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Source, pattern and flux of dissolved carbon in an alpine headwater catchment on the eastern Tibetan Plateau

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Abstract

Dissolved carbon (DC) transported from headwater streams on the eastern Tibetan Plateau is a crucial component of the carbon cycles in the regional river. However, the spatiotemporal variability and sources of DC in these remote headwater streams remains unclear. An investigation into dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) was conducted with high temporal resolution from a glacier terminus, a forest catchment, and the catchment outlet located on the eastern flank of Mt. Gongga, Southwest China. The results showed that (1) the mean DOC concentration at the glacier terminus (2.38 ± 0.71 mg L^{-1}) was significantly higher than at the forest catchment (2.13 ± 0.49 mg L^{-1}) and at the catchment outlet (2.17 ± 0.58 mg L^{-1}), while the DIC concentration increased by 21.6% at the forest catchment and by 18.7% at the catchment outlet relative to that in the glacier terminus. (2) Compared to the monsoon season, DOC concentrations in the forest catchment decreased by 24.6% postmonsoon, and the seasonal variation of DOC concentrations was minor either at the glacier terminus or at the catchment outlet; relative to monsoon values, postmonsoon DIC concentrations increased by 14.9% and 28.8% at the forest catchment and catchment outlet, respectively. Precipitation and stream pH were identified as important factors influencing the seasonal variability of DC. (3) Silicate and carbonate weathering contributed 52.9 ± 12% and 44.4 ± 9%, respectively, to DIC generation in the forest catchment according to ^{13}C analysis. This study provides a valuable dataset on the dynamics of DC in a region where data is sparse, which improves our understanding of DC transport in alpine regions. The unexpected spatiotemporal stability of DC suggests that less frequent rates of sampling might be adequate to estimate carbon export.

KEYWORDS
carbon dynamics, carbon isotope, headwater streams, seasonal pattern, Tibetan plateau

1 | INTRODUCTION

Headwater streams are where the lateral transport of dissolved carbon (C) from landscapes to rivers originates, which is an important and active part of the C cycle (Chan et al., 2021; Downing et al., 2012; Jantze et al., 2015). The environment they provide is where metabolic processes develop, such as the mineralization of a portion of dissolved organic carbon (DOC) into CO_2 emissions that is released into the atmosphere (Argerich et al., 2016), and are also an important source of nutrients for downstream regions (Cole et al., 2007; Wang et al., 2021). However, compared to large rivers, headwater streams remain underinvestigated in terms of the patterns of C transport

between different landscapes, which impedes an accurate understanding of the 'boundless carbon cycle' (Battin et al., 2008).

Studies of headwater carbon transport have been largely focused on tropical and temperate streams in association with rainstorm events (Fellman et al., 2020; Perdrial et al., 2014; Wang et al., 2021) and Arctic and subarctic regions during freeze–thaw events (Giesler et al., 2014; McClelland et al., 2016; Wild et al., 2019). In comparison, headwater streams residing in alpine regions that are heavily affected by glacial meltwater have been less studied. Glaciers have been shown to provide nutrients and dissolved organic matter (DOM) with unique compositions and high degrees of bioavailability to headwater streams (Hemingway et al., 2019; Hood et al., 2015; Yu et al., 2021). Despite this importance, our understanding of how C transport responds to changing glacier conditions remains limited. For example, seasonal precipitation trends are likely important drivers of DOC dynamics, but these controls have not yet been fully assessed. Additionally, downstream changes in catchment landscape, soil thickness, and water residence time could reset the headwater C signals (Bernhardt et al., 2005; Perdrial et al., 2014), and more interpretation of C transport in this geomorphic context is needed.

Dissolved forms of carbon include dissolved inorganic carbon (DIC) and DOC, both of which have profound influences on aquatic food web processes and ecosystem sustainability (Chen et al., 2021; Tank et al., 2010). Below the tree line, terrestrial vegetation and soils constitute a major source of DOC found in streams (Lafreniere & Sharp, 2004), while in the alpine catchment above the tree line, mountain glaciers are an important alternative source because of poorly developed soils (Boix Canadell et al., 2019). Riverine DIC can mainly be categorized as geogenic and biogenic (Campeau et al., 2018). Geogenic DIC originates from carbonate weathering, while biogenic DIC originates from organic carbon mineralization and silicate weathering by H_2CO_3 (Song et al., 2020). Studies of major global rivers have shown that carbonate weathering contributes most of the DIC fluxes (Gaillardet et al., 1999; Goldscheider et al., 2020), but the source of DIC in headwater streams is still not fully understood, especially for glaciated catchments.

