RESEARCH ARTICLE

10.1002/2016JD026397

Key Points:

- Light-absorbing impurity concentrations were much higher in aged snow and granular ice than in fresh snow and snowpits
- BC and dust contributed approximately 20% of the albedo reduction relative to clean snow
- Light-absorbing impurities deposited on the southeastern Tibetan glaciers were significantly affected by emissions from South Asia

Supporting Information:

- Supporting Information S1
- Data Set S1

Correspondence to:

S. Kang,
shichang.kang@lzb.ac.cn

Citation:

Zhang, Y., et al. (2017), Light-absorbing impurities enhance glacier albedo reduction in the southeastern Tibetan plateau, *J. Geophys. Res. Atmos.*, 122, 6915–6933, doi:10.1002/2016JD026397.

Received 18 DEC 2016

Accepted 23 JUN 2017

Accepted article online 4 JUL 2017

Published online 12 JUL 2017

Light-absorbing impurities enhance glacier albedo reduction in the southeastern Tibetan plateau

Yulan Zhang¹ , Shichang Kang^{1,2} , Zhiyuan Cong^{2,3} , Julia Schmale⁴ , Michael Sprenger⁵, Chaoliu Li^{2,3} , Wei Yang^{2,3}, Tanguang Gao⁶, Mika Sillanpää^{7,8}, Xiaofei Li¹, Yajun Liu¹, Pengfei Chen³, and Xuelei Zhang⁹
¹State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, ²CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China, ³Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, ⁴Paul Scherrer Institute, Villigen, Switzerland, ⁵Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland, ⁶Key Laboratory of Western China's Environmental System (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China, ⁷Laboratory of Green Chemistry, Lappeenranta University of Technology, Mikkeli, Finland, ⁸Department of Civil and Environmental Engineering, Florida International University, Miami, Florida, USA, ⁹Key laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, China

Abstract Light-absorbing impurities (LAIs) in snow of the southeastern Tibetan Plateau (TP) and their climatic impacts are of interest not only because this region borders areas affected by the South Asian atmospheric brown clouds but also because the seasonal snow and glacier melt from this region form important headwaters of large rivers. In this study, we collected surface snow and snowpit samples from four glaciers in the southeastern TP in June 2015 to investigate the comprehensive observational data set of LAIs. Results showed that the LAI concentrations were much higher in the aged snow and granular ice than in the fresh snow and snowpits due to postdepositional processes. Impurity concentrations fluctuated across snowpits, with maximum LAI concentrations frequently occurring toward the bottom of snowpits. Based on the SNOW ICE Aerosol Radiative model, the albedo simulation indicated that black carbon and dust account for approximately 20% of the albedo reduction relative to clean snow. The radiative forcing caused by black carbon and dust deposition on the glaciers were between 1.0–141 W m^{−2} and 1.5–120 W m^{−2}, respectively. Black carbon (BC) played a larger role in albedo reduction and radiative forcing than dust in the study area, enhancing approximately 15% of glacier melt. Analysis based on the Fire INventory from NCAR indicated that nonbiomass-burning sources of BC played an important role in the total BC deposition, especially during the monsoon season. This study suggests that eliminating anthropogenic BC could mitigate glacier melt in the future of the southeastern TP.

Plain Language Summary In this study, we focused on light-absorbing impurities (LAIs), including black carbon, organic carbon, and mineral dust in glacial surface snow from southeaster Tibetan glaciers. This study showed the concentrations of LAIs, and estimated their impact on albedo reduction. Furthermore, we discussed the potential source of impurities and their impact to the study area. These results provide scientific basis for regional mitigation efforts to reduce black carbon.

1. Introduction

Light-absorbing impurities (LAIs, including black carbon (BC), organic carbon (OC), brown carbon (BrC), and mineral dust) deposited on snow and glacial surfaces can reduce the albedo, accelerate snow/ice melt, and trigger albedo feedback [Bond et al., 2013; Dumont et al., 2014; Flanner et al., 2007; Gertler et al., 2016; Kaspari et al., 2014; Lau et al., 2010; Ming et al., 2012; Xu et al., 2009a; Yasunari et al., 2010]. LAIs in snow/ice have been identified as one of the major forcing agents affecting regional climate change and general atmospheric circulation, but there is a high level of uncertainty associated with quantifying this effect [Flanner et al., 2007; Gertler et al., 2016; Qian et al., 2015; Ramanathan and Carmichael, 2008]. Considerable efforts are underway to estimate the radiative forcing (RF) of LAIs on a global/regional scale, but uncertainties in observations and simulations remain, particularly regarding the concentrations, spatiotemporal distributions, and optical properties of LAIs [Gertler et al., 2016; Gustafsson and Ramanathan, 2016; Ji et al., 2015; Qian et al., 2015].

BC particles are mainly produced from the incomplete combustion of fossil fuels and biomass [Bond *et al.*, 2013]. BC can strongly absorb solar radiation at visible wavelengths causing warming effects [Bond *et al.*, 2013; Ramanathan and Carmichael, 2008]. Some estimates suggest that BC is the second strongest climate warming forcing agent after carbon dioxide and thus has a profound impact on climate (e.g., it is linked with reductions in precipitation and positive shortwave radiative forcing in the atmosphere) [Bond *et al.*, 2013; Ji *et al.*, 2015; Ramanathan and Carmichael, 2008; Wild, 2012]. BC particles are also thought to have large-scale environmental effects, such as melting of the Himalayan and other glaciers [Kaspari *et al.*, 2014; Lau *et al.*, 2010; Xu *et al.*, 2009a; Xu *et al.*, 2016]. Once deposited on a glacier surface via dry or wet processes, even a small amount of BC can exert significant RF efficiently through albedo reduction, potentially contributing to glacier melt [Flanner *et al.*, 2007; Gertler *et al.*, 2016; Lau *et al.*, 2010; Schmale *et al.*, 2017]. Despite the importance of BC in climate forcing, estimations of albedo reduction and RF by BC yield a large range of possible results for the same region. For example, in the Himalayan cryosphere, RF by BC varies by a factor of approximately 4 in different studies [Gertler *et al.*, 2016; Ming *et al.*, 2008; Kaspari *et al.*, 2014]. A possible reason for these differences may be the systematic bias in the sampling (different snow types from the accumulation zone or ablation zone) and model estimates of the BC deposition flux on glacier surface.

Organic carbon (OC) in the atmosphere mainly originates from the burning of biomass and fossil fuels and the dispersion and disintegration of plant materials, viable microbes, and soil organic matter [Cerqueira *et al.*, 2010; Chakrabarty *et al.*, 2010; Painter *et al.*, 2001; Takeuchi *et al.*, 2006]. The particular fraction of OC that can absorb at visible to UV wavelengths of light is referred to as brown carbon (BrC) [Andreae and Gelencsér, 2006; Bahadur *et al.*, 2012; Moosmüller *et al.*, 2011]. Current climate models typically treat OC as nonabsorbing, underestimating the total warming effect of carbonaceous aerosols by neglecting part of the atmospheric heating, particularly over biomass burning regions that emitted BrC [Andreae and Gelencsér, 2006; Bahadur *et al.*, 2012]. Due to its light-absorbing nature, OC in glacier snow can also darken the glacier surface and reduce albedo. However, OC radiative forcing estimations in snow are highly uncertain owing to the effects of different organic compounds, the state changes of OC when sampling, and the different spectral dependences of OC and BC absorption [Bahadur *et al.*, 2012; Lin *et al.*, 2014; Wang *et al.*, 2015].

Similarly, mineral dust is another main constituent of the LAIs that can increase the absorption of solar radiation, causing further albedo reduction and a positive feedback [Di Mauro *et al.*, 2015; Kaspari *et al.*, 2014; Qu *et al.*, 2014; Wang *et al.*, 2013]. Based on observed reflectance, Di Mauro *et al.* [2015] showed that mineral dust significantly reduced the spectral reflectance of snow at 350–600 nm in the European Alps. The results from East Asia indicate that the absorption of the LAIs in seasonal snow is dominated by mineral dust in the Qilian Mountains and by local soil dust in the Inner Mongolian region [Wang *et al.*, 2013]. It is important to note that the optical properties of mineral dust are dominated by iron oxides. This is a key aspect when determining the refractive indices of dust [Kaspari *et al.*, 2014; Zhang *et al.*, 2015]. Distinguishing the effects of BC from mineral dust is still challenging, especially when dust concentrations in snow are high as this can introduce artifacts into the analysis [Lim *et al.*, 2014; Schwarz *et al.*, 2012]. However, separating the effects is important for attributing the radiative forcing of snow to natural versus anthropogenic sources.

The Tibetan Plateau (TP) is often referred to as the Third Pole due to its large snow- and glacier-covered area. Recent studies suggest that glacial shrinkage is pronounced in the southeastern TP [W. Yang *et al.*, 2015; Yao *et al.*, 2012a]. This shrinkage may have serious consequences since the runoff from the southeastern Tibetan glaciers form the headwaters of major rivers in Asia (e.g., Yarlung Tsangpo, Lancang River, Salween, in Figure 1a), which play an important role for regional climate feedbacks and the hydrological cycle and supply water to major downstream populations [Immerzeel *et al.*, 2010; Yao *et al.*, 2012b]. Previous studies suggest that LAI deposition can lead to enhanced glacier retreat [Gertler *et al.*, 2016; Y. Li *et al.*, 2016; Ramanathan and Carmichael, 2008; Xu *et al.*, 2009a]. Previous studies in the southeastern TP focused primarily on the BC concentrations in ice cores/snowpits [Xu *et al.*, 2009b; Wang *et al.*, 2015] rather than including measurements of mineral dust and other light-absorbing impurities. In addition, sampling was limited to the accumulation zones, rather than expanding over the whole glacier, especially including the ablation zone (where the retreat/melting mainly occurs). Sparse *in situ* data from this region hinders the evaluation of how LAIs affect glacier surface albedos, radiative forcings, and glacier melts.

