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Climate effect of black carbon aerosol in a Tibetan Plateau glacier

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HIGHLIGHTS

- We sampled surface snow and snow pits in the snowmelt season in a Tibetan glacier.
- We depicted the variability of BC, OC, and dust concentrations.
- Scavenging efficiency and enrichment for BC and OC were derived.
- We evaluated BC radiative forcing in snow using SNICAR.

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ABSTRACT

In the Tibetan Plateau, the black carbon (BC) concentration in surface snow and snow pits has received much attention, whereas the seasonal behavior of aerosol-in-snow concentration, vertical profile, melt-scavenging, and enrichment have received relatively little attention. Here we investigate these processes and their impacts on radiative forcing on the Muji glacier in the westernmost Tibetan Plateau during the 2012 snowmelt season. Increasing impurity concentrations were mostly due to post-deposition effects rather than new deposition. On 5 July, BC concentrations in the surface snow were higher than those of fresh snow, implying enrichment via sublimation and/or melting of previous snow. Fresh snow contained 25 ng g^{-1} BC on 27 July; afterward, BC gradually increased, reaching 730.6 ng g^{-1} in September. BC, organic carbon (OC), and dust concentrations co-varied but differed in magnitude. Melt-scavenging efficiencies were estimated at 0.19 ± 0.05 and 0.04 ± 0.01 for OC and BC, respectively, and the BC in surface snow increased by 20–25 times depending on melt intensity. BC-in-snow radiative forcing (RF) was approximately 2.2 W m^{-2} for fresh snow and 18.1–20.4 W m^{-2} for aged snow, and was sometimes reduced by the presence of dust.

1. Introduction

Black carbon (BC) deposited in snow absorbs more sunlight than pure snow due to significant differences between the optical properties of BC and ice (Bond and Bergstrom, 2006; Warren and Brandt, 2008). Slight initial changes in snow albedo due to BC, in conjunction with the rapid adjustments and feedbacks that ensue, can cause significant climate effects (Bond et al., 2013). The local radiative forcing (RF) may reach 4–25 W m^{-2} during spring in the Tibetan Plateau (TP) snowpack (Bond et al., 2013; Flanner and Zender, 2005; Flanner et al., 2007). Increased net radiation fosters earlier snow and glacier melt (Qian et al., 2011). As a result, BC may play an important role (Xu et al., 2009a) in the rapid retreat of TP glaciers (Yao et al., 2012). The complex terrain of TP, spatio-temporal heterogeneity of BC, and difficulty in remotely sensing (Warren, 2013) and modeling BC (Flanner et al., 2009) show that in situ observations are required for accurate estimates of BC concentration, behavior, effects on snowpack energy budgets and climate.

Numerous studies have focused on TP BC recorded in ice cores and in surface snow and snow pits (Kaspari et al., 2011; Ming et al., 2008; Wang et al., 2014; Xu et al., 2009a, 2009b). Few studies have characterized seasonal BC evolution in surface snow (Kaspari et al., 2014; Ming et al., 2009; Xu et al., 2006). Much of our knowledge of the behavior and effects of BC enrichment via melt and sublimation in snowpacks comes from earlier studies with limited snow

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stratigraphy and sites. Conway et al. (1996) conducted an experiment on Snowdome on the Blue glacier in the Olympic Range, USA and found that hydrophilic BC was more likely flushed by meltwater than hydrophobic BC. Both types had a scavenging efficiency <100%, implying residual BC in the surface snow. Based on these results, scavenging factors for two types of BC (3%, 20%) were estimated and used in CLM (Flanner et al., 2007; Oleson et al., 2013).

More recent snow sampling has improved our understanding of the variability of BC concentrations. Xu et al. (2006, 2012) sampled snow in the TP and Tienshan. During summer, both BC and OC concentrations increased by up to two orders of magnitude over those of fresh snow. Xu et al. (2009a) studied the spatio-temporal variation of calculated BC in a southeast TP glacier and found that BC could strongly impact snow albedo in the melt season. Ming et al. (2009) concluded that BC in snow showed a weak negative relationship with the sampling site elevation. Huang et al. (2011) showed BC-in-snow concentrations decrease rapidly towards the northeast and away from major industrial regions. In the Arctic, Doherty et al. (2010) and Forsstrom et al. (2013) showed that the spatial differences in BC depended on the emission source intensity, the distance from the source to the deposition region, and the prevailing wind direction. In the eastern Sierra Nevada, Sterle et al. (2013) noted that BC concentrations in aged snow were enhanced seven-fold relative to those in fresh snow. These studies depict BC-in-snow as highly variable with an estimated melt-scavenging efficiency of 10–30% (Doherty et al., 2013).

