Quantifying light absorption and its source attribution of insoluble light-absorbing particles in Tibetan Plateau glaciers from 2013-2015

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Abstract. Amounts of insoluble light-absorbing particles (ILAPs) deposited on the surface of snow and ice can significantly reduce the snow albedo and accelerate the snow melting process. In this study, 67 ice samples were collected in seven glaciers over the Tibetan Plateau (TP) from May 2013 to October 2015. The mixing ratio of black carbon (BC),

- 5 organic carbon (OC), and mineral dust (MD) was measured using an integrating sphere/integrating sandwich spectrophotometer (ISSW) system associated with the chemical analysis by assuming that the light absorption of mineral dust is due to iron oxide. The results indicated that the mass mixing ratios of BC, OC, and MD showed a large variation of 10-3100 ng g⁻¹, 10-17000 ng g⁻¹, 10-3500 ng g⁻¹, with mean values of 220 ± 400
- 10 ng g⁻¹, 1360±2420 ng g⁻¹, 240±450 ng g⁻¹ on TP glaciers during the entire ice field campaign, respectively. Although the mineral dust was assumed to be the highest contributor to the mass loading of ILAPs, we noted that the averaged light absorption of BC (50.7%) and OC (33.2%) was largely responsible for the measured light absorption in the TP glaciers at the wavelengths of 450-600 nm. The chemical elements and the selected
- 15 carbonaceous particles were also analyzed for the source attributions of the particulate light absorption based on a positive matrix factorization (PMF) receptor model. On average, the industrial pollution (33.1%), biomass/biofuel burning (29.4%), and mineral dust (37.5%) were the major sources of the ILAPs in TP glaciers.

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1 Introduction

Ample evidence indicated that the snow albedo at visible wavelengths is largely dominant by black carbon (BC) (Warren and Wiscombe, 1980, 1985; Brandt et al., 2011; Hadley and Kirchstetter, 2012). For instance, a mixing ratio of 10 ng g⁻¹ of BC in snow can reduce

- 5 snow albedo by 1%, which has a similar effect to that of 500 ng g⁻¹ of dust at 500 nm (Warren and Wiscombe, 1980; Warren, 1982; Wang et al., 2017). Chylek et al. (1984) indicated that the absorbing efficiency of BC is higher in snow than in the atmosphere due to more sunlight scattering in snow. Conway et al. (1996) measured a snow albedo reduction of 0.21 and a 50% increase in the ablation rate of natural snow attributed to 500
- 10 ng g⁻¹ BC contamination. Liou et al. (2011) developed a geometric-optics surface-wave approach to demonstrate the snow albedo reduction by as much as \sim 5–10% due to small amounts of BC internally mixed with snow grains. Totally, BC accounts for 85% of absorption by all insoluble light-absorbing impurities (ILAPs) in snow at the wavelength of 400-700 nm (Bond et al., 2013). Due to the impact of BC on snow and ice albedos, the
- 15 "efficacy" of this BC-snow forcing is twice as effective as CO₂, and may have contributed to global warming of the past century in the Northern Hemisphere (Hansen and Nazarenko, 2004).

The Tibetan Plateau (TP), known as the highest plateau in the world and its surrounding areas, contains the largest store of snow and ice outside the polar regions (Qin et al., 2006).

- 20 However, ~82% of the plateau's glaciers have retreated, and 10% of its permafrost has degraded in the past decade (Qiu, 2008; Yao et al., 2012). Xu et al. (2009a, b) indicated that the BC deposited in snow and ice potentially lead the melting seasons earlier, and the large retreat of these glaciers across the TP regions may affect the atmospheric circulation and ecosystem at regional and global scales in multiple ways (Qian et al., 2011; Skiles et
- al., 2012; Sand et al., 2013). Therefore, the BC content is considered one of the major absorbers to lead great decrease in length and area of TP glaciers (Xu et al., 2006, 2009a; Qian et al., 2015; Li et al., 2016).

In addition to BC, organic carbon (OC) and mineral dust (MD) recognized as the other types of ILAPs that substantially contribute to springtime snowmelt and surface warming through the group derivating effects (Painter et al. 2010, 2012; Huang et al. 2011; Kagneri

30 through the snow darkening effects (Painter et al., 2010, 2012; Huang et al., 2011; Kaspari

et al., 2014; Wang et al., 2013, 2014; Yasunari et al., 2015). However, the optical properties of OC in snow are still absent due to limited small-scale field campaigns and technical limitations. For instance, the OC concentrations extracted at Antarctic sites are unexpectedly higher ranging from 80 to 360 ng g⁻¹ than those reported for Greenland (10–

