We would like to thank the reviewer for their helpful and detailed review. Our responses are bolded.

Response to the referee comments:

Referee comments are repeated in red.

1/ As stated above, the authors do not provide sufficient details on the impurity content measurements method so that the reader can have an idea of the uncertainty associated with the impurity content measurements (section 2.3 is really too short). See specific comments below

Thank you for pointing this out! We have now added the details on the impurity content measurements method and referenced Xu et al. (2006) who reported and employed successfully this method in TP.

2/ The authors also do not provide sufficient detail and analysis on the modelling approach, e.g. for mass balance simulations, how the simulated values compare to field measured values ....., for albedo calculations, how do the SNICAR modelled values compare to the broadband measured values presented in Figure 3. see specific comments below

Page 3- line 88-90 : I don't understand what has been used exactly for the modelled albedo values. This is rather a critical point for the conclusion of the paper and must be explain in more depth. age 3 – line 90 – 'in the coupled ...' please explain in more details, in my mind the reader should be able to understand what has been done without reading section 3.2.

We moved some graphs from Section 3.2 and 3.4 to Section 2.4, and added more detail which explained the Model framework and assumption. However, we did not measure broadband snow/ice albedo at the sample sites, we must infer broadband albedo and light absorbing impurity radiative forcing in snow/ice from modeling constrained by the in situ measurements of LAPs concentrations from LHG

3/ The paper must be reviewed by a English native speaker.

Noted and changed

Specific comments

Page 2- line 61 : 'in replicate with an ....' I think the authors have to be more precise, is it 100m or 50 m ?
Noted and changed.

Section 3.2 – The albedo reduction strongly depends on the value of grain size, and grain size evolves over time .. Is this taken into account in the simulation ? On which basis the diameter of dust was selected for snow and ice ? Which values of snow grain size do you use for simulation of superimposed ice ?
Thanks, noted; We used the maximum value 5.0-10 μm as the dust diameter, according to the volume size distribution of MD in snow/ice at LHG (Dong et al., 2014); Due to lack of more reliable researches of superimposed ice optical properties in the mountain glacier, we regards the superimposed ice as one centimeter-thick dirty snow, and we use the maximum value of snow grain size we observed.

Section 3.4 : It would be really important to compared measured and simulated albedo values ...
Section 3.4 : Over which period is the ablation calculated ? How are the values of fresh snow albedo calculated ? How does that compare to ablation measured in the field ?
Because we did not measure broadband snow/ice albedo and ablation at the sample sites, we must infer broadband albedo and light absorbing impurity melting in snow/ice from modeling constrained by the in situ measurements of LAPs concentrations from LHG; The ablation are calculated from Jul 1st 2013 to Aug 31th 2013 and Jul 1st 2014 to Aug 31th 2014, respectively;

Minor comments

Page 2 -lines 68-69 : what is the accuracy of the measured broadband albedo
We measured albedo as the fraction of the reflected and incoming shortwave radiation, which accuracy is less than 1% in the radiometer. Therefore, the accuracy of the measured broadband albedo could be regarded as high level.

Page 2 – line 80 : typo Cen Page 3- line 98 : what does n stand for ? Page 3- line 104 : Is 5 cm of snow an heavy snow fall ?
Noted and changed; We intended "n" to mean "number of samples"; We removed the phrase "heavy".

Figure 1 : What is the colour bar of the above panel ?

Updated figure. The color bar of the above panel in Figure 1 represents the altitude.

Response to the short comments:

Short comments are repeated in red.

1. "Introduction" (Line 28): the authors provide three references (Hansen and Nazarenko, 2004; Xu et al., 2009; Bond et al., 2013) to support the argument that": : :could be accelerated due to the presence of light absorbing particles (LAPs)". However, these three references all focused on BC only, which is not equivalent to LAPs.

Please also provide 1-2 references on dust-induced accelerated glacier/snow melting.

Thank you for pointing this out! We have now added the papers (Oerlemans et al., 2009;Painter et al., 2007;Painter et al., 2013), which suggest that glacier/snow melting could be accelerated due to dust.