In this study, glacier surface snow/ice (including fresh snow, aged snow, and granular ice, see Figure S1 in the supporting information) and snowpit samples, collected from the ablation zones of the Yarlong, Dongga,

Figure 1. (a, b) Location map of the studied glaciers on the southeastern Tibetan Plateau.

Renlongba, and Demula glaciers on the southeastern TP (Figure 1), are analyzed for BC, OC, and dust concentrations. The spatial variations of their concentrations are discussed, focusing especially on the differences in the accumulation and ablation areas of the glaciers and their vertical distributions in snowpits. By using the SNow ICe Aerosol Radiative (SNICAR) model [Flanner *et al.*, 2007], we also estimate the changes in snow albedo and radiative forcing (RF) caused by BC and mineral dust. Furthermore, the potential sources of the LAIs deposited on the southeastern Tibetan glaciers are also discussed.

2. Methodology

2.1. Study Area

Because of its high altitude (average > 4000 m above sea level (asl)) and large area (> 5 million km^2) [Yao *et al.*, 2012a], the TP plays a significant role in the Earth's climate system [Yanai and Wu, 2006]. The atmospheric circulation patterns over the TP are characterized by the South Asian (Indian) monsoon in summer and the westerlies in winter [Yao *et al.*, 2012b]. Our study area is located along the southeastern margin of the TP

(Figure 1). This region is strongly influenced by the South Asian monsoon, which typically arrives via the Brahmaputra Valley [W. Yang *et al.*, 2015]. The annual precipitation reaches approximately 800–1000 mm in this region, and precipitation is usually much greater at the glacier equilibrium line altitude (ELA) (~2500 mm) [W. Yang *et al.*, 2015]. The temperate glaciers that are typical in the southeastern TP account for approximately 20% of the total number of glaciers in China [Shi, 2008]. Due to their exhibited strong surface melting and rapid terminal movement, these glaciers are subject to extensive mass loss. From the 1970s to the 2000s, glacier lengths in this area decreased at an average rate of $\sim 48 \text{ m yr}^{-1}$ and the glacier-covered area was reduced at an average rate of $0.57\% \text{ yr}^{-1}$ [Yao *et al.*, 2012b; W. Yang *et al.*, 2015].

2.2. Sampling

During expeditions in June 2015, fresh snow, aged snow, and granular ice samples were collected (see Figure S1) from the four glaciers (Yarlong, Dongga, Renlongba, and Demula) with average elevations ranging from 4060 to nearly 5090 m asl (Figure 1b). In addition, samples of three snowpits were collected from the Dongga, Renlongba, and Demula glaciers. However, due to the number of crevasses, snowpit samples were not obtained from the Yarlong glacier. In situ observations included snow thickness, density, and grain size. Information on the sampling sites is listed in Table S1.

Whirl-Pak™ bags were used to collect surface snow samples (approximately 2 L, unmelted) from the upper 4–8 cm of snow, as well as surface granular ice samples when there was no snow cover. Snowpit samples were excavated at a vertical depth of 10 or 15 cm, following the protocol described by Kang *et al.* [2007]. In total, 20 surface snow/ice samples and 24 snowpit samples were collected. Parallel samples were used to average the results.

2.3. Filtering Procedure

All samples were kept frozen until analysis. Before filtration, the samples were rapidly melted via a hot water bath (approximately 20 min for complete melting) and the melt water (typically 1 L) was filtered through a predried (in a desiccator, at 550°C , for 6 h) weighted quartz substrate (Whatman™) using a vacuum pump. Samples were filtered twice and the filtration equipment was rinsed 2 times with ultrapure water ($<18.2 \text{ m}\Omega$) to avoid particle loss [Ming *et al.*, 2008]. The estimated total uncertainty of the particle concentrations is $<1\%$ (including background counts and random counting errors) [Ming *et al.*, 2008]. The BC collection efficiency of the filtration of melted snow samples was determined to be $77 \pm 17\%$ [C. Li *et al.*, 2016]. The filtered water was transferred into precleaned polycarbonate vials (Nalgene Bottle Square PC) for dissolved organic carbon analysis and into precleaned polyethylene vials for major ions and elements analyses.

2.4. Measurements of Dust, BC, and OC

After filtering, the quartz filters were analyzed for dust, BC and OC. The quartz filters were weighted gravimetrically after filtration. Considering that the dust mass on the filters was far larger (2 orders of magnitude) than the BC and OC masses on the filters [Kaspari *et al.*, 2014; Wang *et al.*, 2012], it was assumed that the total dust mass was equal to the difference in the weight of the filters before and after filtration.

Based on an adapted IMPROVE protocol [Cao *et al.*, 2003; Chow *et al.*, 2004], the BC and OC on the filters were measured using the DRI® Model 2001A (Desert Research Institute, USA) thermal-optical carbon analyzer. Because the dust loads in the snow/ice samples were greater than those in the airborne aerosol samples, the method was modified such that, in a 100% helium atmosphere, only one temperature plateau (550°C) was used to reduce the time that the BC was exposed to the catalyzing atmosphere [S. Yang *et al.*, 2015]. The thermal/optical measurement method identified the analytical results as elemental carbon (EC) and organic carbon (OC); here we adapted it to identify BC instead of EC to be consistent with the notation in our model simulation and the literature. The reported OC concentrations from the snow and ice samples can account for only the water-insoluble OC; most of the water-soluble OC is not captured by the filter-based method. The detection limit of the analysis was $0.19 \pm 0.13 \mu\text{g total carbon (TC) cm}^{-2}$, and the filter blank was $1.23 \pm 0.38 \mu\text{g TC cm}^{-2}$, which was much lower (<1 order of magnitude) than the measured sample values.

2.5. Determining Reflectance and Radiative Forcing

During the expeditions to the glaciers in the southeastern TP, reflectance measurements of snow were performed on the Yarlong glacier using an Analytical Spectral Devices Hand Held 2 (ASD HH2) spectroradiometer, which measured the spectral wavelength range of 325–1075 nm with 1 nm spectral resolution.

The ASD FieldSpec HandHeld™ 2 is a portable spectroradiometer that performs rapid, precise, nondestructive, and noncontact measurements. The ASD HH 2 provides extremely accurate, quickly derived reflectance, radiance, and irradiance spectra in a variety of settings. An onboard, tilting color LCD display, integrated computing capability, large internal data storage, laser targeting, and GPS compatibility combine to create a self-contained measurement system. In the field, the measurements were made using a technique approximately equivalent to that described by *Takeuchi et al.* [2015]. The reflectance in this study is given by the ratio of the reflected radiance from a target surface area (glacier surface in this study) in a single direction to the irradiance from the entire hemisphere to the area. The reflected radiance in the visible to near-infrared wavelength range (0.350–1.050 μm) in the nadir direction was measured at a height of approximately 20 cm above the target surface. Measurements at this height provided a field-of-view spot of 10 cm in diameter on the glacier surface (Note: The diameter of the spot size is approximately half of the height). The reflectivities were calculated by dividing the integrated surface radiance by the integrated radiance acquired from the white reference panel.

The SNICAR model can be used to simulate the hemispheric albedo of snow and ice for a unique combination of impurity contents (e.g., BC, dust, and volcanic ash), snow effective grain size, and incident solar flux characteristics [Flanner et al., 2007]. In the SNICAR model, the effective grain sizes of snow were derived from the stratigraphies and ranged from 100 μm for fresh clean snow to 1500 μm for aged snow and granular ice. The model was run with low, central, and high grain size for each snow type to account for the uncertainties in the observed snow grain sizes. The effective grain sizes of snow are listed in Table S2 based on the layer-specific snow types. Snow density varied with crystal size, shape, and the degree of rimming. The snow density data used in the SNICAR model are summarized in Table S3 with low-, central-, and high-density scenarios for the model runs based on a series observations in the TP and previous literatures [Judson and Doesken, 2000; Sjögren et al., 2007]. Measurements of BC and dust concentrations, as well as other observations such as solar zenith angle and snow thickness on the glaciers are provided in Table S4.

When running the SNICAR model, BC was assumed to be coated with sulfate [Flanner et al., 2007; Qu et al., 2014]. The mass absorption cross section (MAC) is an input parameter for the SNICAR model; it is commonly assumed to be 7.5 $\text{m}^2 \text{g}^{-1}$ at 550 nm for uncoated BC particles [Bond et al., 2013]. For sulfate-coated BC particles, the MAC scaling factor was set to be 1 $\text{m}^2 \text{g}^{-1}$, following Qu et al. [2014] and Wang et al. [2015]. Other impurities (such as volcanic ash) were set to zero (Table S4).

Based on the albedo calculations, the BC and dust radiative forcing (RF) can be obtained by equation (1) [Kaspari et al., 2014; S. Yang et al., 2015]:

$$\text{RF} = \sum_{0.325 \mu\text{m}}^{1.075 \mu\text{m}} E(\lambda, \theta) (\alpha_{(r, \lambda)} - \alpha_{(r, \lambda, \text{imp})}) \Delta\lambda \quad (1)$$

Where α is the modeled snow spectral albedo with/without the impurities (imp) of BC and/or dust, E is the spectral irradiance, r is the optical grain size of snow, λ is wavelength (μm), and θ is the solar zenith angle for irradiance. We integrate up to 1075 nm to match the observed data by using ASD HH2.

