOC yields of 4,599 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for SJG, followed by 1,594 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for ASG, 1,357 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for CEG, 1,130 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for ALG, 1,099 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for CUG, and 755 $kg{\cdot}km^{-2}{\cdot}a^{-1}$ for ACG (Table 2).

## 4. Discussion

### 4.1. DOC Concentration and Flux

Glacier runoff is closely related to climate factors, with higher runoff occurring as a result of increases in air temperature and precipitation. Temporal changes in glacier runoff reflect not only the diurnal and

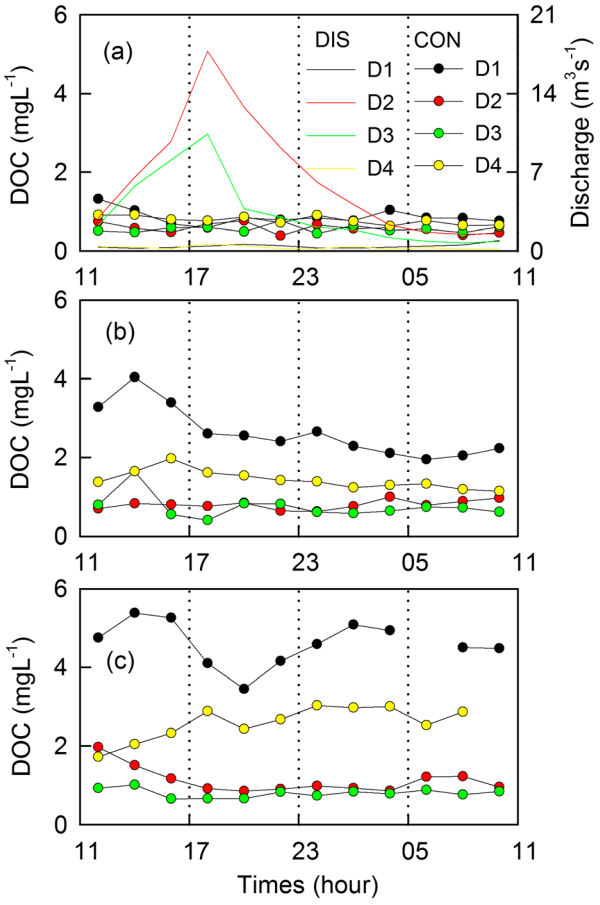


**Figure 3.** Bi-hourly concentrations (CON) and/or meltwater discharge (DIS) from Dongkemadi Glacier proglacial stream at sampling sites S1 (a), S2 (b), and S3 (c) at the diurnal timescales (D1 to D4; see Figure 1) during June to September in 2013. DOC = dissolved organic carbon.

seasonal variations in surface ablation and meltwater generation but also the balance of melting, refreezing, and meltwater storage change in mountain glacial environments (Hodgkins, 2001; Hodgkins et al., 2013). Glaciers support microbially dominated food webs, and its hydraulic configuration governs the distribution of water and nutrients (Tranter, 2005). The snowpack, glacier surface and glacier bed are recognized as key areas of microbial activity, and the wet snow, cryoconite holes, streams, ponds, and moraines are the important habitats of microorganisms in glacial ecosystems (Hodson et al., 2008). Seasonal variations in concentrations of DOC from DG and UG1 highlight the interactions between meltwater and microbial activity and carbonaceous materials across the glacier runoff season (e.g., Bhatia et al., 2006; Hodson et al., 2008; Stibal et al., 2008; Stubbins et al., 2012). Field observation showed that DG and UG1 are covered by the snowpack during the early melt season. The snowpack is fertilized by eolian dust and mineral species (X. Li et al., 2007, 2016; Takeuchi et al., 2000) and provides the inocula, nutrients, and water that cascade throughout glacial ecosystems (Fountain, 1996; Tranter et al., 1996). When snow begins to melt during the early melt season (29 May to 20 June for DG and 29 May to 19 June for UG1), there is storage of water in the snowpack, whose extensive saturation and subsequent ablation allow wet snow and liquid water to flow across glacier surface to the ice-marginal and the glacier interior drainage systems (Hodgkins, 2001; Hodgkins et al., 2013). River discharge is dominated by the release of supraglacially stored meltwater, which leaches DOC from wet snow and/or the glacier surface in the supraglacial ecosystems (Musilova et al., 2017; Spencer, Vermilyea, et al., 2014; Smith et al., 2017), thus leading to higher DOC concentrations. The elution process may affect the removal of DOC from the snowpack. This is suggested by the elution sequences of dissolved species found in the snowpack on UG1 ($SO_4^{2-} > Ca^{2+} > NO_3^- > Cl^- > Mg^{2+} > NH_4^+$; Z. Li et al., 2006). In the proglacial ecosystems, ground ice in the proglacial region of the DG and UG1 basins may also contribute to river discharge (Han et al., 2016; X. Li et al., 2016). The leaching of soil-derived DOC from detritus and/or senescent biomass may therefore contribute to the DOC content of stream runoff (McClelland et al., 2014), because the distance from sampling site to the glacier terminus is 500 m. This can be supported by an obviously increasing concentration of DOC from S1 to S3 at DG during D1 and D4 (Figure 3).