2. "Introduction" Paragraph 2 (Lines 30-42): A recent paper by He et al. (2014) estimated the snow albedo reduction and associated radiative forcing caused by BC deposition over the Tibetan Plateau. They also quantified the uncertainty due to different BC-snow mixing states and snow grain shapes. I suggest including this reference and also adding 1-2 sentences to discuss their findings. Also in Section 3.3, how you're your estimate on BC-snow radiative forcing compare with their results? Please add some discussions.

Reference: He, C., Li, Q. B., Liou, K. N., Takano, Y., Gu, Y., Qi, L., Mao, Y. H., and Leung, L. R.: Black carbon radiative forcing over the Tibetan Plateau, Geophys. Res. Lett., 41, 7806–7813, doi:10.1002/2014gl062191, 2014.

We added some discussions about the comparation between our work based on in-situ observation and their model work in Section 3.3. .However, our estimated RF at LHG is higher than previous modeling studies over the TP because of BC enrichment by melt scavenging and in-situ observed content of BC from an entire glacier during intensive melting season.

3. In Section 2.4 (Line 89): the authors mentioned SNICAR model, however, a number of key model details are missing, which are very important to the understanding of simulation results. For example, what is the data used to drive SNICAR model? How long does the model run to get the results? What are the model assumptions for BC/dust snow mixing state and snow grain shapes? Is the snow aging process considered in the model? I suggest adding more details about the model.

We moved some paragraphs in Section 3.2 and 3.4 to Section 2.4, and added more details in Section 2.4 which explained the Model set-up; We followed the default BC optical properties assumptions of SNICAR mode (external mixing of BC/ice and spherical snow grain) (Flanner et al., 2007). The optical properties of the BC and dust come from general libraries and not this specific region, and therefore the modeling of albedo reduction and associated RF are relatively uncertain.

4. In Section 3.3 (Lines 114-130): the author did not provide any information about the BC/dust-snow mixing state (external? or internal?) assumed in the model simulation. This is very important for the estimate of snow albedo reduction. Liou et al. (2014) used a stochastic snow model to show that BC/dust-induced snow albedo reduction vary significantly based on different BC/dust-snow mixing states and snow grain shapes. Please add descriptions on the model assumption. Also please include this reference and comment on the effects of BC/dust-snow mixing state and snow grain shape on albedo reduction.

Reference: Liou, K. N., Takano, Y., He, C., Yang, P., Leung, L. R., Gu, Y., and Lee, W. L.: Stochastic parameterization for light absorption by internally mixed BC/dust in snow grains for application to climate models, J. Geophys. Res.-Atmos., 119, 7616–7632, doi:10.1002/2014jd021665, 2014.

See also comment to 2.and 3. above.

These can be extended in the future when more data is available.

5. In Section 3.4: the author designed four sensitivity simulations to show the individual and combined effects from BC and dust. Is the combined effect equal to the sum of two individual effects (i.e., linearly additive)?

Based on our simulation, the combined effect is less than the sum of two individual effects, The presence of MD in snow/ice may lessen the efficacy of BC to induce melt, and the impact of BC may be negligible when MD concentrations are high (Kaspari et al., 2014).

Reference

Dong, Z., Qin, D., Chen, J., Qin, X., Ren, J., Cui, X., Du, Z., and Kang, S.: Physicochemical impacts of dust particles on alpine glacier meltwater at the Laohugou Glacier basin in western Qilian Mountains, China, Sci. Total Environ., 493, 930-942, 2014.

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Kaspari, S., Painter, T. H., Gysel, M., Skiles, S. M., and Schwikowski, M.: Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings, Atmos. Chem. Phy., 14, 8089-8103, 2014.

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

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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 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^{-2}. Meanwhile, compared to glacier melting in summer 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

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 the largest reservoir of ice at low and middle altitudes (Qiu, 2008; Yao et al., 2004, 2012). 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 rapidly melting and shrinking (Kang et al., 2010; Yao et al., 2004, 2012), which could be accelerated due to the presence of light absorbing particles (LAPs) (Bond et al., 2013; Hansen and Nazarenko, 2004; Oerlemans et al., 2009; Painter et al., 2007; 2013; Xu et al., 2009).