The Tibetan Plateau (TP), known as the 'Asian water tower', is the cradle of 10 large Asian rivers and is the largest cryosphere outside the Arctic and Antarctic (Chen et al., 2013; Yao et al., 2012). This region is covered by mountain glaciers, which contribute more meltwater to the streamflow during the summer as the temperature rises (Su et al., 2022; Wang et al., 2021). In addition, this region has a continental monsoon climate and is therefore significantly affected by intense precipitation during the summer monsoon (Zhang et al., 2020). Extensive glacier coverage, combined with the influence of the summer monsoon (Figure 1), makes this region an ideal location to assess the relative importance of precipitation and glacier melt as drivers of dissolved carbon transport in mountainous streams. To accomplish this, we conducted high-frequency water sampling along the Hailuogou (HLG) River on the eastern TP and investigated the

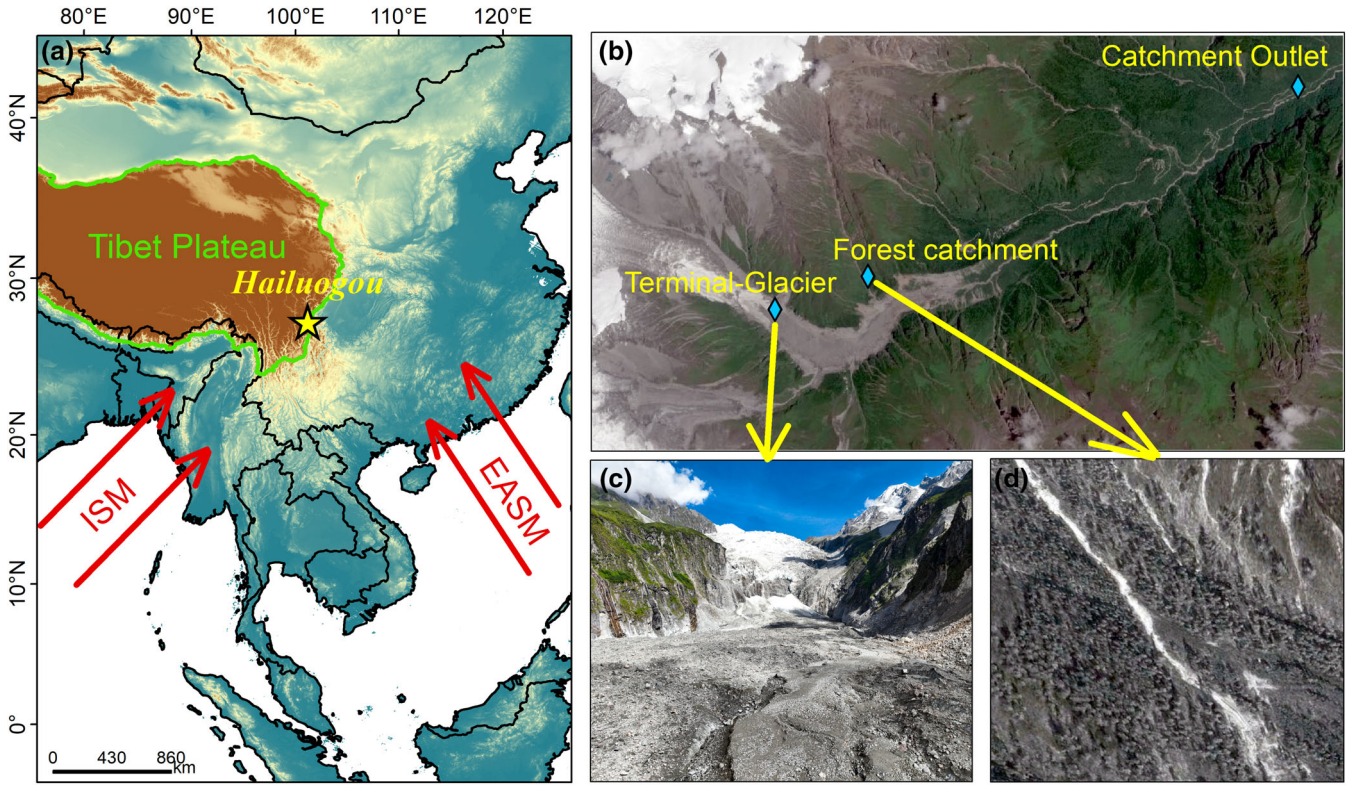

FIGURE 1 (a) Location of the study area in Hailuogou of the Southeast Tibetan Plateau. Red arrows indicate the Indian summer monsoon (ISM) and East Asian summer monsoon (EASM) that dominates in summer. (b) Schematic of catchment sampling sites in the Hailuogou River. (c) and (d) The glacier terminus and forest catchment, respectively.

seasonal dynamics of DOC and DIC in streams at the glacier terminus, forest catchment, and catchment outlet, and the source of DIC was assigned using ^{13}C isotopes. First, we monitored water chemistry and DOC and DIC concentrations daily over a 6-month period to estimate the effects of catchment characteristics on DOC and DIC. Second, we compared variations in DOC and DIC between catchments to analyse the potential impact of seasonal changes on dissolved carbon in streams. Third, the source of DIC was explored.