3. Results and Discussion

3.1. Spatial Distribution of Dust, BC, and OC

LAI concentrations varied broadly (dust from 0.5 to 1657 $\mu\text{g g}^{-1}$, BC from 12.3 to 9803 ng g^{-1} , and OC from 92.7 to 21565 ng g^{-1}), reflecting the large variability of deposited aerosol on the individual glacier and different snow types (Figure 2). The result showed that the dust, BC, and OC concentrations were relatively low at the Demula glacier (Table 1 and Figures 2a–2c). These lower values could be related to the snowfall at the time of sampling, which was not accompanied by strong-blowing snow or melt. The Dongga and Renlongba glaciers contained higher LAI concentrations (Figure 2 and Table 1). However, for the snowpits from the Renlongba, Dongga, and Demula glaciers, all LAI concentrations were comparable to each other (Table 1), indicating the homogeneity of the wet or dry aerosol deposition on the glaciers in this region.

The amounts of impurities in the fresh snow and snowpits were generally lower than those in the aged snow and surface granular ice (Figures 2d–2f). In the previous work, it was found that snow impurities tended to be

Figure 2. Amount of impurities for (a–c) each glacier and (d–f) for fresh snow, aged snow, granular ice and snowpits on the southeastern Tibetan Plateau.

concentrated at the surface during melt [Doherty *et al.*, 2013; Ming *et al.*, 2016; Qu *et al.*, 2014; Xu *et al.*, 2012], as shown in Figure S1 via the visible impurities in the aged snow and granular ice on the glacier surface. This creates a feedback loop that enhances surface melt [Dumont *et al.*, 2014]. The lower concentrations in the fresh snow, compared with those in the aged snow and granular ice, imply that postdeposition processes (e.g., melting or sublimation) play an important role in the distribution of LAIs over the glacier surface.

Figure 3 shows a summary of BC and dust concentrations in the snow and ice cores from the TP and surrounding areas from past years. Ming *et al.* [2009] reported that BC concentrations were highest (more than 100 ng g^{-1}) at the periphery of the TP and at lower elevations, where

the BC may be enriched by the proximity to sources, as well as by melting. In the Tien Shan region, BC and OC concentrations in the surface snow and snowpits reached hundreds of ng g^{-1} , with maximum BC and OC values of ~ 3000 and $\sim 8000 \text{ ng g}^{-1}$ at the Urumqi No. 1 glacier, respectively [Ming *et al.*, 2009, 2016; Schmale *et al.*, 2017; Xu *et al.*, 2012] (Table S5). The minimum BC and OC were approximately 11 and 49 ng g^{-1} [Xu *et al.*, 2012; Ming *et al.*, 2016]. At the northern edge of the TP, BC concentrations ranged from 61 to 849 ng g^{-1} , with an average of 357 ng g^{-1} in the surface snow and ice samples from the Laohugou No. 12 glacier, Qilian Mountain [Y. Li *et al.*, 2016]. At the Muji glacier on the westernmost edge of the TP, the BC in the sufficient melt samples was 730 ng g^{-1} , but only 25 ng g^{-1} in no-melt samples [S. Yang *et al.*, 2015]. For Xiaodongkemadi glacier of the central TP, BC concentrations were found to be in the order: granular ice (3335 ng g^{-1}) greater than aged snow (247 ng g^{-1}) greater than fresh snow (42 ng g^{-1}) [Li *et al.*, 2017]. At the Zhadang glacier in the central TP, Qu *et al.* [2014] reported high BC concentrations in the superimposed ice ($\sim 472 \text{ ng g}^{-1}$) and Ming *et al.* [2009] reported $\sim 600 \text{ ng g}^{-1}$ from a snowpit. Minimal BC concentrations were reported by Kaspari *et al.* [2014] in surface snow at the Mera glacier col on the southern slope of the Himalayas (1.0 ng g^{-1}) and by Ming *et al.* [2009] on the East Rongbuk glacier of Mount Everest (18 ng g^{-1}). Even at the Mera glacier, BC was reported to be as high as 3535 ng g^{-1} due to higher atmospheric concentrations in the troposphere or postdepositional processes leading to the enrichment of impurities [Kaspari *et al.*, 2014]. In addition, ice core BC data from the PLZ4 and Zuoqiupu glaciers (also located in the

Table 1. Average Concentrations of the Mineral Dust, Black Carbon (BC), and Organic Carbon (OC) in the Snow/Ice and Snowpit Samples Collected From the Southeastern Tibetan Plateau

Glacier	Sample Type	Dust ($\mu\text{g g}^{-1}$)	BC (ng g^{-1})	OC (ng g^{-1})
Yarlong	Aged snow	7.52 ± 2.53	79.7 ± 50.1	272 ± 152
Dongga	Snowpit	20.5 ± 8.24	97.3 ± 26.4	281 ± 60.3
Dongga	Aged snow/ice	497 ± 712	1550 ± 2177	3913 ± 5235
Renlongba	Snowpit	37.0 ± 18.0	318 ± 125	818 ± 302
Renlongba	Aged snow/ice	824 ± 766	3648 ± 3092	7956 ± 6829
Demula	Snowpit	21.9 ± 9.91	125 ± 82.8	177 ± 47.3
Demula	Fresh snow/ice	24.5 ± 8.96	56.6 ± 26.1	250 ± 69.5

Figure 3. (a) BC and (b) dust distributions on the Tibetan Plateau and its surroundings.

southeastern TP) ranged from 4.7 to 16.8 ng g⁻¹ and from approximately 3 to 10 ng g⁻¹, respectively [Xu *et al.*, 2009a, 2009b], indicating lower concentrations than the present surface snow. Generally, BC concentrations in the southeastern TP glaciers were most comparable to those in the Himalayan regions but were lower than those in Tien Shan and the northern TP, due to differences in BC emissions or depositions [e.g., Ming *et al.*, 2009; S. Yang *et al.*, 2015]. More generally, significantly higher BC values are detected in the high mountains of Asia than in the northern Greenland surface snow (0.3–2.3 ng g⁻¹) [Aoki *et al.*, 2014], the Arctic (45 ng g⁻¹) [Ruppel *et al.*, 2014], and the Alpine (20 ng g⁻¹) [Thevenon *et al.*, 2009] ice cores (Table S5).

These results indicate that the high amounts of BC emitted in South and East Asia (one of the largest sources of BC globally) are likely to be lofted to the high TP and then deposited, darkening the glacier surfaces [Ramanathan and Carmichael, 2008; Xu *et al.*, 2009a]. It should be noted that the results from the

Figure 4. Light-absorbing impurities across the snowpit and ratios of OC to BC (OC/BC) from the (a) Dongga, (b) Renlongba, and (c) Demula glaciers on the southeastern Tibetan Plateau.

northern TP [Dong *et al.*, 2009, 2013, 2014; Zhang *et al.*, 2016], which is likely due to the enrichment processes triggered by melt events.

3.2. Vertical Variations of LAIs

Vertical changes of LAIs with snowpit depth are shown in Figure 4. The average concentrations of dust, BC, and OC are comparable among the snowpits from the Dongga, Renlongba, and Demula glaciers (Table 1); however, the profiles of the LAIs generally vary strongly across snowpits (Figure 4). For the Dongga glacier (Figure 4a), impurities initially decreased below the surface layer of the snowpit but began to increase at a depth of 60 cm in the firn layer. The maximum dust concentration occurred at the bottom firn layer of the snowpit, while the maximum OC concentration occurred at the top of the snowpit. BC peaks occurred both at the top of the snowpit and at the 80 cm deep firn layer. OC/BC ratios in the snowpits (average of 3.6) were similar to the ratio in aged (or melted) snow/ice samples (average at 4.0) (Figure S2).

The vertical distributions from the Renlongba glacier showed that LAIs were not initially enriched in the surface snow and did not migrate downward (Figure 4b). The ratios of OC/BC ranged from 2 to 3, similar to the insignificantly melted surface snow in the ablation zone of the Renlongba glacier (Figure S2), which also indicated that the BC and OC scavenging processes remained constant [S. Yang *et al.*, 2015]. The enriched LAIs at the Renlongba glacier generally appeared at depths of 50–60 cm near the bottom firn.

various studies are not always directly comparable due to their different analytical methodologies, sampling dates, and snow conditions. However, these comparisons nevertheless reveal a significant range of BC concentrations across different glaciers and regions.

Focusing on the mineral dust concentrations across the TP and surroundings (Table S6), we can compare studies that calculated the mineral dust concentrations from the size distributions from Coulter counters and an average crust density of 2.6 g/cm^3 . The results reflect clear differences between the sites (Figure 3b). Glaciers in the southeastern TP show lower dust concentrations in the snowpits than the ones in Tien Shan and the central-northern TP [Dong *et al.*, 2009, 2013, 2014; Dong and Li, 2011; Wake and Mayewski, 1994; Wu *et al.*, 2010; Zhang *et al.*, 2016] but slightly higher than those in the Himalayas [e.g., Wang *et al.*, 2006; Wu *et al.*, 2010; Zhang *et al.*, 2016]. This suggests a decreasing trend of dust deposition on glaciers from semiarid and arid regions [Zhang *et al.*, 2016] toward the southern TP. However, the dust concentrations in the aged snow of the southeastern TP are comparable to those in the Tien Shan and the

Table 2. Sensitivity Analysis With the SNICAR Model for the Yarlong (YL) Glacier in the Southeastern Tibetan Plateau^a

Site	Measured Reflectance	SA Pure	SA + Dust	SA + BC	SA + BC and Dust	BC (%)	Dust (%)	BC + Dust (%)	DF (%)
YL1	0.7632	0.7607	0.7603	0.7555	0.7552	0.68	0.05	0.72	1.05
YL2	0.7922	0.7473	0.7442	0.7430	0.7400	0.58	0.42	0.99	6.59
YL3	0.5719	0.7599	0.7583	0.7530	0.7522	0.91	0.21	1.00	−31.53
YL4	0.7836	0.7668	0.7658	0.7640	0.7610	0.36	0.14	0.76	2.88
Average	0.7278	0.7587	0.7571	0.7539	0.7521	0.63	0.21	0.87	−3.35

^aSA pure represents the simulated albedo for the pure snow. SA+ Dust represents the simulated albedo with dust in the snow. SA + BC represents the simulated albedo with BC in the snow. BC% and Dust% are the concentrations of BC and dust in the total albedo reduction on the Yarlong glacier. DF% means the differences between the observed reflectance and simulated albedo.

