



# Impacts of black carbon and mineral dust on radiative forcing and glacier melting during summer in the Qilian Mountains, northeastern Tibetan Plateau

Yang Li<sup>1, 5\*</sup>, Jizu Chen<sup>2, 5</sup>, Shichang Kang<sup>2, 3\*</sup>, Chaoliu Li<sup>1</sup>, Bin Qu<sup>4</sup>, Lekhendra Tripathee<sup>1, 5</sup>, Fangping Yan<sup>2, 5</sup>, Yulan Zhang<sup>2</sup>, Junming Guo<sup>1, 5</sup>, Chaman Gul<sup>2, 5</sup>, Xiang Qin<sup>2</sup>

10 Correspondence to: Y. Li (kerwinli@126.com) and S.-C, Kang (shichang.kang@lzb.ac.cn)

**Abstract.** Black carbon (BC) and mineral dust (MD), the most important compositions of light absorbing particles (LAPs), significantly reduce the albedo of glaciers and thus accelerate their melting. In order to investigate the impacts of BC and MD on the glacier radiation balance and ablation, a total of 92 surface snow/ice samples were collected along different elevations from 4300 - 4950 m a.s.l. on Laohugou glacier No.12 (LHG, 39°10′ - 35′ N, 96°10′ - 35′ E), located at Qilian Mountains, northeastern margin of the Tibetan Plateau (TP), during summer of 2013 and 2014. A thermal-optical method was employed to detect the BC (EC - element carbon) concentrations in snow/ice samples. The results

- 15 showed that BC and MD concentrations were much lower in snow than those in ice, and gradually declined with increasing elevation. The effects of BC and MD on albedo reduction at different melting conditions were identified with the SNow ICe Aerosol Radiative (SNICAR) model initiated by in-situ observation data. The sensitivity analysis showed that BC had a stronger impact on albedo reduction than MD on this glacier. The impacts of BC represented around 45 % of albedo reduction while the contribution of MD was 35 % when the glacier surface presented as superimposed ice and experienced intensive melting. During summer, when the surface was covered by snow, BC and MD contributed for 15 % and 9 % respectively. On average, the radiative forcing (RF) caused by BC in the snow/ice, more than MD, was 41.6 ± 37.0 W m<sup>2</sup>. Meanwhile, compared to glacier melting in summer
- 20 of 2013 and 2014 (409 mm w.e. and 366 mm w.e., respectively) calculated using the surface energy-mass balance model, contributions of BC and MD were less than 37 % and 32 % respectively of summer melting, while MD and BC together contributed a maximum of 61 %. This study provided the baseline information on BC and MD concentrations in glaciers of the northeastern TP and their contributions in glacier melting during summer.