2 | DATA AND METHODS

2.1 | Study area

The HLG Glacier (29°34′21″ N, 102°59′42″ E) has a length of 13 km and an area of 25 km^2 and is a typical marine mountain glacier located on the eastern TP. The observed and continuous recession of the HLG Glacier began in ~1823 (He & Tang, 2008). The study area falls within a monsoon temperate region with distinct rainy (June–October) and dry (November–May) seasons. According to records from the local meteorological station, the mean annual precipitation is 1949 mm, most of which (over 70%) falls between June and October, with an average annual potential evaporation of 264 mm. The mean monthly temperature ranged from −4.5°C in February (coldest) to 12.7°C in July (warmest). Soil parent materials in the basin are predominantly biotite schist, granodiorite, and quartzite, with lesser amounts of phyllite, slate and chlorite schist (He & Tang, 2008). The study area is mostly covered by glaciers and forests, and the vegetation consists of *Abies fabri* (*Mast.*) *Craib*, *Rhododendron simsii Planch*, and *Sorbus pohuashanensis*.

2.2 | Sample collection and measurements

To remove the effect of snowmelt on runoff, stream water was collected at least daily during the monsoon (July–September) and post-monsoon (October–December) seasons in 2021 from the two subcatchments (glacier terminus and forest catchment) and catchment outlet (Figure 1). Unfortunately, we lost some samples from the catchment at the glacier terminus, but this did not affect our assessment of solute output from the whole catchment. Samples from the forest catchment were taken from two adjacent streams (Site 1 and Site 2), and samples from the other catchments were collected from a single site in the catchment, which allowed for the compilation of a large dataset that could be used for seasonal analysis.

The pH and electrical conductivity (EC) values of the water samples were measured with a pH electrode (HASH, HQ30D, American) and an EC electrode (LEICI, DDS-307A, China), respectively. Duplicate water samples were collected in prewashed high-density polyethylene (HDPE) bottles. The HDPE bottles were cleaned with soapy water, soaked in 10% HCl solution for 24 h, rinsed three times using hyperpure water before drying, and re-rinsed three times with field stream water prior to sampling. Samples for DOC, total dissolved nitrogen (TDN), and ion analysis were filtered through a 0.45 μm acetate disposable syringe and into 60 mL HDPE bottles on the same day. Water isotope samples were collected in 20 mL centrifuge tubes without headspace. All samples were immediately stored in the dark at 4°C until further processing. Daily discharge at the catchment outlet was obtained from the Gonghecun (GHC) Hydrological Station. Temperature and precipitation data used in this study were obtained from the Gongga weather station.

DOC and TDN concentrations were measured using a liquid C/N analyser equipped with an autosampler (Elementar Vario TOC, Germany). Specifically, water samples for DOC analysis were manually acidified to pH <2 with hydrochloric acid and subjected to automated oxygen (O_2) bubbling to remove inorganic carbon prior to DOC measurement. This was done using a high-temperature catalytic oxidation procedure on a liquid C/N analyzer (Elementar vario TOC, Germany), and the analytical precision (SD for repeated measurements of standards) was ±1%. Total alkalinity was measured on three parallel samples via titration using a titrimeter with 0.02 mol/L hydrochloric acid (Telmer & Veizer, 1999). In general, the stream water was slightly alkaline, with pH values ranging from 7.88 to 8.21 (Table 1), indicating that the stream carbonate system was dominated by HCO_3^-, which is the major component of DIC. The concentrations of ammonia nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were measured using an autoanalyzer (Skalar San++, Netherlands). Dissolved organic N (DON) was calculated by subtracting all inorganic N from the dissolved N.

Stream DIC stable isotopes were measured only in forest catchments, to which we added the end-member isotope values of potential sources (Table 2). Stream DIC stable isotopes were analysed using a GasBench II system interfaced with a Delta V Plus isotope ratio mass spectrometer (Thermo Scientific, Bremen, Germany). Water samples were injected into helium-filled 12 mL septum-capped vials containing 1 mL of 85% phosphoric acid to convert any dissolved CO_2 or H_2CO_3 to gaseous CO_2. All equilibrated gaseous CO_2 was transferred into a helium carrier stream and sampled using a six-port rotary valve. The measurement precision was greater than 0.3‰, and the final data were reported using delta (δ) notation relative to the Vienna Pee Dee Belemnite (V-PDB) in per mil (‰) as follows:

$$\delta^{13}C\,(‰) = \left\{\frac{R_{sample}}{R_{standard}} - 1\right\} \times 1000 \quad (1)$$

where R is the ratio of ^{13}C–^{12}C isotopes in the sample and V-PDB reference standard (Reiman & Xu, 2019).