- 5 40 ng g⁻¹) and Alpine (45–98 ng g⁻¹) for pre-industrial ice (Federer et al., 2008; Preunkert et al., 2011). Furthermore, there are still significant uncertainties in estimating the light absorption by different types of OC associated with both the chemical and optical analyses from snow samples across western North America (Dang et al., 2014). Although the contribution of OC to the global warming is generally lower than BC, but still significant
- 10 mainly over southeastern Siberia, northeastern East Asia, and western Canada (Yasunari et al., 2015). As summarized by Flanner et al. (2009), consideration of OC in snow is a key approach for better estimating the climate effects in global models due to the absorption of solar radiation by other ILAPs from the ultraviolet to visible wavelengths. It is well known that the light absorption capacity of MD mainly depends on the iron oxides
- 15 (hereafter referred to Fe) (Alfaro et al., 2004; Lafon et al., 2004, 2006; Moosmuller et al., 2012). Fe (primarily hematite and goethite) imparted a yellow-red color is a major component, which affects the ability of mineral dust to absorb sunlight at short wavelengths, then alters the dust's radiative properties and may influence the climate (Takahashi et al., 2011; Jeong et al., 2012; Zhou et al., 2017). Cong et al. (2018) indicated that the goethite
- 20 was predominant form of Fe (81% to 98 % in mass fraction) among the glaciers in the TP regions. Painter et al. (2007) pointed out that snow cover duration in a seasonally snow-covered mountain was shortened by 18 to 35 days due to the deposition of disturbed desert dust. Wang et al. (2013) revealed that the light absorption was major dominated by OC across the grassland of Inner Mongolia across northern China, while the snow particulate
- 25 light absorption was mainly contributed by local soil and desert dust at the northern boundary of the TP regions.

Due to the importance of the climate effects by ILAPs, numerous snow surveys have been conducted to investigate the light absorption of ILAPs (Xu et al., 2009a, b; Doherty et al., 2010; Huang et a., 2011; Wang et al., 2013; Dang et al., 2014), and their potential source

attribution in snow and ice (Hegg et al., 2010; Zhang et al., 2013a; Doherty et al., 2014

Jenkins et al., 2016; Li et al., 2016; Pu et al., 2017). Hegg et al. (2009) indicated that the light absorption by ILAPs in Arctic snow is mainly originated from biomass burning, pollution, and marine sources based on a positive matrix factorization (PMF) receptor model. Doherty et al. (2014) found that the source attribution of particulate light absorption

- in seasonal snow is dominated by biomass/biofuel burning, soil dust, and fossil fuel pollution based on the chemical and optical data from 67 North American sites.
 Up to now, the light absorption and emission sources of ILAPs remain poorly understand.
 Increasing the in-situ measurements of ILAPs in snow and ice is the most urgent task to explore the glacier retreat, especially in the TP regions. Here, we performed a large survey
- 10 on collecting column ice samples on seven glaciers in the TP regions during the monsoon and non-monsoon seasons from 2013-2015. By using an integrating sphere/integrating sandwich spectrophotometer (ISSW) system associated with the chemical analysis, the particulate light absorption by BC, OC, and MD in TP glaciers was evaluated. Finally, the relative contributions of their emission sources in these glaciers was explored based on a
- 15 PMF receptor model.

2 Site description and methods

2.1 Site description and sample collection

According to the second Chinese glacier inventory dataset, Fig. 1 exhibits the topographical maps in each glacier associated with the sampling locations (Liu et al., 2014). Fig. S1 shows the pictures of the sampling locations in all seven glaciers, and all these glaciers are arranged from north to south according to their latitude and longitude in this study. Basically, the sampling locations are selected to be at least 50 km apart from the main road and the cities to minimize the effects of local sources. ~67 column ice samples were gathered during monsoon and non-monsoon seasons along a south-north transect over the

25 TP regions from 2013-2015. It is worth noting that the seven glaciers can represent different climate and land surface types gradually from the dry area to wet area along the northern to the southern over the TP regions.

Samples 1 to 19 were collected from 2013 to 2015 during the monsoon season in the center of the Qiyi glacier (QY, 39°14' N, 97°45' E) (Fig. 1a). The QY glacier is a small valley

30 glacier, with the area of 2.98 km² and the length of 3.8 km. It is located in the Qilian

Mountains on the north border of the TP regions. This glacier is recognized as a typical "wet island" in arid region due to its multi-land types (e.g. forests, bushes, steppes and meadows).

Samples 20 to 22 were collected during the non-monsoon season in the southeast

5 Qiumianleiketage glacier (QM, 36°70' N, 90°73' E), which is originated from the Kunlun Mountains of the Qinghai-Tibet Plateau (Fig. 1b). The length of the QM glacier is 2.6 km, and the area is 1.73 km².

Samples 23-32 were collected in the northern Meikuang glacier during both monsoon and non-monsoon season (MK, 35°42' N, 94°12' E). The MK glacier is located in the eastern

10 Kunlun Mountains, where is characterized by alluvial deposits and sand dunes. The MK glacier is 1.8 km in length with an area of 1.1 km² (Fig. 1c). As shown in Fig. 1d, samples 33-44 were collected in the southwest Yuzhufeng glacier (YZF, 35°38' N, 94°13' E). The YZF glacier is adjacent to MK glacier with the highest peak of 6178 m across the eastern Kunlun Mountains at the northern margin of the TP

- regions. The glacier is surrounded by a small quantity of ferns, forests and some bushes due to the high altitude as well as the cold and arid climate.
 Samples 45-49 were collected in the center of Hariqin glacier (HRQ, 33°14' N, 92°09' E), which is located at the headwaters of the Dongkemadi river on the northern slope of the Tanggula Mountains in the central region of the Qinghai-Tibetan Plateau (Fig. 1e). The
- 20 HRQ glacier face north, with a mountain peak of 5820 m a.s.l. to its terminus of 5400 m a.s.l.