#### **1** Introduction

- 25 The Tibetan Plateau (TP) and the surrounding regions are known as the "Third Pole" of the Earth due to their immense area, high elevation, and are the largest reservoir of ice at low and middle altitudes (Yao et al., 2004, 2012; Qiu, 2008). The TP is also known as the "Water Tower of Asia", as it is the major freshwater source for more than 1.4 billion populations in the world (Cyranoski, 2005; Immerzeel et al., 2010). However, glaciers in this region have been undergoing rapid melting and shrinking (Yao et al., 2004, 2012; Qiu, 2008; Kang et al., 2010) and perhaps that could be accelerated due to the presence of light absorbing particles (LAPs) (Hansen and Nazarenko, 2004; Xu et al., 2009; Bond et al., 2013).
- 30 Black carbon (BC) and mineral dust (MD) (mainly hematite) are two primary types of LAPs, as they can immensely absorb the solar radiation in the atmosphere (Sokolik and Toon, 1999; Kandler et al., 2007; Ramanathan et al., 2007; Otto et al., 2009) and reduce albedo after being deposited on the cryosphere (Painter et al., 2007; Qian et al., 2009; Xu et al., 2009; Lau et al., 2010; Painter et al., 2010), thus enhancing absorption of sunlight, promoting snow/ice melting and causing positive climate warming feedback. These physical activities could alter the available amount of water resource in the region (Hansen and Nazarenko, 2004; Flanner et al., 2007; Qian et al., 2015). Numbers of researches have been done on understanding the relationship between BC/MD and albedo reduction as well as their radiative forcing (RF) on glacier melting (e.g. Ming et al., 2008, 2013; Flanner et al., 2008).
- 2009; Yasunari et al., 2010; Ginot et al., 2014; Kaspari et al., 2014; Qu et al., 2014; Gabbi et al., 2015; Wang et al., 2015). Albedo reduction by BC was 4 6 % in the west of China (Ming et al., 2009) whereas average surface RF caused by BC was 1.5 W m<sup>-2</sup> in the TP (Flanner et al., 2007) and varied from 0.8 to 12.1 W m<sup>-2</sup> in the High Asian glaciers (Ming et al., 2013). Over the central TP, during the summer of 2012, average RF caused by MD and BC deposition on the Zhadang Glacier were found to be 2.7 ± 3.4 W m<sup>-2</sup> and 4.8 ± 3.2 W m<sup>-2</sup> respectively (Qu et al., 2014). Whereas in the southern flank of the Himalayan range (Nepal side), Yasunari et al. (2010) estimated that 2.0 5.2 % albedo reduction caused by BC could lead to an increase of 70 204 mm of runoff in annual discharge at Yala glacier. Furthermore, the impact of BC represented less than 16 % of annual potential melting
- 40 while the contribution of MD and BC combined to surface melting represented a maximum of 26 % in Mera Peak (Ginot et al., 2014). In addition, annual ablation was increased by 15-19 % because of the combined impact of BC and Saharan dust, over the past one hundred years compared to pure snow conditions on Claridenfirn, Swiss Alps (Gabbi et al., 2015).

Since the glacier melting results in enrichment of BC and MD in the surface and further accelerates glacial melting; spatial discrepancy and its effects across a whole glacier were

<sup>&</sup>lt;sup>5</sup> <sup>1</sup>Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, 100101, China. <sup>2</sup>State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, 730000, China. <sup>3</sup>CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100085, China. <sup>4</sup>Laboratory of Green Chemistry, Lappeenranta University of Technology, Mikkeli 50130, Finland. <sup>5</sup>University of Chinese Academy of Sciences, Beijing 100049, China.





paid special attention, particularly in areas of high human impact and those surrounded by deserts. However, previous researches mostly focused on the BC and MD sampled from the accumulation area of glaciers (e.g. ice cores and snow pits), and only few paid attention to quantifying effects of BC and MD on albedo reduction, RF (Qu et al., 2014; Yang et al., 2015) and ablation for an entire glacier. Therefore, the primary purpose of this work is to describe the temporal and spatial distribution of BC and MD along the entire east tributary of Laohugou glacier No. 12 (LHG) on the northern TP during summer 2013 and 2014, to investigate the albedo reduction and RF caused by them under different melting conditions applying the SNICAR model, and to quantify the contributions of BC and MD to potential glacier melting using a glacier surface energy-mass balance model.

# 50 2 Methodology

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## 2.1 Description of research site

The LHG, the largest and typical valley glacier in the western Qilian Mountains, northern TP (39°10′ - 35′N, 96°10′ - 35′E, 4260 - 5481 m a.s.l.), is about 9.85 km long and covers an area of 20.4 km² (Du et al., 2008). The climate of LHG is typically continental and arid, because of being controlled by the westerlies and the Siberian anticyclone (Zhang et al., 2013). The annual mean air temperature is -9.3 °C and -11.9 °C in the ablation zones and accumulation zones, respectively, whereas monthly mean air temperatures ranges from - 18.2 °C and -22.7 °C (December) to 3.4 °C and -0.7 °C (July) in the ablation zones and accumulation zones (Sun et al., 2011; Li et al., 2012), respectively. Annual precipitation is 332.9 mm and around 68.1 % occurs between May to September (Li et al., 2012). Meanwhile, this area is highly impacted by anthropogenic activities like intensive agriculture, grazing and industry, and surrounded by arid and semi-arid regions (e.g., Tarim Basin, Taklimakan Deser and Qaidam Basin) (Fig. 1). Whereas glacier area of the Laohugou river basin reduced by11.59 % in the past 50 years (Zhang et al., 2013), the LHG retreated 240 m during1957 - 2005 (Du et al., 2008), elevation decreased by 18.6±5.4 m and the total volume lose was 0.218 km³ between 1957 and 2007 (Zhang et al., 2012).