During the peak flow season (21 June to 3 September for DG and 20 June to 7 September for UG1), the supraglacially stored water runs off glacier surface to the subglacial drainage systems. River discharge is dominated by the release of subglacially stored meltwater, as indicated by high peaks of runoff (Figures 2e and 2f). Observations showed that cryoconite holes are widely distributed in the ablation areas of DG and UG1, and it certainly exerts a major influence on the biogeochemical cycling in glacial ecosystems. Cryoconite holes represent the most active microbial habitat upon snow-free and melting ice and harbor a greater diversity of microorganisms than the snowpack (e.g., Hodson et al., 2008; Takeuchi et al., 2000). After supraglacial meltwater enter the subglacial drainage systems (Hodson et al., 2008; Tranter et al., 1993), the supraglacial, englacial, and subglacial ecosystems may be coupled, and the flushing of meltwater may enable the acquisition of DOC from basal ice/till mixtures in the subglacial ecosystems, hence resulting in higher DOC concentrations during the early stage of the peak flow season (21 June to 28 July for DG and 20 June to 21 July for UG1). During the later stage (29 July to 3 September for DG and 22 July to 7 September for UG1), the potential for DOC leaching increases, yet most of the DOC has been released from the subglacial ecosystems during the early stage, thus leading to lower DOC concentrations. This is supported by river discharge during the late stage, which is 1.0 and 2.5 times higher than those during the early stage for DG and UG1, respectively. Noticeably, DOC concentrations in glacier runoff are quite stable during the late stage, suggesting that glacial discharge is compositionally similar across the main runoff season. During the late melt season (4 to 30

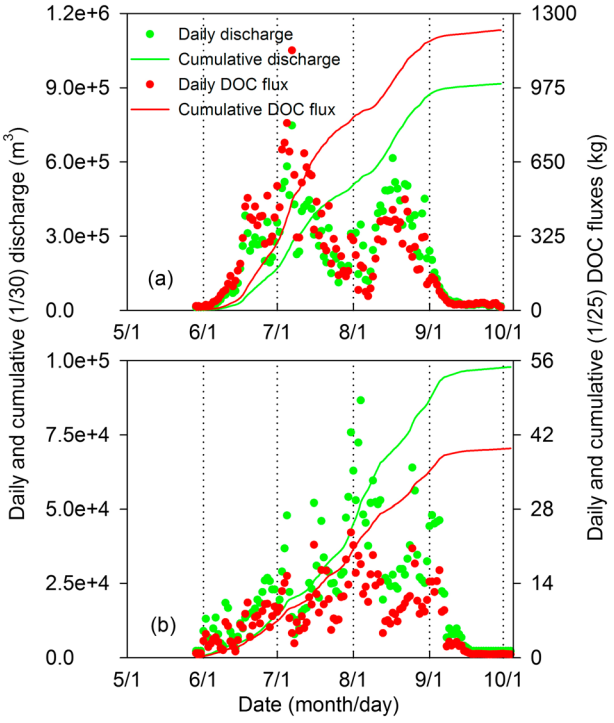


**Figure 4.** Daily and cumulative meltwater discharges, as well as daily and cumulative dissolved organic carbon (DOC) fluxes from Dongkemadi Glacier (a) and Urumqi Glacier No.1 (b) over a full melt season during late May to early October in 2013.

September for DG and 8 September to 4 October for UG1), the supraglacial meltwater store is largely expended, and there is renewed storage of water within the contracting englacial and/or subglacial conduits (Hodgkins, 2001; Hodgkins et al., 2013). River discharge is dominated by the release of subglacially stored meltwater, as indicated by relatively stable runoff (Figures 2c and 2d). DOC may come from the subglacial and/or proglacial ecosystems at this stage of the season (Mindl et al., 2007; Skidmore et al., 2005, 2000). Higher concentrations of DOC from DG may be related to well-developed soils and plants in the proglacial area, in comparison to bare glacial deposits at UG1.

Published concentrations of DOC range from 0.06 to 3.70 mg/L for mountain glaciers, with a mean concentration of 0.54 ± 0.74 mg/L ($n$ = 506; Table 1). The mean and range of DOC concentrations are larger than that (0.37 mg/L, 0.10 to 3.40 mg/L) from mountain glaciers reported by Hood et al. (2015). Our mean concentration of DOC from DG and UG1 is 0.76 mg/L ($n$ = 452), which is within the range of concentrations of DOC from mountain glaciers (Table 1). Concentrations of DOC from mountain glaciers demonstrate high spatial variations, as a result of many factors including atmospheric deposition, biological activity, and distance of sampling sites from the glacier terminus (Table 1). At spatial scale, DOC reveals an increasing concentration from S1 to S3 particularly during D1 and D4 (Figures 3a–3c). In detail, mean DOC concentrations during D1 to D4 increase by 1.9 times from S1 to S2 and by 3.0 times from S1 to S3 (Figure 5). This downstream change is most likely related to the leaching and/or flushing of snow water during D1 and D4, and snow and/or rain water during D3 and D4 (Figures 2c and 2d) from surrounding mountain slopes within the glacial basins. This suggests that the selection of sampling locations in the field is important for studies on glacier meltwater hydrochemistry, and meanwhile, the loss of terrestrial DOC from mountain slopes might outweigh the input of glacial DOC or to a large extent compensate for the loss of glaciers from the headwaters of mountain regions. In addition, sampling seasons also affect the spatial variation of DOC concentrations. For example, if we sampled only during August, mean DOC concentrations would have been 0.75 mg/L from DG and 0.30 mg/L from UG1, which are 1.6 and 1.2 times less than seasonal mean concentrations for DG and UG1, respectively. These values can be compared

**Table 2**
*Annual Fluxes and Yields of DOC in Meltwater Runoff Draining From Mountain Glaciers in Asia (ASG), Alaska (ALG), Western Canada and United States (CUG), Svalbard and Jan Mayen (SJG), Arctic Canada North (ACG), and Central Europe (CEG) During the Current Period 2003–2022, in Comparison to the Fluxes and Yields of DOC From Mountain Glaciers and Ice Sheets Globally*