Samples 50-60 were collected in the southern Xiaodongkemadi glacier (XD, 33°04' N, 92°04' E). The XD glacier is adjacent to HRQ glacier, with an area of 1.767 km² and 2.8 km in length (Fig. 1f). The elevations of the glacier from the peak to its terminus are 5900

and 5500 m a.s.l., respectively. It has a cold steppe landscape mainly surrounded by tundra.
 Samples 61-67 were collected in the eastern Gurenhekou glacier (GR, 30°19' N, 90°46' E).
 The GR glacier is relatively small and cold alpine-type valley glacier in the central part of the southern TP, which is seated about 90 km northwest of Lhasa, the capital city of Tibet (Fig. 1g). The glacier area is 1.4 km², with a length and width of 2.5 km and 0.6 km, and

30 the elevation is in the range of 5600 and 6000 m a.s.l. Kang et al. (2009) and Bolch et al.

(2010) indicated that the Gurenhekou glacier is mainly influenced by both the continental climate of central Asia and the Indian monsoon system.

Wang et al. (2015) pointed out that the annual accumulation of snow/ice at the drilling site over the TP glaciers was around 2 m on average. Therefore, a 1.2-m pure clean plastic bag

- 5 with a diameter of 20 cm was put into a vertical tube to collect the ice samples via wet and dry deposition during monsoon and non-monsoon seasons in each sample location from 2013 to 2015 (Fig. 2). Due to the high altitudes of these glaciers, the wet deposition in these areas were predominant by new fallen snow, while much less formed by precipitation. However, most of the samples were gathered by column ice due to the multi-melting
- 10 processes. Then, the column ice samples were kept frozen under -20 °C and transported to laboratory facilities at the State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute in Lanzhou. Firstly, each sample was cut vertically into four pieces from the top to the bottom as shown in Fig. S2, and only one of the vertical samples was cut at 10 cm resolution following clean protocols,
- 15 resulting in a total of 189 samples used in this study. It should be noted that if there is a significant dirty layer inside, then, this layer will be cut and analyzed separately. Another key issue is that some of the ice samples in the top layer is not uniform due to the multi-melting processes. Therefore, several samples were cut longer or shorter than the other samples (e.g. sites 13 and 26). To minimize the losses of ILAPs to the container walls, each sample was put into a clean glass beaker and melted quickly in a microwave oven. The
- melted water then immediately filtered through Nuclepore filters with a pore size of 0.2- μ m, as were used by Doherty et al. (2010). Further details for filtrate processing can be found in Wang et al. (2013) and Doherty et al. (2014).

2.2 **Optical analysis**

An updated integrating sphere/integrating sandwich spectrophotometer (ISSW) was used to calculate the mass mixing ratio of BC in the ice samples, which is similar with the instrument developed by Grenfell et al. (2011). Compared with the ISSW spectrophotometer developed by Grenfell et al. (2011), the major difference is that we used two integrating spheres instead of the integrating sandwich diffuser to reduce the diffuse radiation during the measuring process. This ISSW spectrophotometer measures the light attenuation spectrum from 400 to 700 nm. The total light attenuation spectrum is extended over the full spectral range by linear extrapolation from 400 to 300 and from 700 to 750 nm. Light attenuation is nominally only sensitive to ILAPs on the filter because of the diffuse radiation field and the sandwich structure of two integrated spheres in the ISSW

5 (Doherty et al., 2014). Briefly, the transmitted light detected by the system for an ice sample, S(λ), is compared with the signal detected for a blank filter, S₀(λ), and the relative attenuation (Atn) is expressed as:

$$Atn=ln[S_0(\lambda)/S(\lambda)]$$
(1)

The MACs and the absorption Ångström exponents (Å) for BC, OC, and Fe used in this

- 10 study could be found in Wang et al. (2013). By using this technique, we can estimate the following parameters included equivalent BC (C_{BC}^{equiv}), maximum BC (C_{BC}^{max}), estimated BC (C_{BC}^{est}), fraction of light absorption by non-BC ILAPs (f_{non-BC}^{est}), the absorption Ångström exponent of non-BC ILAPs (\hat{A}_{non-BC}) and the total absorption Ångström exponent (\hat{A}_{tot}). These parameters are defined as follows:
- 15 1. C_{BC}^{max} (ng g⁻¹): maximum BC is the maximum possible BC mixing ratio in snow by assuming that all light absorption is due to BC at the wavelengths of 650-700 nm.

2. C_{BC}^{est} (ng g⁻¹): *estimated BC* is the estimated true mass of BC in snow derived by separating the spectrally resolved total light absorption and non-BC fractions.

3. C_{BC}^{equiv} (ng g⁻¹): *equivalent BC* is the amount of BC that would be needed to produce absorption of solar energy by all insoluble particles in snow for the wavelength-integrated from 300-750 nm.

4. $Å_{tot}$: *absorption Ångström exponent* is calculated for all insoluble particles deposited on the filter between 450 and 600 nm.

5. $Å_{non-BC}$: non-BC absorption Ångström exponent is derived from the light absorption by non-BC components of the insoluble particles in snow between 450-600 nm.