# 60 2.2 Field sampling and observation

A total of 92 surface snow and ice (0-5 cm) samples were collected during July 27<sup>th</sup> - 29<sup>th</sup> 2013 and August 4<sup>th</sup>-6<sup>th</sup> 2014, in replicate with an approximate altitude difference of 100 m and 50 m of the LHG on the eastern branch (Fig. 1). The glacier surface was covered by fresh snow due to frequent snowfall during sampling period of July 2013. Moreover, in such condition, the surface superimposed ice were sampled loaded with obvious MD below the snow. However, new-fallen snow samples were collected at August 4<sup>th</sup> 2014 after the precipitation, and the snow mostly melted at August 6<sup>th</sup> when the superimposed ice samples were collected (Table 1). Snow/ice sampling procedure followed "Clean hands-Dirty Hands" principle (Fitzgerald, 1999). We collected three parallel snow samples and two ice samples in an area of 50×50 cm <sup>2</sup>and 5 cm depth at each site. The samples were preserved in NALGENE® HDPE wide-mouth bottles (250 mL) and were kept frozen during transportation until laboratory analysis. Snow density was measured with a balance and snow/ice grain sizes were observed by a hand lens (25×) with accuracy of 0.02 mm (Aoki et al., 2011). Albedo was measured as the fraction of the reflected and incoming shortwave radiation from the Kipp & Zonen NR LITE radiometer (spectral range, 305-2800 nm). The sensors were mounted about 1.5 m high above the glacier surface on Automatic Weather Stations (AWS) located at 4550 m a.s.l.

# 70 2.3 Laboratory analyses

The sample-filtering method detailed by Cachier and Pertuisot (1994) and was similar to Xu et al. (2012) and the mass of insoluble MD was the discrepancy between the two weights before and after the filtration using a microbalance (accuracy: 0.1 mg). DRI<sup>®</sup> Model (2001A) was utilized to measure the OC/BC mass on the filters at the Institute of Earth Environment, Chinese Academy of Sciences, following a thermal-optical reflectance method of carbon analysis (Chow et al., 1993; Cao et al., 2003),

#### 2.4 Energy and mass balance model

75 To assess the glacier melting caused by BC and MD, a distributed physical-based energy (SEB) and mass (SMB) balance model was used. The model can be described as following equations (1) and (2):

$$B = \int \left(\frac{Q_M}{L_m} + \frac{Q_L}{L_\nu} + C_m + P_{snow}\right) dt \tag{1}$$

$$Q_M = S^{\downarrow}(1-\alpha) + L^{\downarrow} + L^{\uparrow} + H + LE + Q_G \tag{2}$$

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Here, *B* is the specific mass balance (mm w.e.), whereas  $Q_M$  and  $Q_L$  correspond to the melt energy turbulent and latent heat flux,  $L_m$  and  $L_v$  are the latent heat of ice melt (3.34×105 J kg<sup>-1</sup>) and evaporation/sublimation (2.50×106 J kg<sup>-1</sup>/2.83×106 J kg<sup>-1</sup>),  $C_{en}$  and  $P_{snow}$  refer to refreezing of melt water (not considered in model) and accumulation of solid precipitation, respectively.  $S_1$  and  $\alpha$  indicate the incoming solar radiation and the surface albedo,  $L^1$  and  $L^1$  are the incoming and outgoing long-wave radiation, *H* and *LE* are the sensible and latent heat flux, respectively.  $Q_G$  denotes the subsurface heat flux (Vincent, 2002; Yang et al., 2013). On the right side of Eq. (2), all energy components are defined as positive values when directed to the surface, otherwise they are defined as negative values.