The results from the snowpit from the Demula glacier are similar to those of the Renlongba glacier, with covarying impurity concentrations throughout the snowpit (Figure 4c). Enriched and maximum dust, BC, and OC generally occurred at a depth of 70–80 cm (the snow pit bottom). The OC/BC ratio exhibited a decreasing trend from the upper layer of the snowpit (~8) to its bottom (~0.7) (Figure 4c). The high BC and OC concentrations and low OC/BC ratio may suggest that the BC and OC had redistributed vertically in the glacier, potentially under the control of melting processes or biological melt enhancement effects [Benning *et al.*, 2014; Dong *et al.*, 2016; S. Yang *et al.*, 2015; Takeuchi *et al.*, 2006].

Impurity enrichment varied with snowpit depth and types of impurity. The maximum LAI concentrations frequently occurred at the lower parts of the snowpits, except at the Dongga glacier, where the snowpit contained more melt features (more icy layers) due to its lower elevation. Glaciers in the southern TP have been experiencing serious shrinkage, with negative annual mass balances [W. Yang *et al.*, 2015; Yao *et al.*, 2012b]. The maximum mass loss occurred in the ablation zone at 4160–4220 m asl and reached approximately 2623 millimeters water equivalent (mmwe) for six glaciers [Yang *et al.*, 2010]. The annual precipitation at the glacier equilibrium line altitude (ELA) reached approximately 2500–3000 mmwe [Shi and Liu, 2000]. The snowpit depth (~1200 mm) in this study was approximately 300–400 mmwe, based on the snow density, indicating that the snowpits were located in the ablation zone (below an ELA of ~5400 m asl), and the annual accumulations (or mass balances) at the snowpit sites were negative. These snowpits mostly accumulated from the end of the melting season (October) to the spring (May) and melt away in the summer. Thus, the dirt layers at the bottom of the Renlongba and Demula snowpits may have formed during the previous winter seasons with concentrated LAIs. Some dirty layers were also overlaid with ice (such as the Dongga snowpit), which might be formed in the spring (Figure 4) when slight melting occurs. In addition, some dry deposition of impurities onto the glaciers existed.

3.3. Estimation of Albedo Reduction and Radiative Forcing Caused by BC and Dust

The field reflectance measurement data from the ASD HH2 at the Yarlong glacier are shown in Table 2. Slight variations in the reflectance were observed at the Yarlong glacier due to variations in snow conditions over time across the natural field environment. The simulated albedo was consistent with the measured reflectance (mostly within about 7%), indicating that the albedo results simulated by the SNICAR model can represent the general conditions of the glaciers in the southeastern TP.

The average snow albedo reduction and RF caused by BC and dust are shown in Figure 5 as a function of surface snow types. The albedo reduction ranged from between 0.27 and 23% for the combined effect of BC and mineral dust (Table 3). For the central scenario (as defined in Tables S2 and S3), the albedo reduction caused by the BC and dust ranged from 0.52 to 20%, which is in agreement with other studies in the Himalayas [Gertler *et al.*, 2016; Kaspari *et al.*, 2014; Ming *et al.*, 2008]. The BC and mineral dust were coincident but of low importance to reduce the albedo of fresh snow (Figure 5a and Table 3). However, in aged snow and granular ice, BC and dust can strongly reduce the albedo (up to 20%) (Figure 5a). These results further suggest that the effect of BC on the albedo reduction exceeds the effect of dust in aged snow and granular ice, while dust seems to be more important in fresh snow (Table 3). In the Himalayas and the central TP, mineral dust was found to be more important than BC [Kaspari *et al.*, 2014; Qu *et al.*, 2014], while in the northern TP, BC plays a more important role for albedo reduction [Y. Li *et al.*, 2016]. For the individual glaciers (Table S7), the changes of BC and dust concentrations exert a significant impact on albedo reduction, as indicated by

Figure 5. Effects of the light-absorbing impurities on (a) albedo and (b) radiative forcing relative to the fresh snow. (The results are grouped by samples of fresh snow, aged snow, and granular ice.)

the weak reduction of albedo due to low LAI concentrations in the Yarlong and Demula glaciers (Figure S3a and Table S7). In addition to the impacts of BC and mineral dust on the albedo reduction, it is also important to note that the different surface snow types have measurable effects, due to the snow grain sizes, densities, and postdepositional processes (shown via the different scenarios in this study in Table 3).

Based on the LAI-induced albedo changes, RF was calculated by equation (1) for the different scenarios (according to Tables S2 and S3). The results show that the instantaneous RFs range from $\sim 2 \text{ W m}^{-2}$ in fresh snow to more than 100 W m^{-2} in aged snow or granular ice (Table 3). For the central scenario of fresh snow (Table 3), the estimated BC forcing ($\sim 2 \text{ W m}^{-2}$) is comparable to what has been estimated for the northern slopes of the Himalayas [Ming *et al.*, 2012] and the Muji glacier in the western TP (2.2 W m^{-2} for fresh snow) [S. Yang *et al.*, 2015] but is somewhat lower than those from the inland and northern TP [Ming *et al.*, 2012; Qu *et al.*, 2014], as well as Tien Shan [Ming *et al.*, 2016]. For the Zuoqiupu glacier, also located in the southeastern TP, the annual mean RF induced by BC in an ice core increased from 0.75 to 1.95 W m^{-2} from 1956 to 2006 [Wang *et al.*, 2015], which coincides with our results. However, radiative transfer modeling constrained by measurements at 5400 m at Mera La (on the southern slope of the Himalayas) indicated that BC concentrations in the winter-spring snow/ice horizons were sufficient to reduce albedo by 6–10%, based on the localized instantaneous RF values of $75\text{--}120 \text{ W m}^{-2}$ [Kaspari *et al.*, 2014], which is consistent with our results for aged snow/granular ice (Table 3).

When impurity concentrations are low, the albedo reduction and RF by dust and BC may be comparable to each other, as shown in fresh snow (Figure 5) or at the Yarlong/Demula glacier (Figure S3 and Table S7). However, due to their low concentrations, the albedo reduction and RF are small (Table 3). For the aged snow/granular ice in our study, the average RF associated with the dust and BC is 76 W m^{-2} and 109 W m^{-2} , respectively. This indicates that the RF effect of BC is considerably greater than that of dust in aged

Table 3. Estimates of Albedo Reductions and Radiative Forcing ($W m^{-2}$) for Different Snow Types at Low, Central and High Scenarios (Identified According to Tables S2 and S3 in the supporting information)^a

Snow Types	Scenarios	SA Pure	SA + Dust	SA + BC	SA + BC and Dust	Dust%	BC%	BC + Dust (%)	RF + Dust	RF + BC	RF + BC and Dust
Fresh snow	Low	0.8380 ± 0.0045	0.8367 ± 0.0046	0.8371 ± 0.0045	0.8358 ± 0.0047	0.16	0.11	0.27	1.47 ± 0.65	1.00 ± 0.12	2.46 ± 0.65
Fresh snow	Central	0.8210 ± 0.0048	0.8184 ± 0.0052	0.8192 ± 0.0049	0.8167 ± 0.0052	0.31	0.22	0.52	2.86 ± 1.27	1.95 ± 0.23	4.78 ± 1.27
Fresh snow	High	0.7673 ± 0.0060	0.7626 ± 0.0067	0.7640 ± 0.0061	0.7594 ± 0.0068	0.61	0.43	1.03	5.37 ± 2.39	3.71 ± 0.43	8.98 ± 2.36
Aged snow	Low	0.8070 ± 0.0064	0.7559 ± 0.0339	0.7192 ± 0.0496	0.7009 ± 0.0550	6.30	10.88	11.91	54.90 ± 33.56	93.20 ± 49.35	106.49 ± 55.67
Aged snow	Central	0.7491 ± 0.0072	0.6900 ± 0.0400	0.6476 ± 0.0573	0.6381 ± 0.0615	7.89	13.54	14.81	66.00 ± 39.43	110.87 ± 56.56	122.38 ± 61.10
Aged snow	High	0.7201 ± 0.0084	0.6450 ± 0.0484	0.5917 ± 0.0662	0.5840 ± 0.0677	10.43	17.83	18.91	85.86 ± 48.41	140.53 ± 66.06	149.82 ± 67.95
Granular ice	Low	0.7573 ± 0.0139	0.6930 ± 0.0434	0.6778 ± 0.0484	0.6492 ± 0.0581	8.49	10.50	14.27	72.12 ± 44.13	87.47 ± 48.28	119.36 ± 59.49
Granular ice	Central	0.7238 ± 0.0133	0.6339 ± 0.0507	0.6103 ± 0.0584	0.5787 ± 0.0637	12.43	15.69	20.05	102.17 ± 54.11	126.50 ± 60.58	162.81 ± 67.24
Granular ice	High	0.6891 ± 0.0140	0.5895 ± 0.0522	0.5605 ± 0.0615	0.5293 ± 0.0635	14.45	18.67	23.19	114.62 ± 56.14	144.17 ± 64.23	180.72 ± 67.57

^aSA pure represents the simulated albedo for the pure snow. SA + Dust represents the simulated albedo with dust in the snow. SA + BC represents the simulated albedo with BC in the snow. BC% and Dust% are the concentrations of BC and dust in the total albedo reduction on the glaciers. RF + BC and RF + Dust represent the radiative forcings caused by BC and dust, respectively.

snow and granular ice scenarios (Figure 5b). However, the instantaneous RF caused by mineral dust on snow can be greater than that generated by BC, as suggested by *Kaspari et al.* [2014] and *Qu et al.* [2014]. At Mera La, mineral dust was shown to reduce the albedo by 40–42%, relative to clean snow, yielding a localized instantaneous RF of 488 to 525 $W m^{-2}$, which is higher than the RF associated with BC (75–120 $W m^{-2}$). In the European Alps, a positive instantaneous RF can result in 153 $W m^{-2}$ for those sampling areas with greater concentrations of dust [*Di Mauro et al.*, 2015].