2.3 | Statistical analysis and DIC source apportionment

Daily discharge was combined with measured DOC and DIC concentrations at the catchment outlet to estimate their fluxes during the study period, and it was assumed that the DIC and DOC concentrations were constant for an entire day.

A linear mixed model (LMM) analysis was used to analyse the main effects that specific sites and seasons had on DOC and DIC. The

TABLE 1 Basic statistics of water quality parameters at the study sites.

Parameter	Glacier terminus ($n = 57$)	Forest catchment ($n = 152$)	Catchment outlet ($n = 166$)
DOC (mg L^{-1})	2.38 ± 0.71a	2.13 ± 0.49b	2.17 ± 0.58b
DIC (mg L^{-1})	19.21 ± 5.92c	23.36 ± 4.33b	28.74 ± 9.51a
DOC:DON	154.49 ± 66.18a	66.39 ± 7.14b	117.66 ± 49.81a
pH	8.01 ± 0.21b	8.21 ± 0.36a	7.88 ± 0.41c
EC (μS cm^{-1})	134.78 ± 70.15c	214.54 ± 117.14a	183.08 ± 84.31b

Note: Row-wise nonmatching letters indicate significant differences between sites ($p < 0.05$).
Abbreviations: DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; DON, dissolved organic nitrogen; EC, electrical conductivity; NA, not analysed.

TABLE 2 Carbon isotopic values of potential DIC sources used in the Bayesian tracer mixing models (MixSIAR) and relative contribution of sources.

Sources	$\delta^{13}C$ (‰)	Mean contribution (%)
Atmospheric CO_2	−8.6	71.9 ± 11
Carbonate dissolution	−0.5	22.2 ± 8
Soil CO_2	−25.3	3.2 ± 2
OM respiration	−25.2	2.7 ± 2

Note: Atmospheric CO_2 and soil CO_2 source end-members were measured in the forest catchment of the study area (data un-published). Carbonate dissolution and OM respiration source end-members were adopted from Shan et al. (2021).
Abbreviations: DIC, dissolved inorganic carbon; OM respiration, stream organic matter respiration.

site variable could be assigned three values (including glacier terminus, forest catchment and catchment outlet) while there were two values for the season (monsoon and postmonsoon) and their interactions were treated as fixed factors. The sampling date (a subset of the season) was treated as a random factor. In addition, a LMM was also used to assess the environmental control of seasonal DOC and DIC. Here, sampling site and date were included as random effects, and environmental variables, including pH, EC, precipitation, and air temperature, were included as fixed effects (Barton, 2018). The LMM was established using the R package 'lme4', and the dataset was logarithmized if the residuals of the model did not conform to a normal distribution.

Multiple iterations of the Monte Carlo Markov Chain (MCMC) method were used to obtain the source apportionment of DIC (see Data S1 for more details). Models were run with a Bayesian tracer mixing model using the R package 'MixSIAR' (Stock et al., 2018). MixSIAR is increasingly used to study DIC source estimation in various freshwater ecosystems (Keskitalo et al., 2022; Shan et al., 2021; Song et al., 2020).

3 | RESULTS

3.1 | Hydrochemical characteristics and carbon fluxes

The average annual discharge of the HLG River was 11.29×10^8 m^3 from 2021 to 2022. Its daily discharge ranged from 22.04 to 88.39 m^3 s^{-1} and followed a normal distribution with a maximum of 88.39 ± 17.81 m^3 s^{-1} during the monsoon season (Figure 2). DIC concentrations at the catchment outlet showed a large degree of variability from 11.23 to 57.17 mg L^{-1} with a mean value of 28.74 ± 9.51 mg L^{-1}. Conversely, the DOC concentrations at the catchment outlet were relatively constant and fluctuated by approximately 1.14–4.79 mg L^{-1}, with a mean value of 2.17 ± 0.58 mg L^{-1}. Accordingly, the HLG River DIC and DOC fluxes were estimated to be 20.4 and 1.6 Gg C (1 Gg = 10^9 g) from July to December 2021, respectively, both of which were highest in the monsoon season (July–September), accounting for 59%–65% of the corresponding monitoring period.

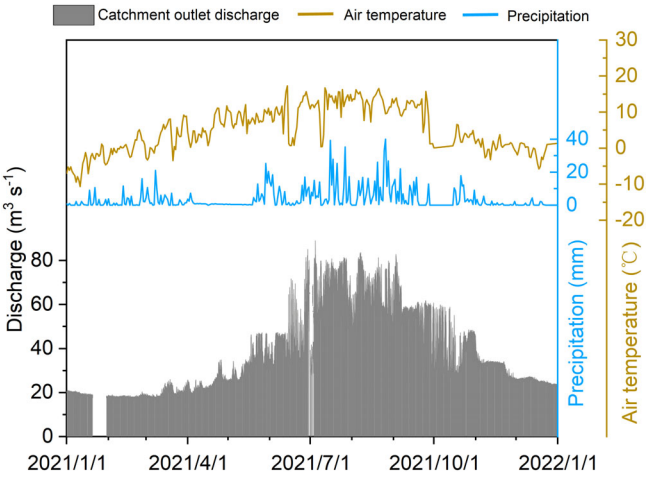

FIGURE 2 Time series of discharge, air temperature, and precipitation during the year of study.