The model is driven by the meteorological data (e.g. air temperature, relative humidity, wind speed and global radiation) collected at the AWS stations. Whereas a, surface





- 85 temperature, turbulence fluxes are parameterized as Hock et al., (2005), Fujita et al., (2000) and Sun et al., (2014), respectively. In addition, L<sup>1</sup> is calculated as Duguay (1993); L<sup>1</sup> is
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calculated by Stefan-Boltzmann law from modeled surface temperature and surface emissivity (being set to 1). The parameters used in calculating of  $L^{\downarrow}$  and  $L^{\uparrow}$  are calibrated by measured incoming and outgoing long-wave radiation at AWS. Moreover, air temperature has a lapse rate of 6°C/km with altitude, relative humidity and wind speed are assumed independent to altitude, and precipitation gradient is 8 %/100m according to the measured value. Based on above parameterizations, SEB and SMB are calculated with 1 h temporal and 30 m spatial resolution. To assess the glacier ablation caused by BC and MD, we calculated the reduction of albedo with SNICAR model, and then the decreased albedo was coupled to albedo mechanism of SEB and SMB model, thus extra energy and glacier ablation affected by BC and MD could be calculated. In the coupled albedo mechanism, altitude effect is also considered, and the gradient value will be introduced in section 3.2.

#### 3 Results & Discussion

## 3.1 BC and MD concentrations and variations

- 95 Altogether 52 surface snow samples and 40 ice samples were collected at fixed period repeatedly for measuring BC and MD concentrations. The daily variations of BC and MD concentrations in surface snow (Table 1) increased from fine-grained snow to firn because of post-depositional enrichment of LAPs (Conway et al., 1996; Wang et al., 2012). For instance, the average BC and MD concentrations were 60.5 ng g<sup>-1</sup> and 6.0 µg g<sup>-1</sup> (n = 7) respectively on July 27<sup>th</sup>, but increased to 160.1 ng g<sup>-1</sup> and 17.5 µg g<sup>-1</sup> (n = 7) respectively on July 28th. After a heavy snowfall on July 29th, however, BC and MD concentrations in fresh snow with an average of 849.3 ng g<sup>-1</sup> and 67.9 µg g<sup>-1</sup> (n = 7) respectively, were greatly higher than those observed in "aged snow". It was likely due to that atmospheric MD and pollutants were transported by the prevailing valley wind from deserts and highly
- 100 polluted industrial centers (e.g., Jiuquan and Jiayuguan) towards the LHG region, which has been proved from the back trajectories analysis researches (Zhao et al., 2012; Dong et al., 2013, 2014; Xu et al., 2014). Past study over the same area has shown significant correlations between the daily mean BC concentration and relative humidity (Zhao et al., 2012). On average, contents of MD in snow reached 30.5±70.2 µg g<sup>-1</sup>, while BC concentration was 356.6±1248.1 ng g<sup>-1</sup> in July 2013. As a result of drastic enrichment, the concentrations of BC and MD reached 20491.4±19855.3 ng g<sup>-1</sup> and 3528.7±3462.6 µg g<sup>-1</sup> (n = 7) respectively in the bottom portion in July 2013. In addition, a heavy snow fell in 3<sup>rd</sup> August 2014 and on the second day, there was a wide snowpack with an average depth of above 5 cm by visual inspection. The average contents of MD in snow were comparable with those of
- 105 2013, while BC concentration was lower than those of the previous year. Two days later, the contents of BC and MD reached 29414.7±62217.1 ng g<sup>-1</sup> and 3712.0 ± 10288.0 µg g<sup>-1</sup> (n = 33), respectively, as a result of the snow melting and the BC and MD re-exposing when the surface was superimposed by ice in August of 2014. Therefore, the BC and MD concentrations in this work were much higher than earlier reported concentrations for snow pit samples in LHG (Dong et al., 2013; Ming et al., 2013) and corresponding figures recorded in ice cores and snow pits in West China (Kang et al., 1999; Ming et al., 2009; Xu et al., 2009; Wu et al., 2010; Wang et al., 2012, 2015). The discrepancy is mostly because the former works were focused on the accumulation area of glaciers (e.g. ice cores and snow pits) which were less drastic enrichment influenced.
- 110 Concentrations of BC and MD in snow/ice decreased with increasing elevation ("altitude effect") on LHG (Fig. 2), similar to that of Zhadang glacier (Qu et al., 2014), suggesting that most of BC and MD in atmosphere was deposited in the lower elevation (or ablation zone) at the beginning of snowfall, and that BC and MD were greatly enriched in the surface of the glacier during the melting season (Conway et al., 1996; Xu et al., 2006, 2012; Wang et al., 2012), particularly at the lower elevation of the glacier (Xu et al., 2009).