Modeling studies of the effects of BC and dust on local RFs have been conducted on and around the TP, but because different methods have been used, significant uncertainties exist with regard to how BC and dust affect the RF of snow/ice. BC size, morphology, and coating in snow are the dominant sources of uncertainty in BC's absorption properties for calculations of BC snow albedo climate forcing [*Flanner et al.*, 2007; *Schwarz et al.*, 2013]. BC particles can be internally and externally mixed with other organic aerosol or nonabsorbing materials. BC in different types of mixing states can exhibit significantly different absorption properties, which affects the efficiency of its absorption, as determined by its mass absorption cross section [*Liou et al.*, 2011; *Gustafsson and Ramanathan*, 2016]. For mineral dust, the real role of iron oxides in the dust absorption properties in snow also limits our estimation of absorption [*Zhang et al.*, 2015]. In this study, the optical properties used for BC and dust are from the general sources used in the literature [*Bond and Bergstrom*, 2006; *Flanner et al.*, 2007] and not from a specific source region, which leads to uncertainties in the modeling; the proportion of dust that originated from local, regional, or long-distance sources has not been constrained, and the contribution of dust from natural sources, as opposed to anthropogenic sources, is not well known. Such uncertainties may have caused biases in our estimations of RF. Additional work is needed to focus on BC and dust absorption properties in snow to assess albedo reduction and RF more precisely.

The light-absorbing OC in atmospheric aerosols has various origins, e.g., soil humics, humic-like substances (HULIS), tarry materials from combustion, bioaerosols, etc. [*Andreae and Gelencsér*, 2006]. The chemical and optical properties of OCs may differ due to the nature of the OC sources or atmospheric processing [*Chen and Bond*, 2010]. In contrast to BC and mineral dust, the optical properties of OC have been examined only in a limited way. In this study, we only measured the concentrations of water-insoluble OCs rather than their compositions and light-absorbing properties because of the limitations of the measurements. Due to the lack of reliable OC optical properties able to span the dimensions of snow grain and OC particle size, the SNICAR model currently does not support the calculation of OC-in-snow forcing in the same way as that of BC [*Flanner et al.*, 2007]. Thus, OC radiative forcing is not considered in our study. However, previous studies suggest

that the RF of the OC deposited on the snow can contribute as much as 24% of the forcing caused by BC in snow/ice, as simulated by one model [Lin *et al.*, 2014]. In the southeastern TP, OC could even contribute 27–43% of the corresponding BC effect on snow albedo, as shown in an ice core study that did not consider the variations of the chemical components of OC [Wang *et al.*, 2015]. It is important to note that BC in the atmosphere tends to mix with OC and inorganic salts during its aging, which enhances its absorption [Gustafsson and Ramanathan, 2016]. In the snow, the internal mixing of brown carbon (light-absorbing OC) could contribute 19% of the total absorption, depending on the coating thickness and mixing state [Liu *et al.*, 2015]. When estimating the RF or simulating the glacier melt caused by LAIs in the snow, OC cannot be ignored due to its potentially significant impact on light absorption in the future.

In this study, due to the limitation of field work, we fell to deal with discretely classified anisotropies for the specific glacier surface. Nargeli *et al.* [2015] pointed out that improvements of estimation of glacier surface albedo may be achieved when using a continual changing anisotropy (from forward and backward scattering), which took account material (defined as debris, dirty ice, water, ice, bright ice, and snow)-dependent scattering abundances within pixels of glacier surface. Because the glacier surface-albedo feedback, influenced by the contamination of surface with LAIs, plays a major role in the melting of mountain glaciers in a warming climate, more insight into the processes driving albedo variations in time and space are urgently needed in order to improve models for quantifying future ice melt at the local to global scale [Nargeli *et al.*, 2015, 2017].

3.4. Implications for the Southeastern TP Glaciers

In the Himalayan region, a 2.0–5.2% albedo reduction from BC depositions could result in an 11.6–33.9% increase in the annual discharge, if the snow layer with reduced albedo remains at the surface of the glacier [Yasunari *et al.*, 2010; Gertler *et al.*, 2016]. If the high-impurity layers (for example, the snowpit bottom layer, Figure 4) that formed during the winter-spring period were covered by fresh snowfall during the summer season, the effect of the LAIs on the summer glacier melt would largely be eliminated. Conversely, if the impurities were exposed at the glacier surface during the melt season, glacier melt would accelerate [Kaspari *et al.*, 2014]. This process would further be strengthened if the melt led to the additional exposure of impurities at the glacier surface, or if the melt season were extended due to a warming climate or macroscale atmospheric circulations [Fujita and Nuimura, 2011; W. Yang *et al.*, 2015]. However, it is a challenge to characterize these processes carefully and to subsequently represent them in models to calculate the resulting albedo change and its implications for glacier melt. Moreover, without having a better understanding of the effect of OC and cryoconite (dark accumulations of fine dust, microbiological material, and small rocks on the glacier surface) [e.g., Cook *et al.*, 2016; Takeuchi *et al.*, 2001], the analysis of LAI-induced snowmelt can only provide a lower estimate.

In this study, based on the albedo changes due to LAIs (Table 2), the snowmelt induced by BC and dust for different scenarios is simulated according to the method (Text S1 in the supporting information) used by Schmale *et al.* [2017]. The results suggest that the glacier melt induced by the LAIs was considerable, at approximately 350 mmwe yr⁻¹ relative to aged snow/granular ice for the central scenarios (Table S8). This indicates that an average of approximately 15% of the total glacier melt (glacier mass balance is averaged at ~1100 mmwe yr⁻¹ by Yao *et al.* [2012b] and W. Yang *et al.* [2015], and precipitation is approximately 1000 mmwe [Shi and Liu, 2000]) can be attributed to the LAIs over the glacial area in the southeastern TP. For the fresh snow, this proportion accounts for less than 2%, related to the lower LAI concentrations and albedo reductions. In our result, this represents the effect of LAIs on snowmelt, mostly for those induced by BC and dust in aged snow/granular ice, namely, in the glacier ablation zone.

In several previous studies of the springtime darkening of the Greenland Ice Sheet in 2009, scientists suggested that microorganisms, such as the pigmented algae that reside in snow and ice, can also cause a substantial reduction in albedo [Aoki *et al.*, 2014; Benning *et al.*, 2014; Uetake *et al.*, 2010; Yallop *et al.*, 2012]. The relative importance of biological activity versus inorganic dust and BC in the darkening of glacial surfaces remains an open question [Benning *et al.*, 2014]. This is a challenge for bridging the gap between modeling and observations.

Ramanathan *et al.* [2005] noted that the annual South Asian atmospheric brown clouds consisted of a roughly 3 km thick mixture of anthropogenic sulfate, nitrate, organics, BC dust, and fly ash particles, as

(a) Summer

Time averaged map of Aerosol Optical Depth 550 nm (Dark Target) Monthly 1deg. (MODIS-Terra MOD08_M3 v051) over 2015Jul-2015 Aug, Region 66.4453E, 20.0391N, 105.1172E, 45N

(b) Winter

Time averaged map of Aerosol Optical Depth 550 nm (Dark Target) Monthly 1deg. (MODIS-Terra MOD08_M3 v051) over 2014 Dec-2015 Feb, Region 66.4453E, 20.0391N, 105.1172E, 45N

Figure 6. MODIS atmospheric optical depth (AOD) fields derived using dark target algorithms over the TP and its surroundings. (<http://giovanni.sci.gsfc.nasa.gov>).

well as natural aerosols, such as sea salt and mineral dust. When deposited on glaciers, these aerosols can darken the surface of the glacier and cause accelerated melting, threatening the survival of the Tibetan glaciers [Ramanathan and Carmichael, 2008; Xu *et al.*, 2009a]. Ice core and atmospheric studies on the southeastern TP show high BC and OC concentrations during the nonmonsoon seasons [Wang *et al.*, 2015]. The high BC and OC values in the premonsoon/postmonsoon seasons and in the winter could mainly result from air pollutants transported from South Asia [Kopacz *et al.*, 2011; C. Li *et al.*, 2016]. The Moderate Resolution Imaging Spectroradiometer Aerosol Optical Depth (MODIS AOD) data from summer and winter indicate that the aerosol optical depths in South Asia are much greater than those in other regions, likely due to heavy atmospheric pollutants (Figure 6). However, in the summer, during the Indian monsoon period, the MODIS AOD data show greater depths than in winter; this may explain the seasonal differences in BC and OC depositions on glaciers.