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 (Kandler et al., 2007; Otto et al., 2009; Ramanathan et al., 2007; Sokolik and Toon, 1999) and reduce albedo after being deposited on the cryosphere (Lau et al., 2010; Painter et al., 2007, 2010; Qian et al., 2009; Xu et al., 2009;), 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 (Flanner et al., 2007; Hansen and Nazarenko, 2004; 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. Flanner et al., 2009; Gabbi et al., 2015; Ginot et al., 2014; Kaspari et al., 2014; Ming et al., 2008, 2013; Qu et al., 2014; Wang et al., 2015; Yasunari et al., 2010).

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^{-2} in the TP (Flanner et al., 2007) and varied from 0.8 to 12.1 W m^{-2} 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^{-2} and 4.8 ± 3.2 W m^{-2} 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 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 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 Snow Ice Aerosol Radiative (SNICAR) model, and to quantify the contributions of BC and MD to potential glacier melting using a glacier surface energy-mass balance model.

2 Methodology

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 km^2 (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℃ 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 (e.g., intensive agriculture, grazing and industry) and surrounded by arid and semi-arid regions (e.g., Tarim Basin, Taklimakan Desert and Qaidam Basin) (Fig. 1). Glacier area of the Laohugou river basin reduced by11.59 % in the past 50 years (Zhang et al., 2013), the LHG retreated 240 m during 1957 - 2005 (Du et al., 2008), elevation decreased by 18.6±5.4 m and the total volume lose was 0.218 km^3 between 1957 and 2007 (Zhang et al., 2012).

2.2 Field sampling and observation

A total of 92 surface snow and ice (0-5 cm) samples were collected during July 27th - 29th 2013 and August 4th-6th 2014, in replicate with an approximate altitude difference of 100 m in 2013 and 50 m in 2014 on the eastern branch of LHG (Fig. 1). The glacier surface was covered by fresh snow due to frequent snowfall during sampling period in July 2013. Moreover, in such condition, the surface superimposed ice were sampled loaded with obvious MD under the snow. However, new-fallen snow samples were collected at August 4th 2014 after the precipitation, and the snow mostly melted at August 6th 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^2 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.

2.3 Laboratory analyses

In the laboratory, snow/ice samples were weighed and melted at room temperature in a class 100 clean room, and immediately filtered through quartz fiber filters which were pre-heated in an oxygen stream for at least 2 h in a tube oven with temperature of 800 °C. The water samples were filtered twice, and both the containers and filtration unit were rinsed three times with ultrapure water (Milli-*Q*, 18.2 MΩ; Millipore) to ensure complete transfer of particles to the filters (Xu et al., 2006). DRI® Model (2001A) was utilized to measure the BC mass on the filters at the Institute of Earth Environment, Chinese Academy of Sciences, following the Interagency Monitoring of Protected Visual Environments (IMPROVE) thermal-optical reflectance protocol (Chow et al 2004). The analytical uncertainty was assessed to be 15% for BC (Xu et al 2012).The MD mass was the discrepancy between the two weights before and after the filtration using a microbalance (accuracy: 0.1 mg).

2.4 Model

2.4.1 Albedo reduction modelling and radiative forcing (RF)

The SNICAR model (Flanner et al., 2007) is applied to simulate the albedo variation caused by BC and dust deposited in the glacier surface in this work, BC optical properties are identical to those applied by (Flanner et al. 2007), who assume external mixtures of BC (coated and uncoated) /ice and aspherical ice particles that conserve the total surface area and volume of the real media. To represent the melting caused by the particles on any given day, the following assumptions were made: (1) The solar zenith angle was identified based on the time and position of the specific sampling sites; (2) Surface spectral distribution (a. Mid-latitude winter, clear-sky, cloud amount < 5; b. Mid-latitude winter, cloudy-sky, cloud amount≥ 5); (3) The snow grain effective radius, thickness and density were taken as the in-situ observation (see Table 1); (4) The albedo of the underlying ground was taken as 0.2 in the visible band and 0.4 in the near-infrared band; (5) The BC mass absorption cross section (MAC) of 7.5 m^2 g^{-1} at 550 nm is recommended by a comprehensive review (Bond et al., 2006), the BC MAC scaling factor (experimental) of BC is set as 1 (default value); (6) We used the maximum value 5.0-10 μm as the diameter of dust, according to the volume size distribution of MD in snow/ice at LHG (Dong et al., 2014); (7) volcanic ash concentration (μg g^{-1}) was inserted as 0 in the model. The detailed parameters used in SNICAR are listed in Table S1.