3.2 | Comparison of DOC and DIC concentrations among different catchments

Differences in stream C concentrations were influenced by landscape heterogeneity and seasonal variation (Figure 3). During the monsoon season, DOC concentrations at the catchment outlet were 2.12 ± 0.42 mg L^{-1}, which was significantly lower than those in the glacier terminus and forest catchment (2.45 ± 0.34 mg L^{-1} and 2.37 ± 0.44 mg L^{-1}, respectively) (Figure 4a; $p < 0.05$), and there was no significant difference between the glacier terminus and forest

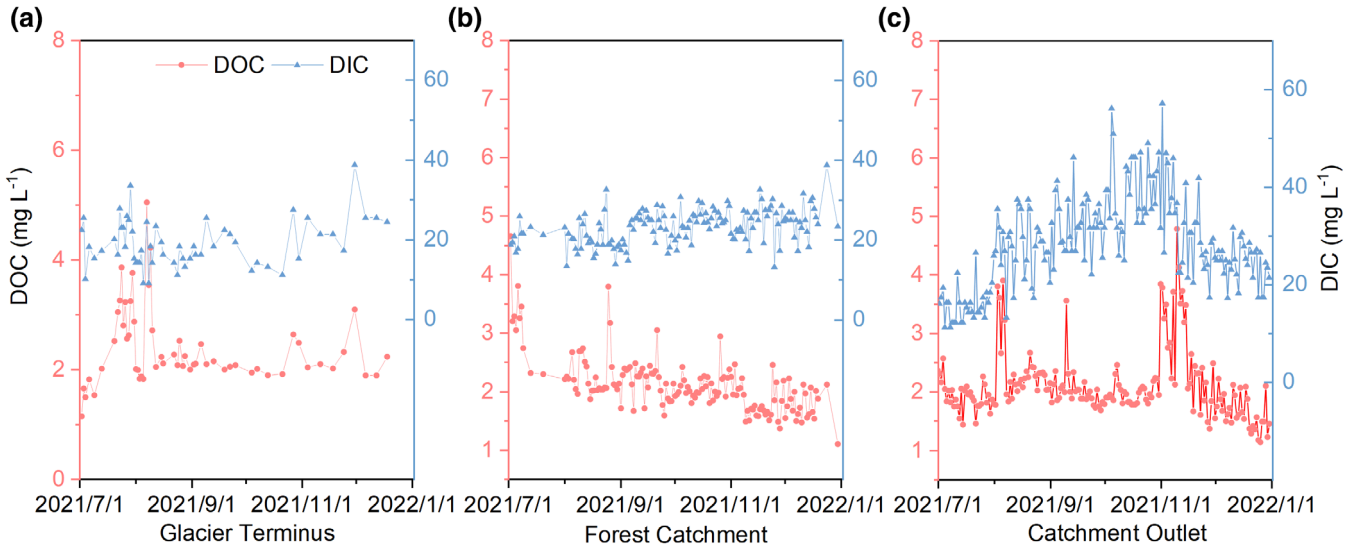

FIGURE 3 Variation in dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) in different catchments.