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6. f_{non-BC}^{est} (%): fraction of light absorption by non-BC light absorbing particles is the integrated absorption due to non-BC light absorbing particles, which is weighted by the down-welling solar flux at the wavelengths of 300-750 nm.

It is well known that the aerosol composition and the size distribution are key parameters that affect the absorption Ångström exponent. Doherty et al. (2010) reported that the value of the absorption Ångström exponent of OC was close to 5, which is consistent with previous studies with values ranging from 4-6 (Kirchstetter et al., 2004). Several studies indicated that the absorption Ångström exponent of mineral dust ranged from 2 to 5 (Fialho et al., 2005; Lafon et al., 2006; Zhou et al., 2017; Cong et al., 2018). The variation of the

- absorption Ångström exponents for urban and industrial fossil fuel emissions is typically in the range of 1.0-1.5 (Millikan, 1961; Bergstrom et al., 2007), which is slightly lower than that of biomass burning aerosols, which primarily falls in the range of 1.5-2.5 (Kirchstetter et al., 2004; Bergstrom et al., 2007). In this study, we noted that the absorption Ångström exponent ($Å_{tot}$) is due to the mix state of BC and non-BC impurities on the filters,
- and the calculations of A_{tot} and A_{non-BC} could be found in the study of Doherty et al. (2014). The A_{non-BC} is calculated as a linear combination of contributions to light absorption due to OC and Fe, and the equation is listed as follows:

 $A_{non-BC} = F_{OC} \times A_{OC} + F_{Fe} \times A_{Fe}$

2.3 Chemical analysis

- The major metallic elements (Al, Cr, Mn, Fe, Ni, Cu, Zn, Cd, Pb) were analyzed by an inductively coupled plasma-mass spectrometry (ICP-MS, X-7 Thermo Elemental) at the Institute of Tibetan Plateau Research in Beijing. The detection limits are Al, 0.238 ng ml⁻¹; Cr, 0.075 ng ml⁻¹; Mn, 0.006 ng ml⁻¹; Fe, 4.146 ng ml⁻¹; Ni, 0.049 ng ml⁻¹; Cu, 0.054 ng ml⁻¹; Zn, 0.049 ng ml⁻¹; Cd, 0.002 ng ml⁻¹; Pb, 0.002 ng ml⁻¹. Briefly, we acidified all melted samples directly to pH<2 with ultra-pure HNO₃, then let settled for 48h. The relative deviation between most of the measured values and the standard reference values
- is within 10%. Details on these procedures are given in Li et al. (2009) and Cong et al. (2010).
- Meanwhile, for the filtrated water samples, we measured the major anions (Cl⁻, NO₂⁻, NO₃⁻, SO₄²⁻) and cations (Na⁺, NH₄⁺, K⁺, Mg²⁺, Ca²⁺) with an ion chromatograph (Dionex 320; Dionex, Sunnyvale, CA) using a CS12 column for cations and an AS11 column for anions at the Institute of Tibetan Plateau Research in Beijing. All the detection limit of the ions was 1 $\mu g \cdot l^{-1}$. In addition, except for the anions and cations and trace elements, CI salt, MD and biosmoke K (K_{Biosmoke}) were determined to assess the mass
- 30 contributions of the major components in the ice samples. CI salt was estimated as follows

in accordance with Pio et al. (2007), by adding to sodium, chloride, and sea-salt contributions of sodium, magnesium, calcium, potassium, and sulfate, as follows:

$$CL_{salt} = Na_{Ss}^{+} + CI^{-} + Mg_{S_{s}}^{2+} + Ca_{S_{s}}^{2+} + K_{S_{s}}^{+} + SO_{4S_{s}}^{2-}$$

= Na_{Ss}^{+} + CI^{-} + 0.12Na_{Ss}^{+} + 0.038Na_{Ss}^{+} + 0.038Na_{Ss}^{+} + 0.25Na_{Ss}^{+}(3)

(4)

(8)

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$$Na_{Ss} = Na_{Total} - Al \cdot (Na/Al)_{Crust}$$

Where $(Na/Al)_{Crust}=0.33$, and represents the Na/Al ratio in the dust materials (Wedepohl, 1995).

The MD content was calculated by a straightforward method, and the Al concentration in dust was estimated as 7% (Zhang et al., 2013b):

10 MD=Al/0.07
$$(5)$$

We determined K_{Biosmoke} as follows (Pu et al., 2017):

$$\mathbf{K}_{\text{Biosmoke}} = \mathbf{K}_{\text{Total}} \cdot \mathbf{K}_{\text{Dust}} \cdot \mathbf{K}_{\text{Ss}}$$
(6)

$$K_{\text{Dust}} = \text{Al} \cdot (\text{K/Al})_{\text{Crust}}$$
(7)

$$K_{SS} = Na_{SS} \cdot 0.038$$

Where $(K/Al)_{Crust}$ is 0.37, which represents the K/Al ratio in the dust materials (Wedepohl, 1995) and Na_{Ss} is estimated by Eq. (4).