RF was defined as

$$RF_x = R_{in-short} * \Delta\alpha_x \qquad (1)$$

where $R_{in\text{-}short}$ 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^{-2}) and August 2014 (542 W m^{-2}).

2.4.2 Energy and mass balance model

The glacier melting caused by BC and MD is calculated with a distributed physical-based energy (SEB) and mass (SMB) balance model.

$$B = \int\left(\frac{Q_M}{L_m} + \frac{Q_L}{L_v} + C_{en} + P_{snow}\right) dt \qquad (2)$$

Here, B is the specific mass balance (mm w.e.), whereas Q_M and Q_L correspond to the melt energy and turbulent latent heat flux, respectively. L_m and L_v are the latent heat of ice melt (3.34×105 J kg^{-1}) and evaporation/sublimation (2.50×106 J kg^{-1}/2.83×106 J kg^{-1}), respectively. C_{en} and P_{snow} refer to refreezing of melt water (not considered in this model) and accumulation of solid precipitation, respectively. Q_M is calculated from the SEB equation:

$$Q_M = S^{\downarrow}(1-\alpha) + L^{\downarrow} + L^{\uparrow} + H + LE + Q_G \qquad (3)$$

where $S_{\downarrow}$ and α indicate the incoming solar radiation and the surface albedo, respectively. $L^{\downarrow}$ and $L^{\uparrow}$ are the incoming and outgoing long-wave radiation, respectively. H and LE are the sensible and latent heat flux, respectively. Q_G denotes the subsurface heat flux (Klok and Oerlemans, 2002; Vincent, 2002; Zuo and Oerlemans, 1996). On the right side of Eq. (3), all energy components are defined as positive values when directed to the surface, otherwise they are defined as negative values. Meteorological data (e.g. air temperature, relative humidity, wind speed and global radiation) collected at AWS drive the model, which is optimized for TP (Jiang et al., 2010; Yang et al., 2013; Zhu et al., 2015). Whereas albedo, surface temperature, turbulence fluxes are parameterized as Hock et al. (2005), Fujita et al. (2000) and Sun et al. (2014), respectively. $L^{\downarrow}$ is calculated as a function of air temperature and humidity according to Duguay (1993); $L^{\uparrow}$ is computed conventionally by Stefan-Boltzmann law from modeled surface temperature and surface emissivity (being set to 1). Moreover, air temperature has a lapse rate of 6℃ km^{-1} with altitude, relative humidity and wind speed are assumed independent to altitude, and precipitation gradient is 0.08 100 m^{-1} according to the measured value.

A sensitivity analysis was performed to evaluate the model results to the chosen input parameters (albedo reductions caused by BC and MD). Four scenarios were examined: (1) factual albedo, (2) factual albedo plus the impact of BC, (3) factual albedo plus the impact of MD, and (4) factual albedo plus the combined impacts of BC and MD. The other parameter are kept constant throughout the experiments in order to separate the LAPs' effect. Based on the above parameterizations, the extra role of LAPs on energy and glacier ablation was calculated with a 1 h temporal and 30 m spatial resolution.

3 Results & Discussion

3.1 BC and MD concentrations and variations

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^{-1} and 6.0 μg g^{-1} (n = 7) respectively on July 27th, but increased to 160.1 ng g^{-1} and 17.5 μg g^{-1} (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^{-1} and 67.9 μg g^{-1} (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 polluted industrial centers (e.g., Jiuquan and Jiayuguan) towards the LHG region, which has been proved from the back trajectories analysis researches (Dong et al., 2013, 2014; Xu et al., 2014; Zhao et al., 2012). 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^{-1}, while BC concentration was 356.6±1248.1 ng g^{-1} in July 2013. As a result of drastic enrichment and re-exposure, the concentrations of BC and MD reached 20491.4±19855.3 ng g^{-1} and 3528.7±3462.6 μg g^{-1} (n = 7) respectively in the bottom portion in

July 2013. In addition, a snow fell in 3rd 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 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^{-1} and 3712.0 ± 10288.0 μg g^{-1} (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.