| Mountain glaciers | Glacial area ($km^2$) | Glacier runoff (Gt/a) | Sample size | Mean concentration (mg/L) | DOC flux (Gg/a) | DOC yields ($kg \cdot km^{-2} \cdot a^{-1}$) | Source |
|---|---|---|---|---|---|---|---|
| ASG | 121,694[a] | 359[b] | 638 | 0.54 ± 0.35 (0.34–1.17) | 194 ± 126 | 1,594 ± 1,035 | This study |
| SJG | 33,922[a] | 73[b] | 32 | 2.14 ± 1.78 (0.88–3.40) | 156 ± 130 | 4,599 ± 3,832 | This study |
| ALG | 86,715[a] | 338[b] | >45 | 0.29 ± 0.09 (0.14–0.38) | 98 ± 30 | 1,130 ± 346 | This study |
| CUG | 14,559[a] | 62[b] | 133 | 0.25 ± 0.21 (0.10–0.40) | 16 ± 13 | 1,099 ± 893 | This study |
| ACG | 145,767[a] | 212[b] | 57 | 0.52 ± 0.40 (0.23–0.80) | 110 ± 85 | 755 ± 583 | This study |
| CEG | 2,063[a] | 9[b] | 52 | 0.31 ± 0.04 (0.27–0.35) | 2.8 ± 0.4 | 1,357 ± 194 | This study |
| Mountain Glaciers | 726,792[a] | 1,667 | 55 | 0.37 ± 0.06 (0.10–3.40) | 580 | 798[c] | Hood et al. (2015) and Bliss et al. (2014) |
| Greenland Ice Sheet | 1,711,279[d] | 963 | 9 | 0.43 ± 0.05 (0.20–0.90) | 216 | 120[c] | Hood et al. (2015), Bhatia et al. (2013), and Bamber et al. (2012) |
| Antarctic Ice Sheet | 12,295,000[e] | 1,621 | 23 | 0.51 ± 0.11 (0.18–1.20) | 243 | 20[c] | Hood et al. (2015) and Rignot et al. (2008) |

[a]Values from Pfeffer et al. (2014). [b]Values from Bliss et al. (2014). [c]Values from DOC flux divided by glacier/ice sheet areas. [d]Value from Kargel et al. (2012) and Pfeffer et al. (2014). [e]Value from Fretwell et al. (2013).

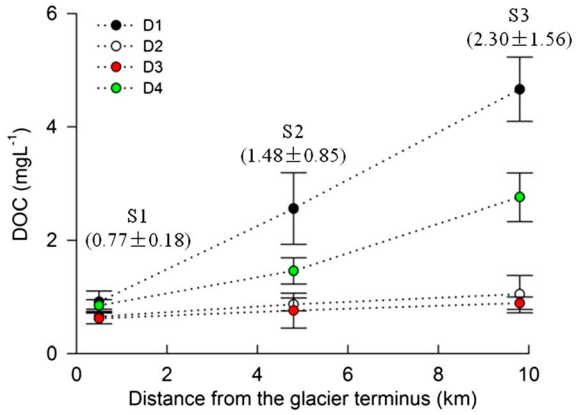


**Figure 5.** Variation in concentration of dissolved organic carbon (DOC) in stream runoff from site S1 to S3 along glacial river at the Dongkemadi Glacier basin during the diurnal cycles D1 (June), D2 (July), D3 (August), and D4 (September) over a full melt season in 2013.

with those from Austre Brøggerbreen Glacier (0.88 mg/L) and Mendenhall Glacier (0.38 mg/L) sampled during the same month (August).

There is also significant seasonality in the fluxes of DOC from DG and UG1, which is closely associated with the release of glacially stored meltwater. The fluxes of DOC from the subglacial stored water during the peak flow seasons are significant compared with those from the supraglacial or subglacial stored water during the early and late melt seasons. Although DOC concentrations are higher during the early melt seasons, their fluxes only account for 9.9% and 8.1% of total DOC fluxes from DG and UG1, respectively. However, during the peak flow seasons they account for 87.0% and 88.6% of total DOC fluxes from DG and UG1, respectively. Although DOC concentrations are lower during the late-summer peak, their fluxes are higher for DG and UG1 due to high levels of glacial discharge (Figures 2 and 4). Temporal variation in fluxes of DOC we observed can largely be attributed to water fluxes, which changed on daily and seasonal timescales. This suggests that glacier meltwater is the dominant source of stream runoff and DOC transport at glacial catchments. This is consistent with previous studies that DOC fluxes are controlled more by glacier runoff volume than by DOC concentration (Bhatia et al., 2013; Hood et al., 2009; Hood & Scott, 2008). Thus, the majority of glacial DOC is annually released during the peak flow season. In comparison, DOC concentrations exhibit a similar seasonal pattern, and DOC export increases with glacial discharge at Bow Glacier and John Evans Glacier catchments (Lafrenière & Sharp, 2004; Barker et al., 2006). Although DOC flux from UG1 is 4.0 times lower than that from LHG (3,917 kg C/a), its yields is 1.5 times higher than that from LHG (192 kg·km$^{-1}$·a$^{-1}$, Yan et al., 2016). This suggests that the efficiency of meltwater production and concomitant microbiological activity together affect the yields of DOC from mountain glaciers.

The overall seasonality in concentration of DOC from DG and UG1 is reflected in the ratios of monthly to seasonal mean concentrations of DOC over a full melt season, which are higher in June (1.08–1.17) and July (1.08–1.12), compared to the following runoff season months of August (0.62–0.93) and September (0.94–0.96). Changes in these ratios reveal the amplitude of seasonal variations of DOC concentrations and provide a template that can be used to estimate seasonal mean concentrations of DOC sampled during the limited periods of glacier runoff season at mountain glacial basins within Asia that have a similar climate and atmospheric environments. Enrichment of DOC during the first half of melt season with higher ratios implies the release of concentrated meltwater from the supraglacial, englacial, and subglacial drainage systems due to the flushing of meltwater and microbiological activity therein.