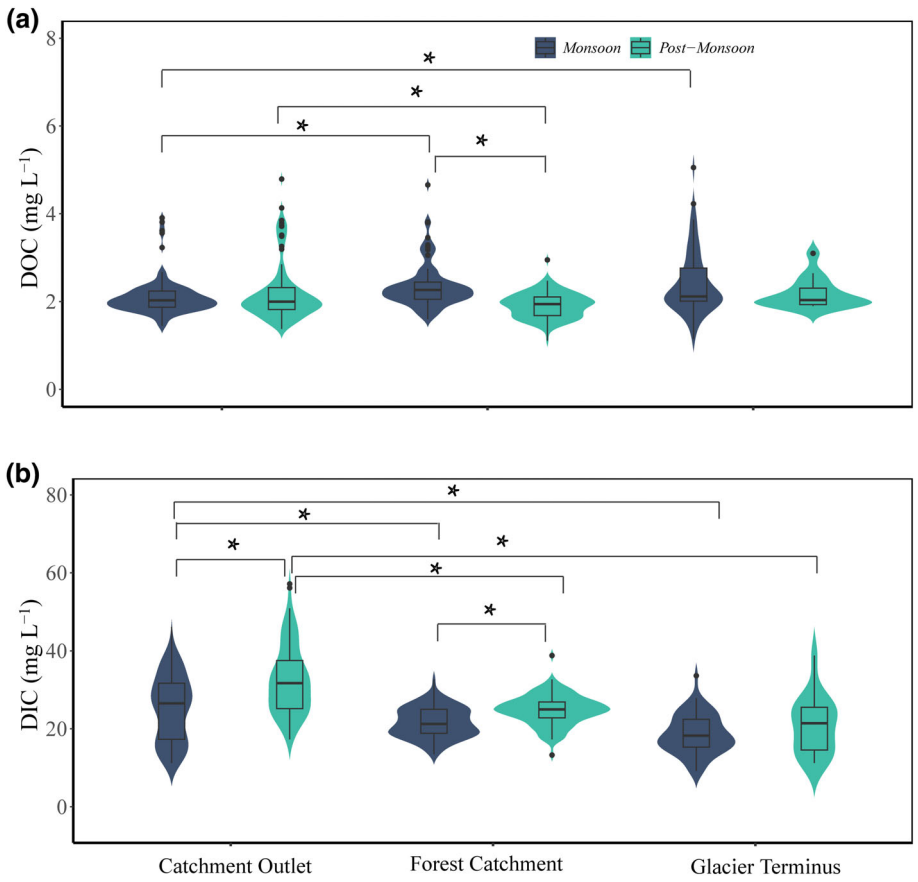

FIGURE 4 Monsoon and postmonsoon season dissolved organic carbon (DOC) (a) and dissolved inorganic carbon (DIC) (b) in different catchments. '*' indicates significant difference between seasons or catchments ($p < 0.05$).

catchment ($p > 0.05$). During the postmonsoon season, DOC concentrations at the catchment outlet were significantly higher than in the forest catchment (Figure 4a; $p < 0.05$) and not significantly different from the glacier terminus. DIC concentrations were significantly higher at the catchment outlet than at the glacier terminus and in the forest catchment in both the monsoon and postmonsoon seasons (Figure 4b; $p < 0.05$). There was no significant difference in DIC concentrations between the glacier terminus and forest catchment (Figure 4b; $p > 0.05$).

Overall, DOC concentrations decreased longitudinally from 2.38 ± 0.71 mg L^{-1} at the glacier terminus to 2.17 ± 0.58 mg L^{-1} at the catchment outlet (Table 1), and conversely, DIC concentrations increased longitudinally from 19.21 ± 5.92 mg L^{-1} at the glacier terminus to 28.74 ± 9.51 mg L^{-1} at the catchment outlet.

TABLE 3 Linear mixed-effect model results of environmental controls on seasonal DOC and DIC.

DOC: Marginal $R^2 = 0.21$, conditional $R^2 = 0.22$				DIC: Marginal $R^2 = 0.11$, conditional $R^2 = 0.48$			
Variables	**Estimate**	***t***	***p***	**Variables**	**Estimate**	***t***	***p***
EC	0.068	1.57	0.117	EC	0.191	4.457	**<0.001**
Temperature	−0.029	−0.627	0.531	Temperature	−0.054	−1.236	0.218
pH	0.191	4.79	**<0.001**	pH	0.206	4.815	**<0.001**
Precipitation	0.412	9.26	**<0.001**	Precipitation	−0.296	−6.2	**<0.001**

Note: Variables are Temperature, average daily air temperature (°C), precipitation, average daily precipitation (mm), EC, and electrical conductivity (μS cm^{-1}). Significant variables are shown in bold.
Abbreviations: DIC, dissolved inorganic carbon; DOC, dissolved organic carbon.

3.3 | Temporal patterns of DOC and DIC concentrations and associated factors

DOC concentrations were generally higher during the monsoon season at all sites and lower during the postmonsoon baseflow periods (Figures 3 and 4a), especially in forest catchments. The pattern of seasonal DIC concentrations was opposite to that of DOC, with higher postmonsoon DIC values than during the monsoon season at all sites.

LMM results showed that the seasonal variation in both DOC and DIC was influenced by pH and precipitation, with EC providing explanatory power for DIC. DOC concentrations were positively correlated with pH and precipitation ($p < 0.05$), whereas DIC concentrations were positively correlated with pH and EC and negatively correlated with precipitation ($p < 0.05$, Table 3).

3.4 | Carbon source apportionment of DIC

The δ^{13}C-DIC values ranged from −11.2‰ to −4.4‰, with the most depleted δ^{13}C-DIC occurring in the postmonsoon season and the most enriched during the monsoon season. According to the results from the MixSIAR model, the chemical weathering of rocks that consume atmospheric CO_2 was a dominant source of stream DIC regardless of the season, contributing 52.1%–89.2% of stream DIC with a mean value of 71.9 ± 11% (Table 2). Silicate and carbonate weathering contributed 52.9 ± 12% and 44.4 ± 9% of the DIC (more details in Data S1), respectively.