2.4 Enrichment factor (EF)

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To evaluate the relative contributions of trace elements from natural (e.g., mineral and soil dust) versus anthropogenic sources (e.g., fossil fuels and vehicle exhaust), an inter-annual comparison of EF values, which represent the enrichment of a given element relative to its concentration in the crust of the earth. The primary uncertainty in these calculations is attributed to the differences between chemical compositions in the snow and the reference crustal composition. The EF is defined as the concentration ratio of a given metal to that of Al, which is a reliable measure of crustal dust, normalized to the same concentration ratio characteristic of the upper continental crust (Wedepohl, 1995), calculated with the

 $EF = \frac{(X/AI)_{snow}}{(X/AI)_{crust}}$ (9)

2.5 Source apportionment

following equation:

The Positive Matrix Factorization (PMF 5.0) is considered as a generally accepted receptor model to determine source apportionment of the ILAPs when source emission profiles are unknown (Paatero and Tapper, 1994). Details of the PMF procedure used in this study are similar to the previous work as discussed in Hegg et al. (2009, 2010). Generally, the mass

- 5 concentration and the uncertainties of the chemical species were used as the input. The final data set used for the PMF analysis contained 189 samples with 18 elements whereby only elements that have high recovery were used. The uncertainty value of each variable in each sample was estimated from an empirical equation. The PMF model was run for 3 to 6 factors with 6 random seeds, but only a three-factor solution could provide the most meaningful results of the ILAPS in TP glaciers. The *Q* values (modified values) for the 3-
- factor solution (both robust and true) were closest to the theoretical Q value of any of the factor numbers for which the model was run, suggesting that the 3-factor solution was optimal.

3. Results and Discussion

15 **3.1** Aerosol optical depth (AOD)

As shown in Fig. 3, the QY, QM, MK, YZF glaciers are located in the northern part of Tibetan Plateau, while XD, HRQ, GR glaciers are located in the southern part of Tibetan Plateau. It worth noting that the aerosol optical depth (AOD) can represent the dry aerosol deposition and its transport pathway, which could provide useful information about the 20 possible sources of the ILAPs in the TP glaciers. Therefore, the spatial distribution of the averaged AOD at 500 nm derived from Aqua-MODIS were retrieved over the TP regions and its adjacent areas from 2013 to 2015. Following the work of Ramanathan et al. (2007), the anthropogenic AOD, which is also called as atmospheric brown clouds (ABC), was larger than 0.3 on the southern side of the Himalayas. Therefore, AOD (500 nm) 25values >0.3 and <0.1 are considered to present the anthropogenic haze and background conditions, respectively. We found that the AOD was much larger across the western TP than that in the central part of TP regions. As a result, the AOD values in the QY, QM, MK, and YZF glaciers were in the range of 0.25 to 0.3 could be highly influenced by human activities. The high values of AOD might thus contribute to the retreat of Himalayan

30 glaciers (Engling and Gelencser, 2010). In contrast, the lower values of AOD (<0.125)

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were observed near the HRQ, XD, and GR glaciers. However, the AOD over the TP regions was much lower than that over Southern Asia, especially over the Indo-Gangetic Plain during the cold season. This is close to previous measurements over the TP regions (Cong et al., 2009; Ming et al., 2010; Yang et al., 2012; Lüthi et al., 2015).

5 3.2 Regional averages of the optical parameters

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The general information of C_{BC}^{est} , C_{BC}^{max} , C_{BC}^{equiv} , f_{non-BC}^{est} , A_{tot} , and A_{non-BC} of the ice samples are given in Table 1 for each glacier. The lower median values of C_{BC}^{est} could be 23 ng g⁻¹, 26 ng g⁻¹ during the monsoon season in the HRQ and GR glaciers on the south of the TP regions, while the higher values of 187 ng g⁻¹ and 165 ng g⁻¹ found in the MK and YZF glaciers on the central part of the TP regions. Compared with the monsoon season, the concentration of C_{BC}^{est} increased very significantly in all seven glaciers than those values

- during the non-monsoon season. We found that the lowest concentration of BC in the ice samples was found in the XD glacier, with a value of $C_{BC}^{est} \sim 10$ ng g⁻¹. In contrast, the highest values of C_{BC}^{est} , C_{BC}^{max} , and C_{BC}^{equiv} were 3100 ng g⁻¹, 3600 ng g⁻¹, and 4700 ng g⁻¹,
- 15 respectively, taken in the GR glacier. Generally, the median of A_{tot} exceeded 1.0 at all locations (Fig. 4, and Table 1). A_{tot} and A_{non-BC} for all ice samples were in the range of 1.4-3.7 and 1.9-5.8, respectively (Table S1). As shown in Fig. 4a, the median values of A_{tot} were 2.62, 2,64, 2,18, and 2.46 in the QY, MK, XD, and GR glaciers, associated with the estimated contributions to absorption by non-BC ILAPs in these regions were ~41%, 44%,
- 20 36%, and 48%, respectively. Compared with these glaciers, the higher values of median \hat{A}_{tot} were found in the QM (2.76), YZF (2.95), and HRQ (2.87) glaciers. Correspondingly, the estimated f_{non-BC}^{est} values in those regions is ~44%, 48%, and 48%, respectively. Except the HRQ glacier, the other glaciers showed an increased trend of the \hat{A}_{non-BC} from the south to north regions in the TP regions (Fig. 4b). Histograms of the \hat{A}_{tot} by regions are shown in
- Fig. 5. We found that there was a large variation of A_{tot} in the XD glacier, not only in the higher values (~2-4), but also for the lower values (<2). The broadness of the A_{tot} distribution is indicative of the complicated sources of particulate light absorption. For instance, Wang et al. (2013) indicated that the higher values of A_{tot} (~3.5-4.5) was highly correlated with the local soil source, while fossil fuel burning may have an absorption
- 30 Ångström exponent lower than 2 (Millikan, 1961; Fialho et al., 2005). Therefore, a