### 4.2. DOC Export and Implication

Although the flux of DOC from mountain glaciers is dominated by glacial discharge, the impact of glacial discharge on the regional and global carbon cycles depends on the magnitude of DOC flux as well as the bioavailability of DOC released. When glacially derived DOC enters downstream aquatic ecosystems, their ecosystem-level significance depends on the mass of DOC from mountain glaciers and also on the behavior of DOC following its release to aquatic ecosystems. Our estimate of current release of DOC from ASG is larger than those from Gulf of Alaska (130 Gg C/a; Hood et al., 2009), European Alps (0.34 Gg C/a; Singer et al., 2012), and Svalbard Archipelago (20 Gg C/a; Zhu et al., 2016). Total release of DOC from ASG, SJG, CUG, ALG, ACG, and CEG is 577 Gg C/a of DOC, which can be compared with global mountain glacier DOC release (Table 2). In addition, the area-weighted flux of DOC from ASG is higher than those from ALG, CUG, ACG, and CEG (Table 2) as well as from European Alps (70 kg·km$^{-2}$·a$^{-1}$; Singer et al., 2012) and Svalbard Archipelago (550 kg·km$^{-2}$·a$^{-1}$; Zhu et al., 2016). Given the high bioavailability of glacially derived DOC, this underscores the regional relevance of Asian mountain glaciers for downstream biogeochemistry. Noticeably, the release and yields of DOC from ASG are far larger than that from ALG despite glacier runoff is similar. This implies a higher concentration of DOC in the ice, the meltwater, or both from ASG. By using glacier mass (8,736–13,702 Gt/a) from ASG (Grinsted, 2013; Huss & Farinotti, 2012; Marzeion et al., 2012; Radić et al., 2014) multiplied by mean concentration (1.01 mg/L) of DOC in surface snow/ice from four glaciers (DG, UG1, LHG, and Yulong [YL]) in Asia (Figure 1; Y. Liu et al., 2016), we estimate that

the mass of DOC stored in ASG ranges from 8,800 to 13,800 (±2,400) Gg C, which accounts for 13–20% of DOC stored in worldwide mountain glaciers (70,000 Gg C; Hood et al., 2015). This is more than the contribution (6–11%) of ASG to the liquid water content of mountain glaciers. It should be noted that we did not take into account the subglacial store of DOC in mountain glaciers because there is no available data enabling us to quantify this component. Our estimate may represent an upper limit of DOC storage in ASG due to higher concentration of DOC in mountain glaciers during recent decades, in which DOC concentrations from ice core has increased due to increased anthropogenic emissions (Lavanchy et al., 1999). Moreover, mean DOC concentration on the surface is significantly higher than that in englacial ice for mountain glaciers (Hood et al., 2015). Under climate warming, higher microbial activity in the supraglacial, englacial, and subglacial ecosystems may also result in higher concentration of DOC in comparison to cold climate (Y. Liu et al., 2016).

Given that these six glacier regions account for 90% of mountain glacier runoff (1,167 Gt/a; Bliss et al., 2014; Hood et al., 2015), if we crudely extrapolate DOC release from these six glacial regions to a global scale by their percentage of glacier runoff, DOC release from mountain glaciers, combined with DOC release (145 Gg C/a) via ice calving from mountain glaciers (Hood et al., 2015), would be 786 Gg C/a. On a global scale, our estimate of DOC release from mountain glaciers is 1.7 and 1.4 times higher than recent estimates for ice sheets (459 Gg C/a) and mountain glaciers (580 Gg C/a) respectively that was based on a lower concentration for mountain glaciers (Hood et al., 2015). It is noteworthy that recent estimate of DOC from Antarctic ice sheet only includes ice calving (Hood et al., 2015), and the surface and subglacial runoff (55.2–253.8 $km^3$/a; Hodson et al., 2017) is completely overlooked. By using this estimated Antarctic surface runoff flux (22.7–156.3 $km^3$/a) multiplied by the median concentration (0.22 ± 0.36 mg/L) of DOC in surface streams (Hodson et al., 2017), DOC release is estimated at 5.0–34.4 Gg C/a. Assuming the DOC content in surface runoff is similar to that in the subglacial runoff, DOC release from the Antarctic ice sheet, combined with DOC release (243 Gg C/a) via ice calving (Hood et al., 2015), would be 255–299 Gg C/a. Our estimate of DOC release from mountain glaciers is therefore 1.5–1.7 times higher than that from the Antarctic and Greenland ice sheets (471–515 Gg C/a). In the context of land-to-ocean organic carbon export, our estimate of DOC flux from mountain glaciers liberated annually equates to 0.5% of the global riverine flux of DOC to the coastal oceans (Dai et al., 2012). Although glacier runoff from mountain glaciers only accounts for 65% of the combined runoff from ice sheets, its area-weighted DOC flux is 15.6 times higher than the mean flux from ice sheets. This suggests that mountain glacial ecosystems have large potential for substantial DOC export in a form that is highly available to downstream aquatic ecosystems.

Although DOC from mountain glaciers is considerable, DOC release into downstream freshwater and marine ecosystems is difficult to constrain. Instream removal affects DOC flux to downstream near-shore ecosystems, particularly with long transit times associated with runoff from ASG to coastal water. Indeed, Singer et al. (2012) showed that the instream removal rate of DOC is 59% within glacier-fed streams. Previous studies have also shown that roughly 1.7 to 50% of riverine DOC is removed in the estuarine environments (Alling et al., 2010; Amon & Benner, 1996; Dai & Martin, 1995; Dai et al., 2012; Moran et al., 1999; Raymond & Bauer, 2000). Since glacial DOC is labile and biologically available, its transformation into $CO_2$ by downstream bacterial production is highly likely, and this might in itself constitute a significant regional carbon flux. For example, a bacterial growth efficiency of 19.4% (Del Giorgio & Cole, 1998; Singer et al., 2012) means that the instream metabolism of DOC from mountain glaciers potentially contributes 187 Gg C/a to respiratory $CO_2$ that eventually leaves glacier-fed streams to the atmosphere. These findings therefore highlight that the role of mountain glaciers might also include non-negligible $CO_2$ evasion fluxes, as well as regionally significant DOC fluxes.