Footprint analyses were also performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis fields with the Lagrangian analysis tool LAGRANTO [Sprenger and Wernli, 2015; Wernli

Figure 7. Footprints of the back trajectories launched over a study glacier (Renlongba) during (a) the monsoon season (June–August 2015) and (b) nonmonsoon season (December 2014 to February 2015). The trajectories starting below 500 hPa were taken into account. Black dots: the air parcel did not pass near a fire during the 96 h prior to arrival at the studied site; Green dots: the air parcel did pass by a fire between -96 h and -48 h, but not afterward; i.e., the “contact” to a fire lies back at least 48 h before the air parcel arrived at Renlongba glacier; Magenta dots: contact with fires occurred between -48 h and 0 h before arriving at site; Red dots: contact with a fire before and after -48 h.

and Davies, 1997]. These were launched every 6 h in the study periods (see Text S1 in the supporting information). The ECMWF fields (horizontal and vertical wind components) were retrieved for 137 model levels and then interpolated onto a $0.25^\circ \times 0.25^\circ$ latitude-longitude grid. The seasonal footprints were derived for the study glaciers from December 2014 to February 2015 and from May 2015 to September 2015 (Figures 7 and S4a). The footprint analysis indicated that the monsoonal air masses originated mainly from South and Central Asia, and western China (including the Taklimakan Desert) (Figure 7a). However,

Figure 8. Contributions of biomass-sourced BC emissions during (a) the monsoon season (June–August 2015) and (b) non-monsoon season (December 2014 to February 2015) for the Renlongba glacier. (A value of 40% at $t = -48$ h, for instance, means that 40% of the trajectories passed a fire spot within the search radius.). The four bars at each time correspond to the neighborhood distances applied in the analysis.

during the nonmonsoon season (Figure 7b), due to the strong westerly pass through, air masses mainly came from the Middle East and South Asia, as noted in a previous study [Wang *et al.*, 2015]; air masses originating from western China were rarer (Figure S4a). The seasonal differences emphasized the importance of source strength changes, which can affect the concentrations of specific impurities in the snow.

Lu *et al.* [2012] and Yang [2016] show, with back trajectory calculations (HYSPLIT model) and WRF-Chem model simulations, that most of the anthropogenic contributions (10–60%) to the atmospheric BC over the southeastern TP originated from South Asia, with higher contributions in the premonsoon season than in the monsoon season. During the monsoon season, the east region of the TP contributed approximately 30% of the BC deposition in the southeast TP [Yang, 2016]. A combined analysis of the $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ fingerprints in the nonmonsoon season also indicated that the biomass-sourced BC, which mainly stemmed from emissions from the Indo-Gangetic Plain (South Asia), plays a quantitatively more important role in TP glaciers [C. Li *et al.*, 2016].

Based on the Fire INventory from NCAR fire emissions inventory [Wiedinmyer *et al.*, 2011] (Text S2 in the supporting information), the contributions from air masses crossing the fire spots and those arriving at the study glaciers are analogous to each other (Figures 8 and S4b). The results from the Renlongba glacier, for example,

indicate that during monsoon season, nonbiomass-burning (e.g., vehicle emission) BC emissions may play a larger role for the Renlongba glacier than other BC deposition, while more than 50% of the BC deposition on glaciers can be influenced by biomass burning (including agricultural waste burning and wildfires) during the nonmonsoon season. Thus, when assessing the impact of LAIs on glacial surface albedos in the southeastern TP, attention needs to be paid to how the seasonal/temporal and spatial factors (e.g., ablation or accumulation zones) can affect simulation results. Extrapolating the impact of the anthropogenic BC emissions, it is likely that the albedo reduction caused by anthropogenic emissions will play an even larger role in the future than it already does in this region. Only stringently eliminating BC emission from contained combustion and severely limiting those from open burning could mitigate the glacier melt in the future, in addition to reducing CO₂ emissions.

4. Conclusions

This study addresses the in situ observations of LAI concentrations in the snow/ice from the southeastern TP over four glaciers. The results show that the average concentrations of dust, BC, and OC in the fresh snow and snowpits are generally lower than those in the surface aged snow/granular ice. The high amounts recorded in the aged snow/granular ice may be related to previous melting that has led to the enrichment of LAIs. Impurity concentrations clearly varied throughout the snowpits. Generally, the maximum dust, BC, and OC concentrations occurred toward the bottom of snowpits, except at the Dongga glacier, which had more melt features, due to its low elevation. The lowest LAI concentrations usually occurred in firn snow and buried (subsurface) old snow samples. More constrained observations are still needed to confirm this phenomenon in the glaciers from the southeastern TP.

The result of the SNICAR model simulation suggests that the albedo reductions caused by BC and dust account for a change of approximately 20% relative to aged snow/granular ice and less than 5% for fresh snow. The RF caused by BC and dust varied between 1.00–140 W m⁻² and 1.47–120 W m⁻² depending on the different scenarios (low, central, and high), respectively. This implies that the effect of BC is considerably larger than that of dust in aged snow and granular ice. While the relative effects of BC and dust on albedo reduction can be relatively well determined with the SNICAR model simulations performed in this work, their absolute magnitudes are subject to uncertainties, owing to the limitations of the modeling of the dust particle size distribution, BC coating and the BC MAC, and the lack of a continual changing anisotropy of glacier surface.

Estimation indicated that the LAIs in the aged snow and granular ice contributed approximately 15% of the total glacier melt, especially in the ablation zone. Based on the discussion of the MODIS AOD and the footprint from the backward trajectories, the LAIs deposited on the southeastern Tibetan glaciers are strongly linked to the South Asian atmospheric brown clouds. The contributions from nonbiomass-sourced BC played a pivotal role for the total BC deposition, especially during the monsoon season. During the nonmonsoon season, biomass burning plays a larger role in the BC deposition in the study area. Reducing the emissions of anthropogenic BC can help mitigate glacier melt in the future in the southeastern TP.

Acknowledgments

This study is supported by National Natural Science Foundation of China (41671067, 41630754, and 41421061), the State Key Laboratory of Cryosphere Science (SKLCS-ZZ-2017), Chinese Academy of Sciences (KJZD-EW-G03-04), and the Foundation for Excellent Youth Scholars of CAREERI (CAS). The authors gratefully acknowledge M. Flanner who gave valuable suggestions on SNICAR model simulations. Thanks to the reviewers for their constructive comments and helpful suggestions on an earlier version of the manuscript. Supporting data are included as tables in the SI file and excel file (Data.xlsx). We also want to acknowledge that the references refer to the supporting information.

References

- Andreae, M. O., and A. Gelencsér (2006), Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols, *Atmos. Chem. Phys.*, 6 (10), 3131–3148, doi:10.5194/acp-6-3131-2006.
- Aoki, T., S. Matoba, S. Yamaguchi, T. Tanikawa, M. Niwano, K. Kuchiki, K. Adachi, J. Uetake, H. Motoyama, and M. Hori (2014), Light-absorbing snow impurity concentrations measured on Northwest Greenland ice sheet in 2011 and 2012, *Bull. Glaciol. Res.*, 32, 21–31, doi:10.5331/bgr.32.21.
- Bahadur, R., P. S. Praveen, Y. Xu, and V. Ramanathan (2012), Solar absorption by elemental and brown carbon determined from spectral observation, *Proc. Natl. Acad. Sci. U.S.A.*, 109(43), 17,366–17,371, doi:10.1073/pnas.1205910109.
- Benning, L. G., A. M. Anesio, S. Lutz, and M. Tranter (2014), Biological impact on Greenland's albedo, *Nature Geosci.*, 7, 691.
- Bond, T. C., and R. W. Bergstrom (2006), Light absorption by carbonaceous particles: An investigative review, *Aerosol Sci. Technol.*, 40(1), 27–67, doi:10.1080/02786820500421521.
- Bond, T. C., et al. (2013), Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos.*, 118, 5380–5552, doi:10.1002/jgrd.50171.
- Cao, J., S. Lee, K. Ho, S. Zou, X. Zhang, and J. Pan (2003), Spatial and seasonal distributions of atmospheric carbonaceous aerosols in Pearl River delta region, China, *China Particul.*, 1 (1), 33–37, doi:10.1016/S1672-2515(07)60097-9.
- Cerqueira, M., C. Pio, M. Legrand, H. Puxbaum, A. Kasper-Giebl, J. Afonso, S. Preunkert, A. Gelencsér, and P. Fialho (2010), Particulate carbon in precipitation at European background sites, *J. Aerosol Sci.*, 41(1), 51–61, doi:10.1016/j.jaerosci.2009.08.002.