significant fraction of the total absorption was not only attributed to BC (49%, shown in Fig. 7), but also contributed by non-BC absorbers (accounting for 51%) due to OC and MD in the XD glacier. In contrast, a common feature in the other regions was that the major dominated values of $Å_{tot}$ range from 2 to 3. The $Å_{non-BC}$ and $Å_{tot}$ in each site are also given

- 5 as red dots and blue triangles, respectively, in Fig. S3. Figure 6 shows the regional variations of BC, OC, and Fe concentration in each glacier during monsoon and non-monsoon seasons. Although there were significant differences between the median and average values of the ILAPs concentration in each glacier, we found that all kinds of ILAPs exhibited a similar variation from the northern QY glacier to
- 10 southern GR glacier. In addition, we collected the ice samples during both monsoon and non-monsoon seasons in five glaciers, only except the QY and QM glaciers. On average, the BC and OC concentrations in the HRQ, XD, and GR glacier during non-monsoon season were several orders of magnitude higher than those in monsoon seasons. The result was highly consistent with the previous study by Cong et al. (2015), who found that
- 15 although the transport pathways of air masses arriving the middle Himalayas during monsoon and non-monsoon were similar, a distinctly higher carbonaceous aerosol level was found only in the non-monsoon season. Lüthi et al. (2015) also exhibited that the atmospheric brown cloud over South Asia can climb across the Himalayan and transport of polluted air mass, which may have serious implications of the cryosphere in the TP
- 20 regions. However, there appeared to be no apparent difference in the mixing ratios of ILAPs between monsoon and non-monsoon seasons in two adjacent (MK and YZF) glaciers. This can be mainly explained that, except the long-range transport of ILAPs, local air pollutants could also affect the ILAPs in the central TP regions. For instance, Huang et al. (2018) investigated that the air masses across the MK and YZF glaciers were originated
- from the arid western TP and Taklimakan desert regions, and the concentration of trace elements in the YZF glacier was closer to the dust sources indicating that YZF glacier was less influenced by human activities. The median values of the C_{BC}^{est} and C_{OC} (referred as the mass concentration of OC) obviously showed a slightly decreasing trend from the northern TP to the southern TP. The mass concentration of BC in northern TP glaciers was

higher than that in southern TP glaciers, which showed a good agreement with Ming et al. (2013).

To quantify the regional status of ILAPs in each glacier, the statistics of the ILAPs in snow and ice in the studied TP glaciers and other related glaciers by previous studies are shown

- 5 in Table 2. During this field campaign, twelve ice samples were collected in the YZF glacier. The depths of these ice samples collected in the YZF glacier were ranging from 15 to 45 cm (Table S1). As shown in Fig. S4, most values of C_{BC}^{est} in this region ranged from ~100-1000 ng g⁻¹, with a few values lower than 100 ng g⁻¹. One notable feature is that the highest concentrations of C_{BC}^{max} and C_{OC} for the surface layer were 1600 ng g⁻¹ and 9160
- 10 ng g⁻¹ at site 41. We pointed out that the light absorption in the surface glacier at site 41 was not only influenced by BC, but also possibly related to the OC and MD due to the high value of f_{non-BC}^{est} (0.56). In the YZF glacier, A_{tot} generally varied between ~2 and 3.7, and the average value of f_{non-BC}^{est} was close to 50%, so these results also revealed that the ILAPs in ice samples are heavily influenced by anthropogenic air pollutants. Large variations of
- 15 C_{OC} were also observed, with values ranging from ~10 to 17000 ng g⁻¹. Except site 23, the values of C_{BC}^{est} in the MK glacier were much lower than those in the YZF glacier, which were in the ranges of ~20-670 ng g⁻¹, with a median value of 130 ng g⁻¹ (Fig. S5). The median C_{OC} was ~600 ng g⁻¹ in the MK glacier. The fraction of total particulate light absorption due to non-BC constituents was typically ~16-62%, and A_{non-BC} (5.12) in this 20 region was highly similar to that found in the YZF glacier (5.06).
- In the QY glacier (Fig. S6), the C_{BC}^{est} were much similar with those in the MK glacier, with values ranging from ~20-720 ng g⁻¹, which did not include the highest value of 1900 ng g⁻¹ at site 13. The fraction of total particulate light absorption due to non-BC constituent f_{non-BC}^{est} was typically ~20-70%, with a median value of 41%. This information along with
- the lower A_{tot} (2.6) indicated that BC played the dominant role in influencing the light absorption in this region. Compared with the other TP glaciers, we noted that the vertical profiles of ILAPs in the QY glacier were collected in the monsoon season from 2014 to 2015 (Table S1). The mixing ratios of OC and Fe ranged from 80-10100 ng g⁻¹ and 20-340 ng g⁻¹, respectively. Fig. S7 shows that the vertical profiles of the mass mixing ratios of
- 30 BC, OC, and Fe for the ice samples in the XD glacier were more variable than those for

the other regions. With the exception of the surface layer at sites 53 and 54, most values of C_{BC}^{est} ranged from 10 to 280 ng g⁻¹ in the XD glacier; therefore, this glacier was the cleanest region among all the studied glaciers. At sites 56-58, f_{non-BC}^{est} was lower than 38%, and A_{tot} ranged from 1-2.5. These results were consistent with the fossil fuel combustion source due to industrial activities

5 due to industrial activities.