Our estimates contain substantial uncertainty. The largest source of uncertainty is the scarcity of data on concentrations of DOC from mountain glaciers. There is a great deal of regional variability in concentrations of DOC and the data assembled here do not allow for any statistically valid inferences about how atmospheric deposition or glacier size influences the concentrations of DOC in glacier runoff. For example, DG has a higher mean DOC concentration than either UG1, which is substantially smaller than DG, or LHG, which is larger than DG (Table 1). This implies that our extrapolation from a small number of glaciers to produce the regional and global estimates of the DOC flux from mountain glaciers have a high degree of uncertainty. However, even using the average concentration (0.56 ± 0.72 mg/L, $n > 957$) of DOC from worldwide mountain glaciers as the global average concentration of DOC in mountain

glacier runoff equates to a global flux of 799 ± 985 Gg C/a from mountain glaciers, which is close to the value (786 Gg C/a) discussed above. This suggests that our estimate is representative of DOC release from mountain glaciers to date.

## 5. Conclusions

Concentrations of DOC from DG and UG1 were continuously monitored over the full melt season of 2013. DOC concentrations exhibited a significant seasonal variation, with higher values in early melt seasons and lower values in late peak flow seasons. Utilizing current data, combined with published data, produced an estimate of the storage/release of DOC. Storage of DOC in ASG ranges from 8,800 to 13,800 Gg C, which accounts for 13–20% of DOC stored in mountain glaciers. Release of DOC from ASG (194 Gg C/a) and from other glacial regions (SJG, CUG, ALG, ACG, and CEG) indicate the release of DOC at 786 Gg C/a, which is 1.4 times higher than that estimated by Hood et al. (2015) prior to this work. Although our results contain substantial uncertainty, our findings provide strong evidence that current release of DOC is far larger than recent estimates from mountain glaciers. Further evaluation is crucial for improving our understanding of downstream ecological impacts of glacier runoff in a warming climate.

**Acknowledgments**

Supporting data are included as Tables S1 and S2 in an SI file; any additional data may be obtained from Xiangying Li (email: shaanxilxy@163.com). This work was funded by the National Natural Science Foundation of China (91647102 and 41671053), Fundamental Research Funds for the Central Universities (2018B10214), National Natural Science Foundation of China (41730751, 41771040, 41671071 and 41761017), Open Foundation of the State Key Laboratory of Cryospheric Sciences (SKLCS-OP-2017-03), Open Foundation of the State Key Laboratory of Frozen Soil Engineering (SKLFSE201411), Special Fund of State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (20145027312), Academy of Finland (268170), and the Independent Program of the State Key Laboratory of Cryospheric Sciences (SKLCS-ZZ-2018), this work was also supported by the Department of Interior Alaska Climate Science Center. We thank Rui Xu and Dongying Hui for laboratory analysis and Wanqin Guo for helping to draw Figure 1, as well as Hodson Andy and the anonymous reviewers for their constructive suggestions.

## References

Alling, V., Sanchez-Garcia, L., Porcelli, D., Pugach, S., Vonk, J. E., van Dongen, B., et al. (2010). Nonconservative behavior of dissolved organic carbon across the Laptev and East Siberian seas. *Global Biogeochemical Cycles*, *24*, GB4033. https://doi.org/10.1029/2010GB003834

Amon, R. M. W., & Benner, R. (1996). Photochemical and microbial consumption of dissolved organic carbon and dissolved oxygen in the Amazon River system. *Geochimica et Cosmochimica Acta*, *60*(10), 1783–1792. https://doi.org/10.1016/0016-7037(96)00055-5

Anesio, A. M., & Laybourn-Parry, J. (2012). Glaciers and ice sheets as a biome. *Trends in Ecology & Evolution*, *27*(4), 219–225. https://doi.org/10.1016/j.tree.2011.09.012

Bamber, J., van den Broeke, B. M., Ettema, J., Lenaerts, J., & Rignot, E. (2012). Recent large increases in freshwater fluxes from Greenland into the North Atlantic. *Geophysical Research Letters*, *39*, L19501. https://doi.org/10.1029/2012GL052552

Bardgett, R. D., Richter, A., Bol, R., Garnett, M. H., Bäumler, R., Xu, X., et al. (2007). Heterotrophic microbial communities use ancient carbon following glacial retreat. *Biology Letters*, *3*(5), 487–490. https://doi.org/10.1098/rsbl.2007.0242

Barker, J. D., Sharp, M. J., Fitzsimons, S. J., & Turner, R. J. (2006). Abundance and dynamics of dissolved organic carbon in glacier systems. *Arctic, Antarctic, and Alpine Research*, *38*(2), 163–172. https://doi.org/10.1657/1523-0430(2006)38[163:AADODO]2.0.CO;2

Battin, T. J., Wille, A., Sattler, B., & Psenner, R. (2001). Phylogenetic and functional heterogeneity of sediment biofilms along environmental gradients in a glacial stream. *Applied and Environmental Microbiology*, *67*(2), 799–807. https://doi.org/10.1128/AEM.67.2.799-807.2001

Bhatia, M. P., Das, S. B., Longnecker, K., Charette, M. A., & Kujawinski, E. B. (2010). Molecular characterization of dissolved organic matter associated with the Greenland ice sheet. *Geochimica et Cosmochimica Acta*, *74*(13), 3768–3784. https://doi.org/10.1016/j.gca.2010.03.035

Bhatia, M. P., Das, S. B., Xu, L., Charette, M. A., Wadham, J. L., & Kujawinski, E. B. (2013). Organic carbon export from the Greenland ice sheet. *Geochimica et Cosmochimica Acta*, *109*, 329–344. https://doi.org/10.1016/j.gca.2013.02.006

Bhatia, M. P., Sharp, M., & Foght, J. (2006). Distinct bacterial communities exist beneath a high Arctic polythermal glacier. *Applied and Environmental Microbiology*, *72*(9), 5838–5845. https://doi.org/10.1128/AEM.00595-06

Bianchi, T. S. (2011). The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect. *Proceedings of the National Academy of Sciences*, *108*(49), 19,473–19,481. https://doi.org/10.1073/pnas.1017982108