4 | DISCUSSION

4.1 | Variation in DOC and DIC concentrations between catchments

DOC concentrations in the glacier terminal outflow (Table 1) were higher than those in other mountain glaciers in Asia (0.54 mg L^{-1}) (Li et al., 2018) and higher than the global glacier average (0.97 mg L^{-1}) (Hood et al., 2015). In contrast, DIC concentrations were similar to those of other glaciers in Asia (Hindshaw et al., 2011; Vargas et al., 2018; Yu et al., 2021). The ice of mountain glaciers has higher DOC concentrations, receives more external OC inputs, and has higher in situ productivity compared with other glaciers (Hood et al., 2015; Stibal et al., 2012). Observations have shown that cryoconite holes are widely distributed in the ablation areas of the HLG glaciers, and they undoubtedly have a major influence on biogeochemical cycling in glacial ecosystems (Li et al., 2018). Cryoconite holes are the most active microbial habitats on melt ice and are fertilized by mineral species, and meltwater flushing may have provided additional DOC to both subglacial and supraglacial ecosystems (Hodson et al., 2008; Singer et al., 2012).

DOC concentrations in the forest catchment are similar to those in European alpine streams (1.1–3.5 mg L^{-1}) (Peter et al., 2014) and lower than those in boreal streams and wetlands (3.9–18.3 mg L^{-1}) (Billett et al., 2004; Dawson et al., 2001), while DIC concentrations in the forest catchment are significantly higher than those in boreal streams and wetlands (1.5–13.2 mg L^{-1}). The lower concentrations of DOC in rivers on the TP may be due to easily labile and attenuated DOC in the region (Qu et al., 2017). Higher stream DIC concentrations could be associated with upstream glacial meltwater recharge. Although storm and high-flow events have been shown to dilute stream DIC concentrations in forests (Peter et al., 2014), chemical denudation in glacial catchments has similarly increased chemical weathering within catchments (Yu et al., 2021). Therefore, the DIC concentrations delivered to the downstream forest catchments were high.

Hydrological connectivity is directly related to the export of dissolved carbon into the aquatic network (Eimers et al., 2008; Senar et al., 2018). Our study showed that as the catchment scales up from the glacier terminus to the forest catchment, the ability to predict the DOC concentrations within a stream using only the major landscape signal was reduced (Table 1). Although soil C pools are good predictors of stream DOC concentrations, this relationship is likely to be stronger in small catchments (Aitkenhead et al., 1999; Fellman et al., 2014). Higher concentrations of DOC from the glacier terminus could be related to the widespread distribution of cryoconite holes on the glacier surface, which provide a stable source of DOC for the glacier terminus catchment (Li et al., 2018). The spatial pattern of DIC concentrations was opposite to that of DOC, with higher postmonsoon DIC values than during the monsoon season at all sites, which is related to the high chemical weathering rates on the TP (Zhang et al., 2013). The distinct lithology within the HLG River catchment results in high carbonate and silicate weathering rates (He & Tang, 2008), which are important sources of DIC in river water.

4.2 | Seasonal variation in stream DOC, DIC, and associated factors

During the monsoon season, when the water table is elevated in the soil surface horizons, the dominant flow paths for water moving into the stream switch from predominantly deeper flow paths to the upper soil horizons, resulting in the flushing of abundant DOC by surface waters (Raymond et al., 2016; Senar et al., 2018). As stream flow recedes after the monsoon, deeper groundwater could become the dominant contributor to stream discharge (Tiwari et al., 2014), which causes higher seasonal variability in DOC in the forest catchment. DOC from the HLG glacier terminus showed slightly higher concentrations during the postmonsoon season when significant seasonality was absent. Previous studies have shown that DOC concentrations are high in glacial rivers in the northern TP due to summer permafrost melt, while DOC decreases significantly after the monsoon (Gao et al., 2019). In this study, there was no significant seasonal variation in glacier terminus DOC, probably due to dilution of stream DOC by monsoon precipitation (Hodgkins, 2001). A previous study noted that precipitation contributed ~22.7% of HLG River discharge (Liu et al., 2010). DIC concentrations exhibited maxima during postmonsoon baseflow conditions, supporting previous research showing that elevated DIC concentrations typically occur during periods of low streamflow when soil water tables are depressed, and hydrologic flow paths are predominantly located in deeper soil horizons (Fellman et al., 2020; Leach et al., 2016; Wang et al., 2021).