## 3.2 Albedo reduction due to BC and MD depositions

For this study, we used the in-situ BC and MD concentrations to investigate their impact on glacier energy and mass balance via changes in surface albedo. The online version of 115 the SNICAR model (Flanner et al., 2007) was used to simulate the albedo declines produced by different magnitude of concentrations of BC and MD, with several simplistic assumptions. Here, we focused mainly on the albedo variation attributed to BC and MD (Table S1). To represent the melting caused by the particles on any given day, the following assumptions were made, (1) Surface spectral distribution (a. Mid-latitude winter, clear-sky, cloud amount < 5; b. Mid-latitude winter, cloudy-sky, cloud amount ≥ 5); (2) the dust diameter was taken as 1.0-2.5 µm (5.0-10 µm ) in snow (ice) (Dong et al., 2014); (3) The albedo of the underlying ground was taken as 0.2 in the visible band and 0.4 in the nearinfrared band; (4) The mass absorption cross-section (MAC) of BC was set as 1, which is the median of typical MAC values (Hadley and Kirchstetter, 2012); (5) incident radiation

- 120 was selected direct and (6) volcanic ash concentration (µg g<sup>1</sup>) was inserted as 0 in the model. In order to assess the contribution of BC and MD to the decreased albedo, we measured albedo as the fraction of the reflected and incoming shortwave radiation from the Kipp & Zonen NR LITE radiometer. New-fallen snow can increase albedo above 0.8, and the albedo decreased even below 0.2 as the snow melts and the BC and MD concentrating (Fig. 3). The average surface albedo of snow cover was 0.67 and 0.62 in July 2013 and August 2014, respectively. Correspondingly, those of ice cover were 0.23 and 0.25 at the same period.
- The simulations were designed for two different scenarios, i.e. assuming the addition of departures (slopes) of BC and MD on the average basis (Table 1). The separate effects of 125 the above parameters on the albedo can be calculated using SNICAR model, and this method has been successfully used in the previous works (Ming et al., 2013; Qu et al., 2014). The results showed that BC and MD in the snow reduced the broadband albedo by 15 % and 9 %, respectively (Fig. 4). BC and MD in ice here can reduce the albedo by 0.15 and 0.12, respectively, and BC and MD combined can reduce the broadband albedo by 70 %. A similar work done in the Zhadang glacier of western Nyainqentanglha (Qu et al., 2014), showed that BC and MD contributed less in the reduction of snow/ice albedo in Zhadang glacier in comparison to LHG. This can probably be due to the contents of BC and MD





over LHG which were much higher than Zhadang glacier. Whereas the average albedo reduction by BC and MD in snow/ice decreased generally with increasing elevation ("altitude
 effect") on LHG (Table S1), the gradient value of BC and MD in snow (ice) were 0.0029/100 m and 0.0003/100 m (0.0164/100 m and 0.0172/100 m), respectively.

# 3.3 Additional absorbed radiative forcing

BC and MD deposited on the glacier surface can absorb extra energy and accelerate glacier melting. The RF affects the glacier by increasing the cold snow's temperature in the accumulation area and melting the snow that reaches melting temperature in the ablation area (Kaspari et al., 2014). In order to assess the amount of excess absorbed solar energy due to the presence of BC and MD, RF was estimated using the following equation:

# 135 $RF_x = R_{in-short} * \Delta \alpha_x$ (3)

where  $R_{in-short}$  indicates incident short-wave solar radiation measured by Kipp & Zonen Net Radiation LITE radiometer,  $\Delta \alpha_x$  denotes the reduction of albedo as simulated by SNICAR model. In this work, we calculated the RF of snow/ice by the average daytime short-wave solar radiation during the whole July 2013 (509 W m<sup>-2</sup>) and August 2014 (542 W m<sup>-2</sup>).