3.3 Scavenging and washing efficiencies

Previous studies have illustrated that the ILAPs could become trapped and integrated at the surface of the snowpack due to melting and sublimation to enrich the surface concentrations (Conway et al., 1996; Painter et al., 2012; Doherty et al., 2013). For instance,

- 10 Doherty et al. (2013) found that the ILAPs could be scavenged with the snow meltwater to lead to a much higher concentration of BC in the surface snow. Flanner et al. (2007, 2009) indicated that the melt amplification due to concentrated BC in melted snow would amplify snow-albedo reduction, and therefore provide a positive feedback to radiative forcing. However, it still remains unclear what happens to the vertical ILAPs in the deeper layer of
- 15 snow and ice during the multi-melting processes due to limited in-situ observations. In this study, the mixing ratios of ILAPs in most of the ice samples increased remarkably from the top to the bottom in QY glacier. This result seemed inconsistent with a previous study by Doherty et al. (2013). However, Xu et al. (2012) observed that the concentrations of BC were higher not only at the snow surface, but also found at the bottom due to the
- 20 percolation time of meltwater and superimposed ice by the temperature decline in the snowpack. Another notable feature was that the surface mixing ratios of C_{BC}^{est} at sites 52-54 in the XD glacier were significantly larger than those in the sub-surface layers, possibly because of the accumulation of BC via dry/wet deposition on the surface samples. We found that the mechanism of the ILAPs in the vertical ice samples in the QY and XD glacier
- 25 could be difference. The ice samples in the QY glacier were collected in the monsoon season. Due to the higher temperature in the monsoon season, the strong melting processes could wash out the ILAPs in ice samples to lead a higher concentration in the bottom layer in QY glaciers. In contrast, the ice samples were collected in XD glacier in both monsoon and monsoon seasons. Therefore, it can be seen clearly that a decreasing trend of the ILAPs
- 30 in the ice samples was found from the top to the bottom in XD glacier due to the high

scavenging effect during the non-monsoon season (Fig. S7a-S7f, only except Fig. S7e and S7g), while a opposite trend due to the washing effect during the monsoon season (Fig. S7h and Fig. S7j). Because the single layer samples are not shown, the vertical profiles of C_{BC}^{est} are plotted in Fig. S8 for all ice samples, which were collected in the QM, HRQ, and GR glaciers. Except for the sites in Fig. S8d, S8e, S8i, and S8h, the other sites revealed the trapping and scavenging effects of a higher mass concentration of BC in the surface layer

due to the melting processes.

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3.4 Contributions to particulate light absorption by ILAPs

- The fractional contributions to total absorption by BC, OC, and Fe (assumed to be in the 10 form of goethite) at 450 nm in each glacier are shown in Fig. 7, and further details of the concentrations of BC, OC, and Fe are given in Table S1. BC played a dominant role in particulate light absorption with average values ranging from ~44%-54% in all glacier regions. OC was the second highest absorber in glacier regions, and there are large variations of light absorption of OC during the field campaign (~25%-46% on average).
- 15 The contributions to total absorption due to BC and OC were relatively comparable in the QY, YZF and HRQ, which are located in the eastern TP regions. The highest fraction of BC was accounting for 54% in the QM glaciers, which is located in the western TP regions. So the light absorption due to ILAPs in the TP glacier regions was not only from BC and OC, but also with a small contribution from Fe. The average fraction of total light absorption due to Fe was ~11%-31% in all seven glaciers, with the highest light absorption
- of Fe in the GR glacier. The relative contributions to total light absorption by BC, OC, and Fe for surface ice samples in each sampling location are also shown in Fig. S9 and Table 1. This result was an indication that mineral dust played a key role in affecting the spectral absorption properties of ILAPs in ice samples from the TP glaciers.
- 25 **3.5 Enrichment factor (EF)**

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Briefly, the EF values ranging from 0.1 to 10 indicate significant input from crustal sources. Conversely, EF values that larger than 10 exhibit a major contribution from anthropogenic activities. Referring to the EF analysis (Fig. 8), the mean EF of Fe < 5 in each glacier can be assumed to customarily originate from crustal sources. Recent studies have also indicated that light-absorbing particles in snow are dominated by local soil dust in some typical regions over northern China (Wang et al., 2013), and northern America (Doherty et al., 2014). Comparable with Fe, the other trace metals with the mean EF of \geq 5.0 were moderately to highly enriched from anthropogenic emissions (Hsu et al., 2010). For example, Pacyna and Pacyna (2001) reported that fossil fuel combustion is a major source

- 5 of Cr. Cu primarily originates from emissions from fossil fuel combustion and industrial processes, while Pb and Zn are known to be drawn from the traffic-related activities and coal burning (Christian et al., 2010; Contini et al., 2014). Hence, the high EF values observed for Cu, Zn, and Cd in our ice samples clearly suggested that the TP glaciers have already been polluted by human activities, such as biomass burning, fossil fuel burning,
- 10 and the coal burning.