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 scavenged 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; Wang et al., 2012; Xu et al., 2006, 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 the SNICAR model (Flanner et al., 2007) was used to simulate the albedo declines produced by different magnitude of concentrations of BC and MD. Here, we focused mainly on the albedo variation attributed to BC and MD (Table S1). 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 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, due to the contents of BC and MD over LHG 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.

A recent paper by He et al. (2014) indicated that BC-snow internal mixing enhances snow albedo reduction by 30-90% relative to external mixing over the TP, and the use of non-spherical Koch snowflakes leads to 20-40% lower snow albedo reductions than spherical snow grains which produce stronger forward scattering (Liou et al. 2014). In this work, we followed the default BC optical properties assumptions of SNICAR mode (BC-snow external mixing and spherical snow grain) (Flanner et al., 2007). The optical properties of the BC and dust come from general libraries and not this specific region, and therefore the modeling of albedo reduction and associated RF are relatively uncertain.

3.3 Additional absorbed radiative forcing

BC and MD deposited on the glacier surface can absorb extra energy and accelerate glacier melting. The RFs 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). The simulation showed that the RF caused by BC and MD deposition on the LHG varied between 2.5-128.8 W m^{-2} and 1.4-120.5 W m^{-2} (Table. S1), respectively. The BC RFs of exceeded MD in both snow and ice. On average, the MD RF was 30.7 ± 32.9 W m^{-2} and BC RF was 41.6 ± 37.0 W m^{-2} in the summer of 2013 and 2014.

These values are higher than RFs of Zhadang glacier (Qu et al., 2014) , Muji glacier (Yang et al., 2015) during the melting season in 2012, and the numerous modeling studies of BC RF conducted over the High Asia glaciers (Flanner et al., 2007; He et al., 2014; Ming et al., 2013; Nair et al., 2013; Qian et al., 2011) and those in the Arctic (Wang et al., 2011; Flanner et al., 2013), which suggest that LAPs enrichment by melt scavenging 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 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). 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 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^{-1} and 2801.0±1948.7 μg g^{-1}, 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 (81.6 ± 24.6 W m^{-2}). 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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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^{-1})	Avg. of MD conc. (μg g^{-1})	Snow grain size (mm)	Snowpack density (kg m^{-3})	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±17210.7	2774.0±1827.4	0.6-2.0	400	1	6	Superimposed ice