- Chakrabarty, R. K., H. Moosmüller, L.-W. A. Chen, K. Lewis, W. P. Arnott, C. Mazzoleni, M. K. Dubey, C. E. Wold, W. M. Hao, and S. M. Kreidenweis (2010), Brown carbon in tar balls from smoldering biomass combustion, *Atmos. Chem. Phys.*, *10*(13), 6363–6370, doi:10.5194/acp-10-6363-2010.
- Chen, Y., and T. Bond (2010), Light absorption by organic carbon from wood combustion, *Atmos. Chem. Phys.*, *10*, 1773–1787.
- Chow, J. C., J. G. Watson, L.-W. A. Chen, W. P. Arnott, H. Moosmüller, and K. Fung (2004), Equivalence of elemental carbon by thermal/optical reflectance and transmittance with different temperature protocols, *Environ. Sci. Technol.*, *38*(16), 4414–4422, doi:10.1021/es034936u.
- Cook, J., A. Edwards, N. Takeuchi, and T. Irvine-Fynn (2016), Cryoconite: The dark biological secret of the cryosphere, *Prog. Phys. Geogr.*, doi:10.1177/0309133315616574.
- Di Mauro, B., F. Fava, L. Ferrero, R. Garzonio, G. Baccolo, B. Delmonte, and R. Colombo (2015), Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV and satellite observations, *J. Geophys. Res. Atmos.*, *120*, 6080–6097, doi:10.1002/2015JD023287.
- Doherty, S. J., T. C. Grenfell, S. Forsström, D. L. Hegg, R. E. Brandt, and S. G. Warren (2013), Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow, *J. Geophys. Res. Atmos.*, *118*, 5553–5569, doi:10.1002/jgrd.50235.
- Dong, Z., and Z. Li (2011), Characteristics of atmospheric dust deposition in snow on glacier no.72 Mount Tuomuer, China, *Arct. Antarct. Alp. Res.*, *43*(4), 517–526.
- Dong, Z., Z. Li, F. Wang, and M. Zhang (2009), Characteristics of atmospheric dust deposition in snow on the glaciers of the eastern Tien Shan, China, *J. Glaciol.*, *55*(193), 797–804.
- Dong, Z., Z. Li, W. Wang, K. Li, and P. Zhou (2013), Characteristics of atmospheric dust deposition in snow on glacier no.4 Mt Bogeda, China, *Environ. Earth Sci.*, *70*, 1423–1433, doi:10.1007/s12665-013-3228-z.
- Dong, Z., D. Qin, S. Kang, J. Ren, J. Chen, X. Cui, Z. Du, and X. Qin (2014), Physiochemical characteristics and sources of atmospheric dust deposition in snow packs on the glaciers of western Qilian Mountains, China, *Tellus-B*, *66*, 20956, doi:10.3402/tellusb.v66.20956.
- Dong, Z., D. Qin, S. Kang, Y. Liu, Y. Li, J. Huang, and X. Qin (2016), Individual particles of cryoconite deposited on the mountain glaciers of the TP: Insights into chemical composition and sources, *Atmos. Environ.*, *138*, 114–124, doi:10.1016/j.atmosenv.2016.05.020.
- Dumont, M., E. Brun, G. Picard, M. Michou, Q. Libios, J.-R. Petit, M. Geyer, S. Morin, and B. Josse (2014), Contribution of light-absorbing impurities in snow to Greenland's darkening since 2009, *Nature Geosci.*, *7*, 509–512, doi:10.1038/NGEO2180.
- Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch (2007), Present-day climate forcing and response from black carbon in snow, *J. Geophys. Res.*, *112*, D11202, doi:10.1029/2006JD008003.
- Fujita, K., and T. Nuimura (2011), Spatially heterogeneous wastage of Himalayan glaciers, *Proc. Natl. Acad. Sci. U.S.A.*, *108*(34), 14,011–14,014, doi:10.1073/pnas.1106242108.
- Gertler, C. G., S. P. Puppala, A. Panday, D. Stumm, and J. Shea (2016), Black carbon and the Himalayan cryosphere: A review, *Atmos. Environ.*, *125*, 404–417, doi:10.1016/j.atmosenv.2015.08.078.
- Gustafsson, Ö., and V. Ramanathan (2016), Convergence on climate warming by black carbon, *Proc. Natl. Acad. Sci. U.S.A.*, doi:10.1073/pnas.1603570113.
- Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens (2010), Climate change will affect the Asian water towers, *Science*, *328* (5984), 1382–1385, doi:10.1126/science.1183188.
- Ji, Z., S. Kang, Z. Cong, Q. Zhang, and T. Yao (2015), Simulation of carbonaceous aerosols over the Third Pole and adjacent regions: Distribution, transportation, deposition, and climatic effects, *Clim. Dyn.*, doi:10.1007/s00382-015-2509-1.
- Judson, A., and N. Doesken (2000), Density of freshly fallen snow in the central Rocky Mountains, *Bull. Am. Meteorol. Soc.*, *81*(7), 1577–1587.
- Kang, S., Q. Zhang, S. Kaspari, D. Qin, Z. Cong, J. Ren, and P. A. Mayewski (2007), Spatial and seasonal variations of elemental composition in Mt. Everest (Qomolangma) snow/firn, *Atmos. Environ.*, *41*(34), 7208–7218, doi:10.1016/j.atmosenv.2007.05.024.
- Kaspari, S., T. H. Painter, M. Gysel, S. M. Skiles, and M. Schwikowski (2014), Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings, *Atmos. Chem. Phys.*, *14*(15), 8089–8103, doi:10.5194/acp-14-8089-2014.
- Kopacz, M., D. L. Mauzerall, J. Wang, E. M. Leibensperger, D. K. Henze, and K. Singh (2011), Origin and radiative forcing of black carbon transported to the Himalayas and TP, *Atmos. Chem. Phys.*, *11*, 2837–2852, doi:10.5194/acp-11-2837-2011.
- Lau, W. K. M., M.-K. Kim, K.-M. Kim, and W.-S. Lee (2010), Enhanced surface warming and accelerated snow melt in the Himalayas and TP induced by absorbing aerosols, *Environ. Res. Lett.*, *5*, doi:10.1088/1748-9326/5/2/025204.
- Li, C., C. Bosch, S. Kang, A. Andersson, P. Chen, Q. Zhang, Z. Cong, B. Chen, D. Qin, and Ö. Gustafsson (2016), Sources of black carbon to the Himalayan-TP glaciers, *Nat. Commun.*, *7*, 12574, doi:10.1038/ncomms12574.
- Li, X., et al. (2017), Light-absorbing impurities accelerate glacier melt in the central Tibetan plateau, *Sci. Total Environ.*, doi:10.1016/j.scitotenv.2017.02.169.
- Li, Y., et al. (2016), Impacts of black carbon and mineral dust on radiative forcing and glacier melting during summer in the Qilian Mountains, northeastern TP, *Cryosphere Discuss.*, doi:10.5194/tcd-2016-32.
- Lim, S., X. Fain, M. Zanatta, J. Cozic, J.-L. Jaffrezo, P. Ginot, and P. Laj (2014), Refractory black carbon mass concentrations in snow and ice: Method evaluation and inter-comparison with elemental carbon measurement, *Atmos. Meas. Tech.*, *7*, 3307–3324, doi:10.5194/amt-7-3307-2014.
- Lin, G., J. E. Penner, M. G. Flanner, S. Sillman, L. Xu, and C. Zhou (2014), Radiative forcing of organic aerosol in the atmosphere and on snow: Effects of SOA and brown carbon, *J. Geophys. Res. Atmos.*, *119*, 7453–7476, doi:10.1002/2013JD021186.
- Liou, K. N., Y. Takano, and P. Yang (2011), Light absorption and scattering by aggregates: Application to black carbon and snow grains, *J. Quant. Spectrosc. Radiat. Transfer*, *112*, 1581–1594.
- Liu, S., et al. (2015), Enhanced light absorption by mixed source black and brown carbon particles in UK winter, *Nat. Commun.*, *6*, doi:10.1038/ncomms9435.
- Lu, Z., D. G. Streets, Q. Zhang, and S. Wang (2012), A novel back-trajectory analysis of the origin of black carbon transported to the Himalayas and TP during 1996–2010, *Geophys. Res. Lett.*, *39*, L01809, doi:10.1029/2011GL049903.
- Ming, J., H. Cachier, C. Xiao, D. Qin, S. Kang, and J. Xu (2008), Black carbon record based on a shallow Himalayan ice core and its climatic implications, *Atmos. Chem. Phys.*, *8*, 1343–1352, doi:10.5194/acp-8-1343-2008.
- Ming, J., C. Xiao, H. Cachier, D. Qin, X. Qin, Z. Li, and J. Pu (2009), Black carbon (BC) in the snow of glaciers in west China and its potential effects on albedos, *Atmos. Res.*, *92*(1), 114–123, doi:10.1016/j.atmosres.2008.09.007.
- Ming, J., C. Xiao, Z. Du, and X. Yang (2012), An overview of black carbon deposition in high Asia glaciers and its impacts on radiation balance, *Adv. Water Resour.*, doi:10.1016/j.advwat.2012.05.015.
- Ming, J., C. Xiao, F. Wang, Z. Li, and Y. Li (2016), Grey Tienshan Urumqi glacier no.1 and light-absorbing impurities, *Environ. Sci. Poll. Res.*, doi:10.1007/s11356-016-6182-7.