Bliss, A., Hock, R., & Radić, V. (2014). Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research: Earth Surface*, *119*, 717–730. https://doi.org/10.1002/2013JF002931

Dai, M.-H., & Martin, J.-M. (1995). First data on trace metal level and behaviour in two major Arctic river-estuarine systems (Ob and Yenisey) and in the adjacent Kara Sea, Russia. *Earth and Planetary Science Letters*, *131*(3-4), 127–141. https://doi.org/10.1016/0012-821X(95)00021-4

Dai, M.-H., Yin, Z., Meng, F., Liu, Q., & Cai, W.-J. (2012). Spatial distribution of riverine DOC inputs to the ocean: An updated global synthesis. *Current Opinion in Environmental Sustainability*, *4*(2), 170–178. https://doi.org/10.1016/j.cosust.2012.03.003

Deepak, S., Kumar, A., Verma, A., & Swaroop, S. (2014). Characterization of suspended sediment in meltwater from glaciers of Garhwal Himalaya. *Hydrological Processes*, *28*, 969–979.

Del Giorgio, P. A., & Cole, J. J. (1998). Bacterial growth efficiency in natural aquatic systems. *Annual Review of Ecology, Evolution, and Systematics*, *29*(1), 503–541. https://doi.org/10.1146/annurev.ecolsys.29.1.503

Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., et al. (2015). Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nature Geoscience*, *8*(9), 716–722. https://doi.org/10.1038/ngeo2513

Fellman, J. B., Hood, E., Spencer, R. G. M., Stubbins, A., & Raymond, P. A. (2014). Watershed glacier coverage influences dissolved organic matter biogeochemistry in coastal watersheds of southeast Alaska. *Ecosystems*, *17*(6), 1014–1025. https://doi.org/10.1007/s10021-014-9777-1

Fountain, A. G. (1996). The effect of snow and firn hydrology on the physical and chemical characteristics of glacier runoff. *Hydrological Processes*, *10*(4), 509–521. https://doi.org/10.1002/(SICI)1099-1085(199604)10:4<509::AID-HYP389>3.0.CO;2-3

Fretwell, P. T., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., et al. (2013). Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, *7*(1), 375–393. https://doi.org/10.5194/tc-7-375-2013

Grinsted, A. (2013). An estimate of global glacier volume. *The Cryosphere*, *7*(1), 141–151. https://doi.org/10.5194/tc-7-141-2013

Han, T., Li, X., Gao, M., Sillanpää, M., Pu, H., & Lu, C. (2015). Electrical conductivity during the ablation process of the Glacier No.1 at the headwater of the Urumqi River in the Tianshan Mountains. *Arctic, Antarctic, and Alpine Research*, *47*(2), 327–334. https://doi.org/10.1657/AAAR00C-13-138

Han, T., Pu, H., Cheng, P., & Jiao, K. (2016). Hydrological effects of alpine permafrost in the head of Urumqi River, Tianshan Mountains. *Sciences in Cold and Arid Regions*, *8*, 241–249.

Hodgkins, R. (2001). Seasonal evolution of meltwater generation, storage and discharge at a non-temperate glacier in Svalbard. *Hydrological Processes*, *15*(3), 441–460. https://doi.org/10.1002/hyp.160

Hodgkins, R., Cooper, R., Tranter, M., & Wadham, J. (2013). Drainage-system development in consecutive melt seasons at a polythermal, Arctic glacier, evaluated by flow-recession analysis and linear-reservoir simulation. *Water Resources Research*, *49*, 4230–4243. https://doi.org/10.1002/wrcr.20257

Hodson, A., Anesio, A. M., Tranter, M., Fountain, A., Osborn, A. M., Priscu, J., et al. (2008). Glacial ecosystems. *Ecological Monographs*, *78*(1), 41–67. https://doi.org/10.1890/07-0187.1

Hodson, A., Bøggild, C., Hanna, E., Huybrechts, P., Langford, H., Cameron, K., & Houldsworth, A. (2010). The cryoconite ecosystem on the Greenland ice sheet. *Annals of Glaciology*, *51*(56), 123–129. https://doi.org/10.3189/172756411795931985

Hodson, A., Gurnell, A., Tranter, M., Bogen, J., Hagen, J. O., & Clark, M. (1998). Suspended sediment yield and transfer processes in a small High-Arctic glacier basin, Svalbard. *Hydrological Processes*, *12*(1), 73–86. https://doi.org/10.1002/(SICI)1099-1085(199801)12:1<73::AID-HYP564>3.0.CO;2-S

Hodson, A., Nowak, A., Sabacka, M., Jungblut, A., Navarro, F., Pearce, D., et al. (2017). Climatically sensitive transfer of iron to maritime Antarctic ecosystems by surface runoff. *Nature Communications*, *8*, 14499. https://doi.org/10.1038/ncomms14499

Hood, E., Battin, T. J., Fellman, J., O'Neel, S., & Spencer, R. G. M. (2015). Storage and release of organic carbon from glaciers and ice sheets. *Nature Geoscience*, *8*(2), 91–96. https://doi.org/10.1038/ngeo2331

Hood, E., Fellman, J., Spencer, R. G. M., Hernes, P. J., Edwards, R., D'Amore, D., & Scott, D. (2009). Glaciers as a source of ancient and labile organic matter to the marine environment. *Nature*, *462*(7276), 1044–1047. https://doi.org/10.1038/nature08580

Hood, E., & Scott, D. (2008). Riverine organic matter and nutrients in Southeast Alaska affected by glacial coverage. *Nature Geoscience*, *1*(9), 583–587. https://doi.org/10.1038/ngeo280

Huss, M., & Farinotti, D. (2012). Distributed ice thickness and volume of all glaciers around the globe. *Journal of Geophysical Research*, *117*, F04010. https://doi.org/10.1029/2012JF002523

IPCC (2013). In T. F. Stocker, et al. (Eds.), *Climate Change 2013: The Physical Science Basis*. Cambridge, U.K. Cambridge University Press.