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

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

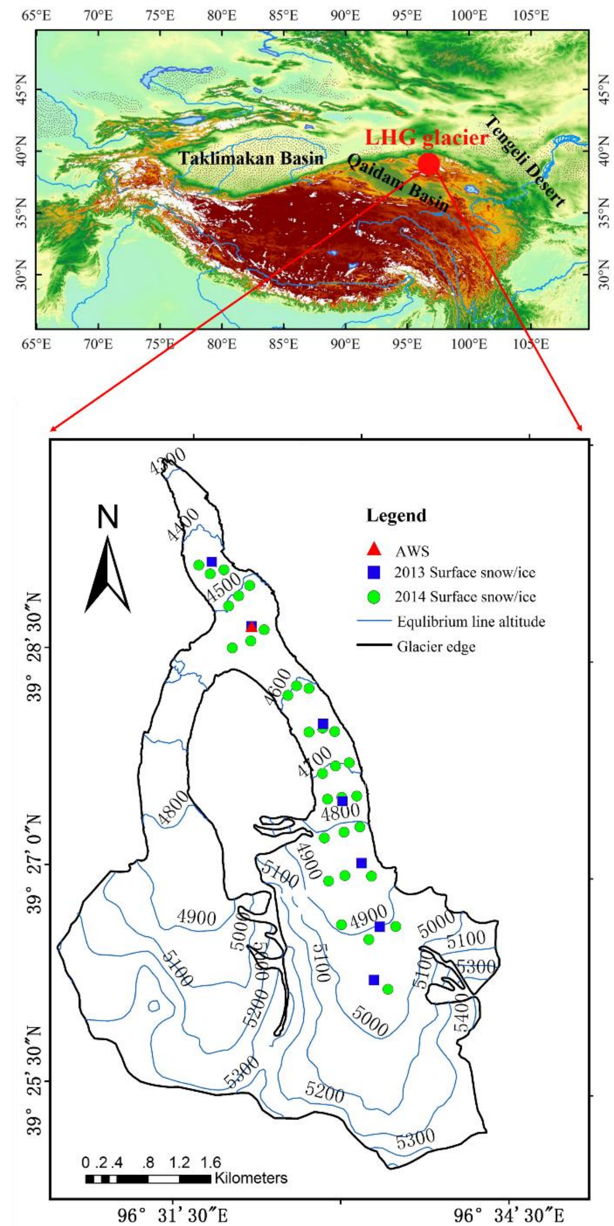

Figure 1. Topographic map of Laohugou glacier No.12 and sampling sites

620

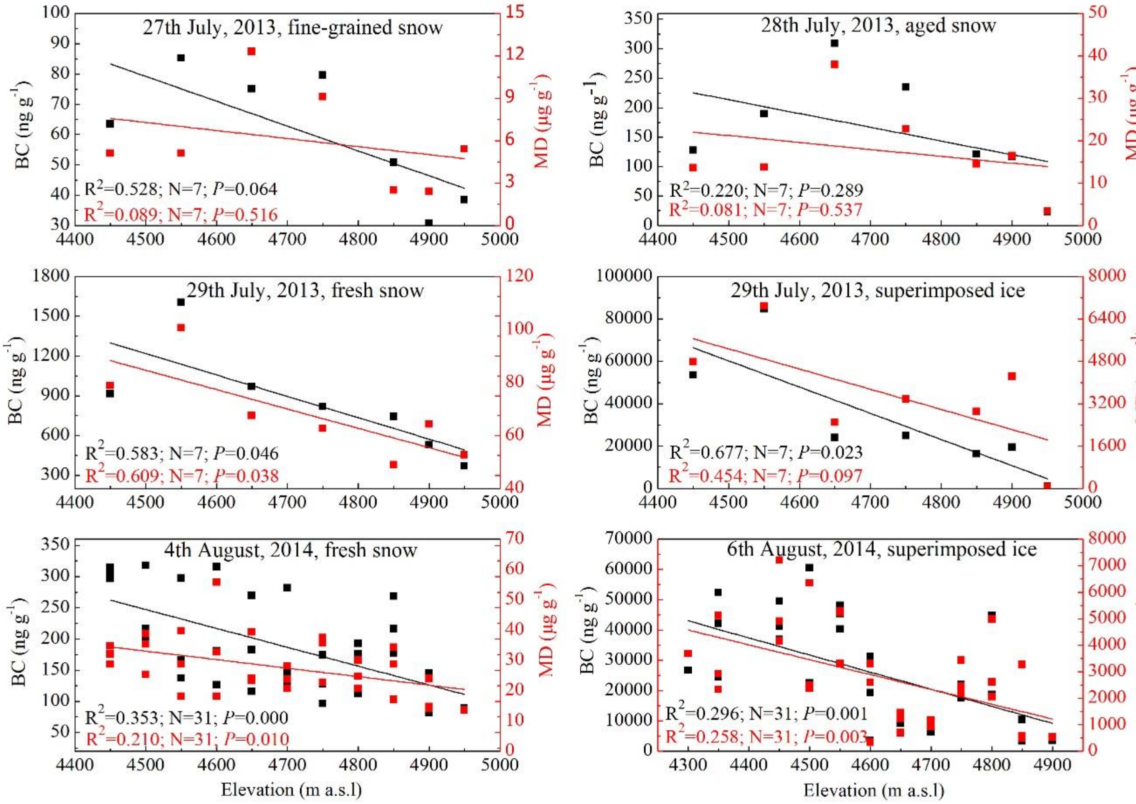

Figure 2. Variations of BC and MD in surface snow/ice from the Laohugou glacier No.12 with increasing elevation