Data in the vast TP is insufficient to fully characterize BC variation in snow, its RF, or impacts on snow energy balance. Our study (1) depicts the spatio-temporal and vertical variability of BC and other light-absorbing materials, (2) derives the melt-scavenging and enrichment of OC and BC, and (3) estimates the BC RF in snow in the westernmost TP during the 2012 snowmelt season.

2. Samples and methods

Muji glacier (39.19 °N, 73.74 °E), which is ~20 km northeast of Lake Karakul, westernmost TP and under the control of the prevailing westerly jet stream (Xu et al., 2009a), has dry-cold climate with mean annual precipitation 76.3 mm and temperature −3.8 °C (Fig. 1) (Williams and Konovalov, 2008). During the 2012 snowmelt season, we staked the glacier (13 stakes, Fig. 1). The top ~8–10 cm of snow was sampled. Snow pits were also excavated, and samples were collected downward at 10 cm intervals at elevations of 5460 m and 4910 m.

Samples were melted at room temperature in a clean laboratory. Immediately after melt, the liquid was sonicated and filtered through quartz fiber filters (Supplemental Materials) (Schwarz et al., 2012; Wang et al., 2012). BC and OC on the filters were measured using a method similar to the IMPROVE protocol (Cao et al., 2003; Chow et al., 2004). Because the filters had more dust load than those collected from ice core samples or aerosol samples (Wang et al., 2012), we modified the method that in 100% helium atmosphere, only a temperature plateau (550 °C) was arranged to reduce the time that BC was exposed in catalyzing atmosphere. BC results were reported regardless of the optical signal. To identify uncertainty stemming from instrumental instability and uneven distribution of carbon particles in filters, duplicates of ~40% of samples were analyzed separately, with consistent results ($R^2 = 0.979$).

The stratigraphy of other snow properties was also investigated. The presence of dust was monitored by drying the quartz fiber filters and weighting the mass on them (Kaspari et al., 2014; Painter et al., 2012). Snow density was measured with a stainless steel tube-type cutter and a scale (Conger and McClung, 2009).

We evaluated the daily mean BC RF in the snowpack using the SNICAR model (Flanner et al., 2007; Toon et al., 1989; Wiscombe and Warren, 1980), which has 470 solar bands, constrained by the BC and dust concentrations in surface snow. We estimated the clear-sky and cloudy spectral flux with a 30-min time step, using the SBDART model (Ricchiazzi et al., 1998; Stamnes et al., 1988). Calculations were done for clear-sky and cloudy conditions with a 30-min time step and weighted equally to obtain BC RF in snow (Eq. (1), (2)) (Kaspari et al., 2014; Sterle et al., 2013):

$$RF = \sum_{0.305\mu m}^{4.995\mu m} E(\lambda,\theta)\left(\alpha_{(r,\lambda)} - \alpha_{(r,\lambda,imp)}\right)\Delta\lambda \quad (1)$$

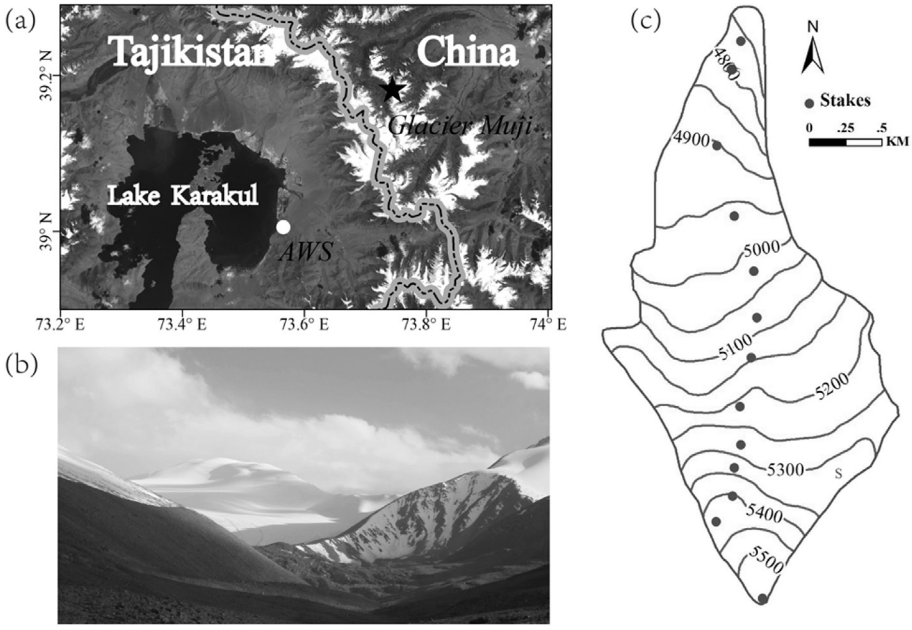

Fig. 1. (a) Muji glacier and Lake Karakul (circle: AWS, star: glacier); (b) Muji glacier close-up; and (c) Topography (m) of Muji glacier with the distribution of stakes.