- Moosmüller, H., R. K. Chakrabarty, K. M. Ehlers, and W. P. Arnott (2011), Absorption Ångström coefficient, brown carbon, and aerosols: Basic concepts, bulk matter, and spherical particles, *Atmos. Chem. Phys.*, *11*(3), 1217–1225, doi:10.5194/acp-11-1217-2011.
- Nargeli, K., A. Damm, M. Huss, M. Schaepman, and M. Hoelzle (2015), Imaging spectroscopy to assess the composition of ice surface materials and their impact on glacier mass balance, *Remote Sens. Environ.*, *168*, 388–402.
- Nargeli, K., A. Damm, M. Huss, M. Schaepman, and M. Hoelzle (2017), Cross-comparison of albedo products for glacier surface derived from airborne and satellite (Sentinel-2 and Landsat 8) optical data, *Remote Sens.*, *9*(110), doi:10.3390/rs9020110.
- Painter, T. H., B. Duval, W. H. Thomas, M. Mendez, S. Heintzelman, and J. Dozier (2001), Detection and quantification of snow algae with an airborne imaging spectrometer, *Appl. Environ. Microb.*, *67*(11), 5267–5272, doi:10.1128/AEM.67.11.5267-5272.2001.
- Qian, Y., T. J. Yasunari, S. J. Doherty, M. G. Flanner, W. K. M. Lau, J. Ming, H. Wang, M. Wang, S. G. Warren, and R. Zhang (2015), Light-absorbing particles in snow and ice: Measurement and modeling of climatic and hydrological impact, *Adv. Atmos. Sci.*, *32*(1), 64–91, doi:10.1007/s00376-014-0010-0.
- Qu, B., J. Ming, S. Kang, G. Zhang, Y. Li, C. Li, S. Zhao, Z. Ji, and J. Cao (2014), The decreasing albedo of the Zhadang glacier on western Nyainqentanglha and the role of light-absorbing impurities, *Atmos. Chem. Phys.*, *14*(20), 11,117–11,128, doi:10.5194/acp-14-11117-2014.
- Ramanathan, V., and G. Carmichael (2008), Global and regional climate changes due to black carbon, *Nat. Geosci.*, *1*(4), 221–227, doi:10.1038/ngeo156.
- Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild (2005), Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, *Proc. Natl. Acad. Sci. U.S.A.*, *102*(15), 5326–5333, doi:10.1073/pnas.0500656102.
- Ruppel, M. M., I. Isaksson, J. Ström, E. Beaudon, J. Svensson, C. A. Pedersen, and A. Korhola (2014), Increase in elemental carbon values between 1970 and 2004 observed in a 300-year ice core from Holtedahlfonna (Svalbard), *Atmos. Chem. Phys.*, *14*, 11,447–11,460, doi:10.5194/acp-14-11447-2014.
- Schmale, J. M., G. Flanner, S. Kang, M. Sprenger, Q. Zhang, J. Guo, Y. Li, M. Schwikowski, and D. Farinotti (2017), Central Asian anthropogenic black carbon outweighs other impurities in driving regional snow melt, *Sci. Rep.*, *7*, 40501, doi:10.1038/srep40501.
- Schwarz, J. P., R. S. Gao, A. E. Perring, J. R. Spackman, and D. W. Fahey (2013), Black carbon aerosol size in snow, *Sci. Rep.*, *3*, 1356, doi:10.1038/srep01356.
- Schwarz, J. P., S. J. Doherty, S. T. Ruggiero, C. E. Tanner, A. E. Perring, R. S. Gao, and D. W. Fahey (2012), Assessing single particle soot photometer and integrating sphere/integrating sandwich spectrophotometer measurement techniques for quantifying black carbon concentrations in snow, *Atmos. Meas. Tech.*, *5*, 2581–2592, doi:10.5194/amt-5-2581-2012.
- Shi, Y. (2008), *Concise Glacier Inventory of China*, pp. 1–194, Shanghai Popular Science Press, Shanghai.
- Shi, Y., and S. Liu (2000), Estimation on the response of glaciers in China to the global warming in the 21st century, *Chin. Sci. Bull.*, *45*(7), 668–672.
- Sjögren, B., O. Brandt, C. Nuth, E. Isaksson, V. Pohjola, J. Kohler, R. S. W. Van de Wal (2007), Instruments and methods determination of firm density in ice cores using image analysis, *J. Glaciol.*, *53*(182), 413–419, doi:10.3189/002214307783258369.
- Sprenger, M., and H. Wernli (2015), The LAGRANTO Lagrangian analysis tool—Version 2.0, *Geosci. Model Dev.*, *8*, 2569–2586, doi:10.5194/gmd-8-2569-2015.
- Takeuchi, N., J. Uetake, K. Fujita, V. B. Aizen, and S. D. Nikitin (2006), A snow algal community on Akkem glacier in the Russian Altai mountains, *Ann. Glaciol.*, *43*, 378–384, doi:10.3189/172756406781812113.
- Takeuchi, N., S. Kohshima, and K. Seko (2001), Structure, formation, darkening process of albedo reducing material (cryoconite) on a Himalayan glacier: A granular algal mat growing on the glacier, *Arct. Antarct. Alp. Res.*, *33*, 115–122.
- Takeuchi, N., Y. Fujisawa, T. Kadota, S. Tanaka, M. Miyairi, T. Shirakawa, R. Kusaka, A. N. Fedorov, P. Konstantinov, and T. Ohata (2015), The effect of impurities on the surface melt of a glacier in the Suntar-Khayata Mountain range, Russian Siberia, *Front. Earth Sci.*, *3*, 82, doi:10.3389/feart.2015.00082.
- Thevenon, F., F. S. Anselmetti, S. M. Barnasconi, and M. Schwikowski (2009), Mineral dust and elemental carbon records from an Alpine ice core (Colle Gnifetti glacier) over the last millennium, *J. Geophys. Res.*, *114*, D17102, doi:10.1029/2008JD011490.
- Uetake, J., T. Naganuma, M. B. Hebsgaard, H. Kanda, and S. Kohshima (2010), Communities of algae and cyanobacteria on glaciers in west Greenland, *Polar Sci.*, *4*, 71–80.
- Wake, C., and P. A. Mayewski (1994), Modern eolian dust deposition in central Asia, *Tellus* *46B*, 220–223.
- Wang, N., L. G. Thompson, and M. E. Davis (2006), Variations of atmospheric dust loading in the southern and northern Tibetan plateau over the last millennium recorded in ice cores, *Quat. Res.*, *26*(5), 752–761.
- Wang, M., B. Xu, H. Zhao, J. Cao, D. Joswiak, G. Wu, and S. Lin (2012), The influence of dust on quantitative measurements of black carbon in ice and snow when using a thermal optical method, *Aerosol Sci. Technol.*, *46*, 60–69.
- Wang, M., et al. (2015), Carbonaceous aerosols recorded in a southeastern Tibetan glacier: Analysis of temporal variations and model estimates of sources and radiative forcing, *Atmos. Chem. Phys.*, *15* (3), 1191–1204, doi:10.5194/acp-15-1191-2015.
- Wang, X., S. J. Doherty, and J. Huang (2013), Black carbon and other light-absorbing impurities in snow across northern China, *J. Geophys. Res. Atmos.*, *118*, 1471–1492, doi:10.1029/2012JD018291.
- Wernli, H., and H. C. Davies (1997), A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications, *Quart. J. Roy. Meteor. Soc.*, *123*, 467–489.
- Wiedinmyer, C., S. K. Akagi, R. J. Yokelson, L. K. Emmons, J. A. Al-Saadi, J. J. Orlamdo, and A. J. Soja (2011), The fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning, *Geosci. Model Dev.*, *4*, 625–641, doi:10.5194/gmd-4-625-2011.
- Wild, M. (2012), Enlightening global dimming and brightening, *Bull. Am. Meteorol. Soc.*, *93*(1), 27–37, doi:10.1175/BAMS-D-11-00074.1.
- Xu, B., et al. (2009a), Black soot and the survival of Tibetan glaciers, *Proc. Natl. Acad. Sci. U.S.A.*, *106*(52), 22,114–22,118, doi:10.1073/pnas.0910444106.
- Xu, B., M. Wang, D. R. Joswiak, J. Cao, T. Yao, G. Wu, W. Yang, and H. Zhao (2009b), Deposition of anthropogenic aerosols in a southeastern Tibetan glacier, *J. Geophys. Res.*, *114*, D17209, doi:10.1029/2008JD011510.
- Xu, B., J. Cao, D. R. Joswiak, X. Liu, H. Zhao, and J. He (2012), Post-depositional enrichment of black soot in snow-pack and accelerated melting of Tibetan glaciers, *Environ. Res. Lett.*, *7*, 014022, doi:10.1088/1748-9326/7/1/014022.
- Xu, Y., V. Ramanathan, and W. M. Washington (2016), Observed high-altitude warming and snow cover retreat over Tibet and the Himalayas enhanced by black carbon aerosols, *Atmos. Chem. Phys.*, *16*, 1303–1315, doi:10.5194/acp-16-1303-2016.
- Yallop, M. L., et al. (2012), Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet, *ISME J.*, *6*, 2302–2313, doi:10.1038/ismej.2012.107.
- Yanai, M., and G. Wu (2006), Effects of the TP, in *The Asian Monsoon*, edited by B. Wang, pp. 513–549, Springer, Berlin.

- Yang, J. (2016), Modeling atmospheric aerosols' distribution, source, and radiation effect over the TP, University of Chinese Academy of Sciences, Diss. pp. 1–125.
- Yang, S., B. Xu, J. Cao, C. S. Zender, and M. Wang (2015), Climate effect of black carbon aerosol in a TP glacier, *Atmos. Environ.*, *111*, 71–78, doi:10.1016/j.atmosenv.2015.03.016.
- Yang, W., T. D. Yao, B. Q. Xu, L. L. Ma, Z. H. Wang, and M. Wan (2010), Characteristics of recent temperate glacier fluctuations in the Parlung Zangbo River basin, southeast Tibetan plateau, *Chin. Sci. Bull.*, *55*(20), 2097–2102, doi:10.1007/s11434-010-3214-4.
- Yang, W., X. Guo, T. Yao, M. Zhu, and Y. Wang (2015), Recent accelerating mass loss of southeast Tibetan glaciers and the relationship with changes in macroscale atmospheric circulations, *Clim. Dyn.*, *1–11*, doi:10.1007/s00382-015-2872-y.
- Yao, T., et al. (2012a), Different glacier status with circulations in TP and surroundings, *Nature Clim. Change*, doi:10.1038/NCLIMATE1580.
- Yao, T., et al. (2012b), Third Pole environment (TPE), *Environ. Development*, *3*, 52–64, doi:10.1016/j.envdev.2012.04.002.
- Yasunari, T., P. Bonasoni, P. Laj, K. Fujita, E. Vuillermoz, A. Marinoni, P. Cristofanelli, R. Duchi, G. Tartari, and K.-M. Lau (2010), Estimated impact of black carbon deposition during pre-monsoon season from Nepal climate observatory—Pyramid data and snow albedo changes over Himalayan glaciers, *Atmos. Chem. Phys.*, *10*(14), 6603–6615, doi:10.5194/acp-10-6603-2010.
- Zhang, X., G. Wu, C. Zhang, T. Xu, and Q. Zhou (2015), What is the real role of iron oxides in the optical properties of dust aerosols?, *Atmos. Chem. Phys.*, *15*, 12,159–12,177, doi:10.5194/acp-15-12159-2015.
- Zhang, Y., et al. (2016), Chemical records in snowpits from high altitude glaciers in the TP and its surroundings, *PLoS One*, *11*(5), e0155232, doi:10.1371/journal.pone.0155232.