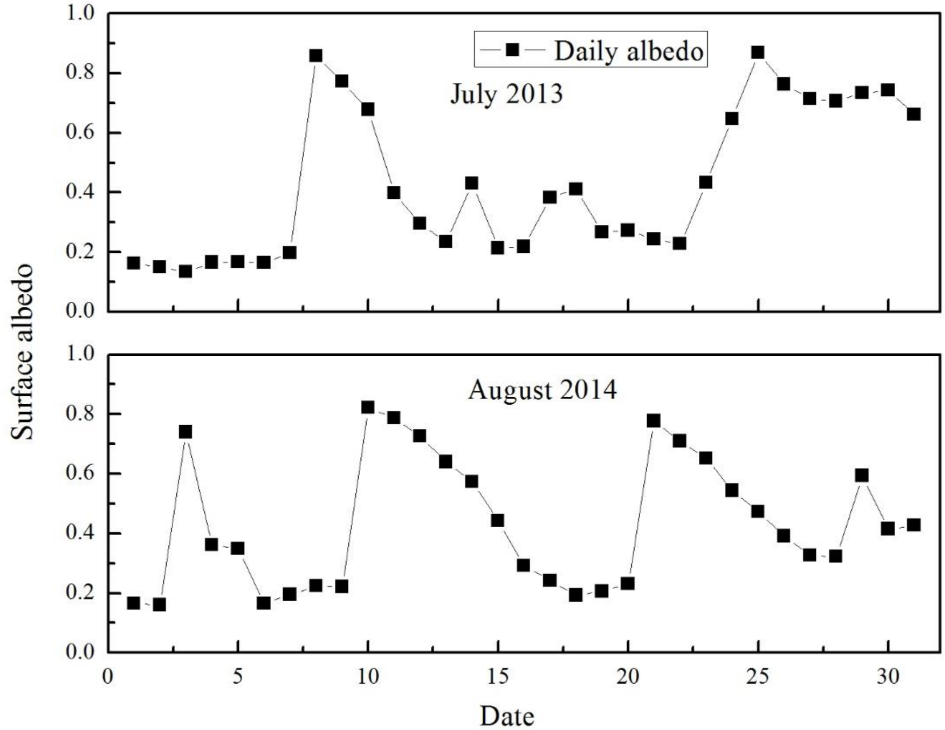

Figure 3. Variations of the surface albedo of the Laohugou glacier No.12 in July 2013 and August 2014 from the AWS.