Kargel, J. S., Ahlstrøm, A. P., Alley, R. B., Bamber, J. L., Benham, T. J., Box, J. E., et al. (2012). Greenland's shrinking ice cover: "Fast times" but not that fast. *The Cryosphere*, *6*(3), 533–537. https://doi.org/10.5194/tc-6-533-2012

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, *549*(7671), 257–260. https://doi.org/10.1038/nature23878

Lafrenière, M. J., & Sharp, M. J. (2004). The concentration and fluorescence of dissolved organic carbon (DOC) in glacial and nonglacial catchments: Interpreting hydrological flow routing and DOC sources. *Arctic, Antarctic, and Alpine Research*, *36*(2), 156–165. https://doi.org/10.1657/1523-0430(2004)036[0156:TCAFOD]2.0.CO;2

Lavanchy, V. M. H., Gäggeler, H. W., Schotterer, U., Schwikowski, M., & Baltensperger, U. (1999). Historical record of carbonaceous particle concentrations from a European high-alpine glacier (Colle Gnifetti, Switzerland). *Journal of Geophysical Research*, *104*(D17), 21,227–21,236. https://doi.org/10.1029/1999JD900408

Lawson, E. C., Wadham, J. L., Tranter, M., Stibal, M., Lis, G. P., Butler, C. E. H., et al. (2014). Greenland ice sheet exports labile organic carbon to the Arctic oceans. *Biogeosciences*, *11*(14), 4015–4028. https://doi.org/10.5194/bg-11-4015-2014

Li, X., He, X., Kang, S., Sillanpää, M., Ding, Y., Han, T., et al. (2016). Diurnal dynamics of minor and trace elements in stream water draining Dongkemadi Glacier on the Tibetan Plateau and its environmental implications. *Journal of Hydrology*, *541*, 1104–1118. https://doi.org/10.1016/j.jhydrol.2016.08.021

Li, X., Li, Z., Ding, Y., Liu, S., Zhao, Z., Luo, L., et al. (2007). Seasonal variations of pH and electrical conductivity of a snow-firn pack on Glacier No.1, eastern Tianshan, China. *Cold Regions Science and Technology*, *48*(1), 55–63. https://doi.org/10.1016/j.coldregions.2006.09.006

Li, X., Qin, D., Jing, Z., Li, Y., & Wang, N. (2013). Diurnal hydrological controls and non-filtration effects on minor and trace elements in stream water draining the Qiyi Glacier, Qilian Mountain. *Science China: Earth Sciences*, *56*(1), 81–92. https://doi.org/10.1007/s11430-012-4480-6

Li, Z., Edwards, R., Mosley-Thompson, E., Wang, F., Dong, Z., You, X., et al. (2006). Seasonal variabilities of ionic concentration in surface snow and elution process in snow-firn packs at PGPI Site on Glacier No.1 in Eastern Tianshan, China. *Annals of Glaciology*, *43*, 250–256. https://doi.org/10.3189/172756406781812069

Liu, S., Yao, X., Guo, W., Xu, J., Shangguan, D., Wei, J., et al. (2015). The contemporary glaciers in China based on the Second Chinese Glacier Inventory. *Acta Chimica Sinica*, *70*, 3–16.

Liu, Y., Xu, J., Kang, S., Li, X., & Li, Y. (2016). Storage of dissolved organic carbon in Chinese glaciers. *Journal of Glaciology*, *62*(232), 402–406. https://doi.org/10.1017/jog.2016.47

Loder, T. C., & Hood, D. W. (1972). Distribution of organic carbon in a glacial estuary in Alaska. *Limnology and Oceanography*, *17*(3), 349–355. https://doi.org/10.4319/lo.1972.17.3.0349

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, *4*(7), 587–592. https://doi.org/10.1038/nclimate2237

Marzeion, B., Jarosch, A. H., & Hofer, M. (2012). Past and future sealevel change from the surface mass balance of glaciers. *The Cryosphere*, *6*(6), 1295–1322. https://doi.org/10.5194/tc-6-1295-2012

McClelland, J. W., Townsend-Small, A., Holmes, R. M., Pan, F., Stieglitz, M., Khosh, M., & Peterson, B. J. (2014). River export of nutrients and organic matter from the North Slope of Alaska to the Beaufort Sea. *Water Resources Research*, *50*, 1823–1839. https://doi.org/10.1002/2013WR014722

Mindl, B., Anesio, A. M., Meirer, K., Hodson, A. J., Laybourn-Parry, J., Sommaruga, R., & Sattler, B. (2007). Factors influencing bacterial dynamics along a transect from supraglacier runoff to proglacial lakes of a high Arctic glacier. *FEMS Microbiology Ecology*, *59*(2), 307–317. https://doi.org/10.1111/j.1574-6941.2006.00262.x

Moran, M. A., Sheldon, W. M. J., & Sheldon, J. E. (1999). Biodegradation of riverine dissolved organic carbon in five estuaries of the southeastern United States. *Estuaries*, *22*(1), 55–64. https://doi.org/10.2307/1352927

Musilova, M., Tranter, M., Wadham, J., Telling, J., Tedstone, J., & Anesio, A. M. (2017). Microbially driven export of labile organic carbon from the Greenland ice sheet. *Nature Geoscience*, *10*(5), 360–365. https://doi.org/10.1038/ngeo2920

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., et al. (2014). The Randolph Glacier Inventory: A globally complete inventory of glaciers. *Journal of Glaciology*, *60*, 537–552.