Previous studies have shown that discharge, temperature, and precipitation are the main drivers of seasonal variability in river carbon (Tian et al., 2015; Wang et al., 2020; Winterdahl et al., 2014). In this study, pH and precipitation were important variables for predicting the seasonal variability of DOC and DIC (Table 3). Both DOC and DIC concentrations were positively related to pH. The study by Groeneveld et al. (2020) supports this finding, in that higher pH leads to fewer available DOM adsorption sites and then reduces soil adsorption of DOM into rivers. This is particularly noticeable in the Uppland region, which is characterized by calcareous soils (as in our study area). In contrast, water in headwater streams has a shorter residence time, weak buffering capacity, and spends an insufficient time in contact with rocks. Therefore, high pH increases the contribution of soil and atmospheric CO_2 to DIC and should be considered when calculating their contributions, even though their contribution may be low (Gaillardet et al., 2019; Qin et al., 2019).

Precipitation is the primary meteorological element that influences soil erosion and the subsequent lateral movement of soil organic carbon (Kim et al., 2009; Wang et al., 2020). Globally, high runoff and the corresponding high carbon flux are associated with river basins subjected to high precipitation (Meybeck, 1982). The climate of the southern TP is projected to become warmer and drier (Yao et al., 2012; Zhang et al., 2020), which will have a variety of impacts on hydrological fluxes. These projections imply that the subalpine ecosystems in the region will suffer from a continued decline in precipitation and accelerated glacial melt, leading to greater winter runoff and more pronounced summer drying (Kang et al., 2010; Kuang & Jiao, 2016). Our findings suggest that future changes in precipitation intensity will reduce DOC loss from forest catchments (see section 4.1), further limiting downstream DOC transport. In contrast, DIC in stream water increases with decreasing precipitation, as rainwater typically has lower DIC concentrations than stream water (Song et al., 2020), and the increase in DIC with runoff during winter baseflow can be attributed to the input of subsurface flow and groundwater rich in weathering products (Giesler et al., 2014; Walvoord & Striegl, 2007). Therefore, future climate change may lead to an increase in the contribution of DIC to dissolved carbon in the watershed. All of these expected changes in hydrological forcing are likely to have significant and largely unquantified impacts on dissolved carbon in the HLG watershed.

4.3 | Potential sources of DIC

Carbonate weathering has been reported to account for ~68% of the alkalinity measured in the solute loads of large rivers worldwide (Gaillardet et al., 1999), despite the comparatively small proportion (15.2%) of carbonate rock outcropping on continents (Goldscheider et al., 2020). The relatively slow dissolution kinetics of silicates limits their rate of weathering compared to carbonate (Liu et al., 2011). For the Yangtze and Yellow Rivers, which originate from the TP, a study showed that the chemical weathering of carbonate rocks contributed 95 ± 5% of the riverine DIC in the headwaters of the Yangtze River, whereas chemical weathering of silicate rocks contributed 55 ± 17% of the DIC in the headwaters of the Yellow River (Shan et al., 2021). This suggests that the potential sources of riverine DIC are largely dependent on the environmental and geological settings of each river catchment.

The contributions to DIC from the weathering of carbonate rocks and silicate rocks were 44.4 ± 9% and 52.9 ± 12%, respectively, indicating that the consumption of atmospheric and soil CO_2 during silicate rock weathering is an important source of DIC in the HLG catchment. Glacial runoff has a high flushing rate and short residence time, and this runoff regime favours the dissolution of carbonate minerals (Anderson et al., 1997), although it could be inhibited by higher pH (>8.0). In addition, the study area is covered by large glaciers, and the subglacial bedrock is generally silicate-rich, which is transported to the downstream catchment; therefore, the contribution of silicate weathering to DIC is greater in the forest catchment.

5 | CONCLUSIONS

Our findings highlight the importance of catchment characteristics for the export of dissolved carbon from glacial runoff. Glacial meltwater and precipitation increase the lateral transport of DOC within the HLG catchment during the monsoon season, whereas DOC concentrations tended to decrease following the monsoon, especially in the forest catchment. The seasonal pattern of DIC concentrations was opposite to that of DOC, and postmonsoon DIC concentrations

increased at all sites compared to the monsoon season. Anticipated climate change (Chen et al., 2013) and glacier retreat are likely to significantly affect carbon transported within glacier runoff, which has critical implications for downstream river biogeochemical cycling. Therefore, in the future, high-temporal-resolution information during storms and more in-depth analyses are needed to understand these processes and mechanisms and to better estimate carbon fluxes in alpine headwater catchments.

Available data on the carbon isotopes of DIC measured in mountain glacier runoff around the world are very limited. The stream $\delta^{13}C$ of DIC ($\delta^{13}C$-DIC) varied from −11.2‰ to −4.4‰, with a mean value of −7.5 ± 2.2‰. Our results suggest that the consumption of atmospheric and soil CO_2 during silicate rock weathering is an important source of stream DIC. This finding is crucial for a better understanding of the sources of DIC in alpine catchments that have undergone glacial retreat.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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