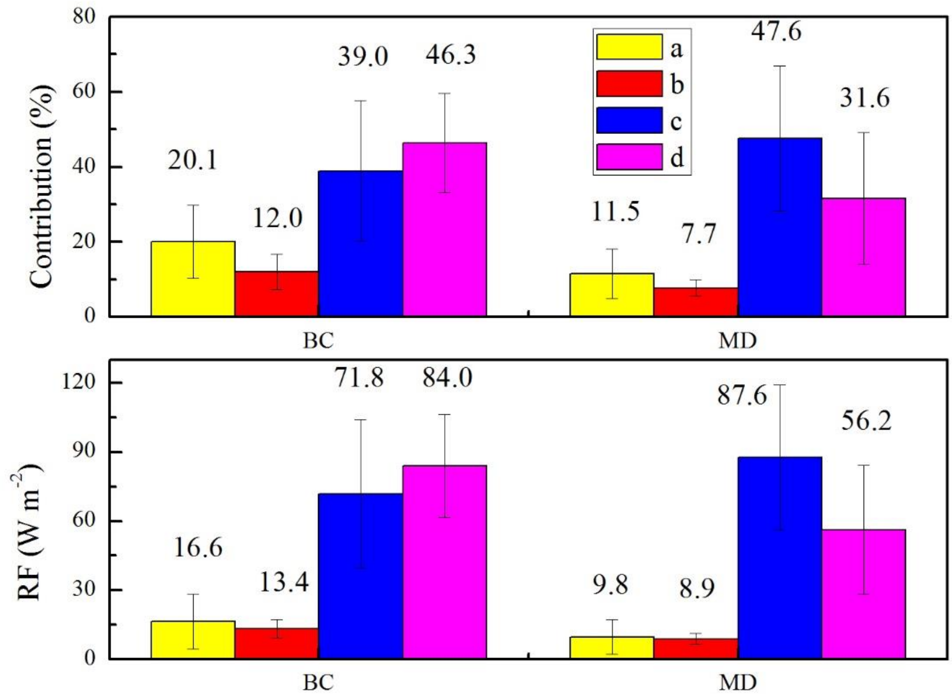

Figure 4. Mid-day RFs of BC and dust on the Laohugou glacier No.12 and the contribution (resulted from the SNICAR model) showing the reduction of albedo in surface snow cover area under three different melting conditions: (a) and (b), where the glacier was covered by snow of July 2013 and August 2014,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

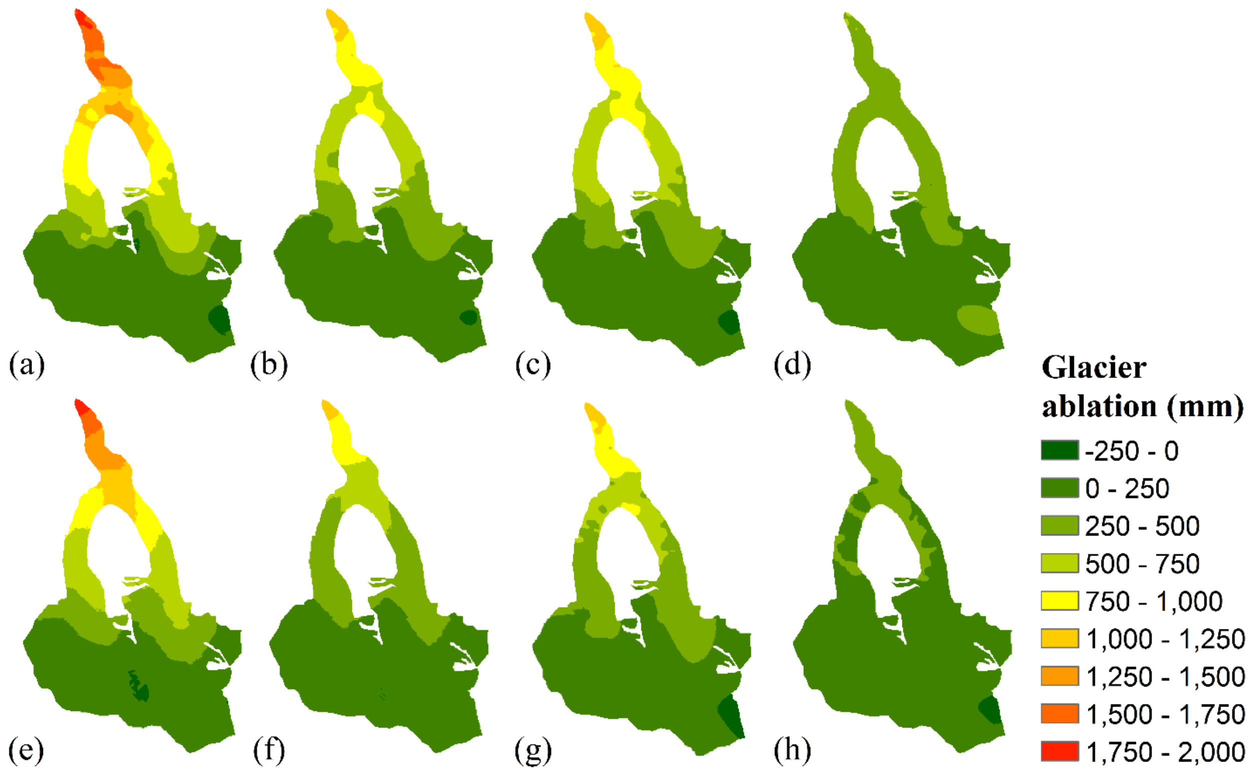

Figure 5. Simulated glacier ablation caused by BC and MD. (a) and (e), actual ablation of 2013 and 2014,respectively; (b) and (f), actual ablation except the impact of BC of 2013 and 2014,respectively; (c) and (g), actual ablation except the impact of MD of 2013 and 2014,respectively; (d) and (h), actual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