140 The simulation showed that the RF caused by BC and MD deposition on the LHG varied between 2.5-128.8 and 1.4-120.5 W m<sup>2</sup> (Table. S1), respectively. The RFs of BC exceeded MD in both snow and ice. On average, the RFs of MD in the summer of 2013 and 2014 was 30.7 ± 32.9 W m<sup>2</sup> and those caused by BC was 41.6 ± 37.0 W m<sup>2</sup>. These values are higher than those of Zhadang glacier (Qu et al., 2014), Muji glacier (Yang et al., 2015) during the 2012 glacier melting season, and the numerous modeling studies of BC RF conducted over the High Asia glaciers (Flanner et al., 2007; Qian et al., 2011; Ming et al., 2013; Nair et al., 2013) and those in the Arctic (Wang et al., 2011; Flanner et al., 2013), suggesting enrichment of BC and MD can absorb more solar radiation when the glaciers experienced strong melting, and the forcing over a whole glacier may be underestimated in the high altitude glacier regions.

### 3.4 Assessing glacier melting caused by BC and MD

BC and MD are likely to accelerate glacier melting and thus influence water resources on condition that the timing and magnitude of runoff is changed (Kaspari et al., 2014). We used the distributed surface energy-mass balance model (Hock, 2005) to quantify the effects on glacier ablation by BC and MD. The model calculated the components of the surface energy balance for every hour based on meteorological data collected at the AWS stations (Table 2).

A sensitivity analysis was performed to evaluate the sensitivity of the model results to the chosen input parameters (albedo reductions caused by BC and MD). Four scenarios of the impacts of LAPs on glacier ablation were examined: (1) entire ablation, (2) ablation except the impact of BC, (3) ablation except the impact of MD, and (4) ablation except the impacts of BC and MD combined. The simulated ablation caused by BC and MD deposition and concentrating on the LHG was shown as Fig. 5. Similarly, BC was the dominant factor on ablation during the summer. Overall, mean potential melting caused by BC alone was 143 mm w.e. while MD and BC combined was 236 mm w.e., compared to the summer's ablation of 2013 and 2014 measured using the mass and energy balance, i.e. 409 mm w.e. and 366 mm w.e. respectively, the mean impact of BC represented less than 37 % of summer potential melting while the contribution of dust and BC combined to surface melting represented a maximum of 61 %, which was much higher than the effects of BC and MD sampled from firn/ice core on annual ablation in Mera Peak (Ginot et al., 2014) and Claridenfirn (Gabbi et al., 2015). During summer, precipitation and ablation is also

155 at maximum over the glaciers in Qilian Mountains. Hence, glacier melting would be accelerated due to the exposure of BC and MD on the surface when the glacier melts at high rate. Whereas melting would result in the re-exposure of BC and MD at the glacier surface, and/or ablation season would be extended because of a warming climate (Fujita, 2007; Yasunari et al., 2010).