Radić, V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E., & Cogley, J. G. (2014). Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, *42*(1-2), 37–58. https://doi.org/10.1007/s00382-013-1719-7

Raymond, P. A., & Bauer, J. E. (2000). Bacterial consumption of DOC during transport through a temperate estuary. *Aquatic Microbial Ecology*, *22*, 1–12. https://doi.org/10.3354/ame022001

Rignot, E., Bamber, J. L., Van Den Broeke, M. R., Davis, C., Li, Y., Van De Berg, W. J., & Van Meijgaard, E. (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience*, *1*(2), 106–110. https://doi.org/10.1038/ngeo102

Singer, G. A., Fasching, C., Wilhelm, L., Niggemann, J., Steier, P., Dittmar, T., & Battin, T. J. (2012). Biogeochemically diverse organic matter in Alpine glaciers and its downstream fate. *Nature Geoscience*, *5*(10), 710–714. https://doi.org/10.1038/ngeo1581

Singh, V. B., Ramanathan, A. L., Pottakkal, J. G., & Kumar, M. (2014). Seasonal variation of the solute and suspended sediment load in Gangotri glacier meltwater, central Himalaya, India. *Journal of Asian Earth Sciences*, *79*, 224–234. https://doi.org/10.1016/j.jseaes.2013.09.010

Skidmore, M., Anderson, S. P., Sharp, M., Foght, J., & Lanoil, B. D. (2005). Comparison of microbial community compositions of two subglacial environments reveals a possible role for microbes in chemical weathering processes. *Applied and Environmental Microbiology*, *71*(11), 6986–6997. https://doi.org/10.1128/AEM.71.11.6986-6997.2005

Skidmore, M., Foght, J., & Sharp, A. M. (2000). Microbial life beneath a High Arctic Glacier. *Applied and Environmental Microbiology*, *66*(8), 3214–3220. https://doi.org/10.1128/AEM.66.8.3214-3220.2000

Smith, H. J., Foster, R. A., McKnight, D. M., Lisle, J. T., Littmann, S., Kuypers, M. M. M., & Foreman, C. M. (2017). Microbial formation of labile organic carbon in Antarctic glacial environments. *Nature Geoscience*, *10*(5), 356–359. https://doi.org/10.1038/ngeo2925

Spencer, R. G. M., Guo, W., Raymond, P. A., Dittmar, T., Hood, E., Fellman, J., & Stubbins, A. (2014). Source and biolability of ancient dissolved organic matter in glacier and lake ecosystems on the Tibetan Plateau. *Geochimica et Cosmochimica Acta*, *142*, 64–74. https://doi.org/10.1016/j.gca.2014.08.006

Spencer, R. G. M., Vermilyea, A., Fellman, J., Raymond, P., Stubbins, A., Scott, D., & Hood, E. (2014). Seasonal variability of organic matter composition in an Alaskan glacier outflow: Insights into glacier carbon sources. *Environmental Research Letters*, *9*(5), 055005. https://doi.org/10.1088/1748-9326/9/5/055005

Stibal, M., Šabacká, M., & Žárský, J. (2012). Biological processes on glacier and ice sheet surfaces. *Nature Geoscience*, *5*(11), 771–774. https://doi.org/10.1038/ngeo1611

Stibal, M., Tranter, M., Benning, L. G., & Rehak, J. (2008). Microbial primary production on an Arctic glacier is insignificant in comparison with allochthonous organic carbon input. *Environmental Microbiology*, *10*(8), 2172–2178. https://doi.org/10.1111/j.1462-2920.2008.01620.x

Stubbins, A., Hood, E., Raymond, P. A., Aiken, G. R., Sleighter, R. L., Hernes, P. J., et al. (2012). Anthropogenic aerosols as a source of ancient dissolved organic matter in glaciers. *Nature Geoscience*, *5*(3), 198–201. https://doi.org/10.1038/ngeo1403

Takeuchi, N., Kohshima, S., Yoshimura, Y., Seko, K., & Fujita, K. (2000). Characteristics of cryoconite holes on a Himalayan glacier, Yala Glacier Central Nepal. *Bulletin of Glaciological Research*, *17*, 51–59.

Tockner, K., Malard, F., Uehlinger, U., & Ward, J. V. (2002). Nutrients and organic matter in a glacial river-floodplain system (Val Roseg, Switzerland). *Limnology and Oceanography*, *47*(1), 266–277. https://doi.org/10.4319/lo.2002.47.1.0266

Tranter, M. (2005). Geochemical weathering in glacial and proglacial environments. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on Geochemistry* (Vol. 5, pp. 189–205). London, UK: Elsevier.

Tranter, M., Brown, G. H., Hodson, A. J., & Gurnell, A. M. (1996). Hydrochemistry as an indicator of subglacial drainage system structure: A comparison of Alpine and sub-polar environments. *Hydrological Processes*, *10*(4), 541–556. https://doi.org/10.1002/(SICI)1099-1085(199604)10:4<541::AID-HYP391>3.0.CO;2-9

Tranter, M., Brown, G. H., Raiswell, R., Sharp, M., & Gurnell, A. (1993). A conceptual model of solute aqusistion by Alpine glacial meltwaters. *Journal of Glaciology*, *39*(133), 573–581. https://doi.org/10.1017/S0022143000016464

Wang, J., Xu, J., Zhang, S., Liu, S., & Han, H. (2010). Chemical denudation rates and carbon dioxide sink in Koxkar Glacierised region at the south slope of Mt. Tianshan, China. *Environmental Sciences*, *31*, 903–910.

Yan, F., Kang, S., Li, C., Zhang, Y., Qin, X., Li, Y., et al. (2016). Concentration, sources and light absorption characteristics of dissolved organic carbon on a medium-sized valley glacier, northern Tibetan plateau. *The Cryosphere*, *10*(6), 2611–2621. https://doi.org/10.5194/tc-10-2611-2016

Zhu, Z., Wu, Y., Liu, S., Wenger, F., Hu, J., Zhang, J., & Zhang, R. (2016). Organic carbon flux and particulate organic matter composition in Arctic valley glaciers: Examples from the Bayelva River and adjacent Kongsfjorden. *Biogeosciences*, *13*(4), 975–987. https://doi.org/10.5194/bg-13-975-2016