#### 4 Summary and conclusions

- To our knowledge, this study constitutes the first quantitative dataset of the impacts of LAPs on glacier ablation estimated directly from the northeastern edge of the TP. The average concentrations of BC and MD in surface snow and ice at LHG were much higher than those detected in snow pits and ice cores in TP and Tien Shan mountains. Moreover, the most remarkable finding in this study was that BC and MD concentrations were highest in surface ice (23890.6 ± 18411.0 ng g<sup>-1</sup> and 2801.0±1948.7 µg g<sup>-1</sup>, respectively). The decreasing concentrations of BC and MD in surface snow/ice along with increasing elevation, mainly triggered by enrichment process of BC and MD during glacier melting, was more intensive in the ablation area than in the accumulation area. Under all covered conditions, BC in ice had the most significant contribution to albedo reduction (44.8 % ± 14.5 %) and to RF
- 165 (81.6 ±24.6 W m<sup>-2</sup>). Furthermore, the impact of BC contributed less than 37 % of summer potential melting while MD and BC combined contributed a maximum of 61 %, indicating that BC rather than MD played the most important role in ablation of Qilian glaciers. Moreover, the albedo reduction, forcing and ablation caused by BC and MD in this study were also much higher than those determined in snow pits and ice cores in High Asia, indicating that the previous reports might have underestimated during intensive melting season, and thus the enrichment of BC and MD could absorb more solar radiation when the glaciers experienced strong melting, and the forcing over a whole glacier may be underestimated in the high altitude glacier regions.





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285 Table 1. Sampling information: two expeditions were conducted on the LHG, and samples (snow/ice) were collected under six melting conditions of the glacier in the summer of 2013 and 2014. We collected two to three snow/ice samples at each site. In total, 52 snow and 40 ice samples were obtained for the conditions. The mean concentrations of BC

and MD are listed here.								
Sample date	No. of samples	Avg. of BC conc. (ng g <sup>-1</sup> )	Avg. of MD conc. (μg g <sup>-1</sup> )	Snow grain size (mm)	Snowpack density (kg m <sup>-3</sup> )	Snowpack Thickness (cm)	Cloud amount (10=100 %)	Scene type
27 Jul 2013	7	60.5±21.1	6.0±3.6	0.2-0.4	343	14	5	Fine-grained snow
28 Jul 2013	7	160.1±93.0	17.5±10.7	0.3-0.7	344	11	8	Aged snow
29 Jul 2013	7	849.3±394.8	67.9±17.5	0.1-0.4	250	18	8	Fresh snow
29 Jul 2013	7	28636.5±23452.5	3528.7±2111.9	0.6-1.5	400	1	8	Superimposed ice
4 Aug 2014	31	191.6±77.3	27.9±9.3	0.2-0.6	258	8	4	Fresh snow
6 Aug 2014	33	$24920.3 \pm 17210.7$	2774.0±1827.4	0.6-2.0	400	1	6	Superimposed ice





Element	Sensor type	Accuracy	Height (m)
Air temperature (°C)	Vaisala 41382	±0.2°C	1.5, 3.5
Relative humidity (%)	Vaisala 41382	<u>+2</u>	1.5, 3.5
Air pressure (hPa)	PTB 210	±0.5 hPa	1.5
Wind speed (m s <sup>-1</sup> )	Young 05103	±0.3 m s-1	1.5, 3.5
Wind direction ( )	Young 05103	±3 °	1.5, 3.5
Shortwave radiation (W m <sup>-2</sup> )	CNR1	±10 for daily total	1.5
Longwave radiation (W m <sup>-2</sup> )	CNR1	±10 for daily total	1.5
Precipitation	Geonor T200B	±0.1	1.7

Table 2. Technical parameters and installation heights of sensors on AWS









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Figure 2. Variations of BC and MD in surface snow/ice from the Laohugou glacier No.12 with increasing elevation







Figure 3. Variations of the surface albedo of the Laohugou glacier No.12 in July 2013 and August 2014 from the AWS.







Figure 4. Mid-day RFs of BC and dust on the Laohugou glacier No.12 and the contribution (resulted from the SNICAR model) showing the reduction of albedo in surface snow cover area under three different melting conditions: (a) and (b), where the glacier was covered by snow of July 2013 and August 2014, respectively; (c) and (d), where the glacier was covered by bare ice of July 2013 and August 2014, respectively; Error bars show the uncertainties.







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Figure 5. Simulated glacier ablation caused by BC and MD. (a) and (e), actual ablation of 2013 and 2014, respectively; (b) and (f), actual ablation except the impact of BC of 2013 and 2014, respectively; (c) and (g), actual ablation except the impact of MD of 2013 and 2014, respectively; (d) and (h), actual ablation except the impacts of BC and MD combined of 2013 and 2014, respectively.