3.6 Source apportionment

Given the importance of the climate effect in our understanding of the ILAPs in TP glaciers, we applied a PMF receptor model to analyze the source attribution of ILAPs light absorption in these glaciers. In this study, the mass concentrations of the chemical components and the ILAPs in ice associated with the uncertainty datasets were used to run the PMF 5.0 model. The details of the techniques have already been illustrated by Hegg et al. (2009, 2010) and Pu et al. (2017). The factor loadings (apportionment of species mass to individual factors) for the 3-factor solution of the source profiles based on the PMF 5.0 model are given in Fig. 9 (in both measured mass concentration and the % total mass allocated to each factor). It was evident that the first factor (top panel) was obviously characterized by high loadings of Cl⁻, Cl salt, SO²⁻, and NO₃, which are well known markers for the urban or local industrial pollutions (Alexander et al., 2015). Although Cl⁻ to Cl salt, reflecting another source in addition to sea salt such as

industrial emission and coal combustion (Hailin et al., 2008; Kulkarni, 2009). Additionally, the highest loading of NH₄⁺ is also suggested as an indicator of coal combustion (Pang et al., 2007). Compared with the first factor, Al (90.3%) and Fe (87.3%) usually regarded as major indicators for the urban or regional mineral dust (Pu et al., 2017). Therefore, the second factor was easily interpretable as a natural mineral dust source. It was notable that *C^{max}_{BC}* showed a high mass loading in this factor. K⁺ and K_{Biosmoke} are the major

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indicators of biomass burning (Zhang et al., 2013a). Therefore, it was easily interpretable that the highest loadings of K^+ and K_{Biosmoke} were well representative for the biomass burning source (Fig. 9c). However, the lowest mass loading of C_{BC}^{max} in this factor is a bit unexpected. Indeed, the C_{BC}^{max} is not only attributed to the biomass burning emission, but also associated with the industrial activities associated with the local mineral dust (Bond et

5 also associated with the industrial activities associated with the local mineral dust (Bond et al., 2006). Therefore, we interpreted the third factor normally considered a predominantly biomass burning product.

Finally, the chemical composition and mean source apportionment of the ILAPs to the three sources in the TP glaciers were given in Fig. 10. Note that the apportionment was of

- 10 the light absorption by insoluble particles in the surface glaciers. On average, the source appointment of the ILAPs in all TP glaciers by mineral dust was close to 37.5%, while the industrial emission and biomass burning contributed 33% and 29.4%, respectively. Specifically, the largest biomass burning contribution of the light-absorption of ILAPs was found in the QY glacier, which is close to the human activity regions (Guan et al., 2009;
- 15 Li et al., 2016). In the MK, QM, GR, and XD glaciers, the mineral dust contribution of light absorption was much larger (>47.9%) than that of industrial pollution and biomass burning, especially in the MK glacier. In these regions, the percent of the light absorption due to soil dust ranged from 20.4-31.1%, while the light absorption by biomass burning was in the range of 18.5-35.8%. Industrial pollution constituted a major fraction in the YZF
- 20 glacier. Chemical analysis showed that the percentages of the chemical species in the YZF and MK glaciers were much similar. The attribution of the total anions by chloride, nitrate, and sulphate were higher than the other chemical species in the YZF and MK glaciers. In the HRQ glacier, the largest contribution of the sulphate was up to 45.4%. As shown in Fig. 10, the source of the light absorption by insoluble particles in the surface glaciers was
- 25 dominated by mineral dust and the industrial pollution in most glaciers. The only exception was the YZF glacier where a large fraction of the light absorption was due to biomass burning in the YZF glacier. These results were highly consistent with the previous studies (Andersson et al., 2015). They found that the contributions of coal-combustion-sourced BC are the most significant for the TP glaciers.
- 30 4 Conclusions

In this study, the ILAPs observations in seven glacier regions across the Tibetan Plateau were presented using the ISSW technique along with chemical analysis. 67 vertical profiles of ice samples collected during the monsoon and non-monsoon seasons from 2013-2015 were analyzed. On average, the BC and OC concentrations in the HRQ XD, and GR glacier

- 5 during non-monsoon season were several orders of magnitude higher than those in monsoon seasons. However, it remains unclear that the ILAPs in the MK and YZF glaciers were comparable during the monsoon and non-monsoon seasons, which could be investigated by future survey studies across these regions. By excluding some of the highest ILAPs values in the ice samples, the mass concentration of BC, OC, and Fe ranged from
- 10 100-1000 ng g⁻¹, 10-2700 ng g⁻¹, and 10-1000 ng g⁻¹, respectively. Among the samples, the lower concentrations of BC were found in the XD, HRQ and GR glaciers, with the median concentrations of 33 ng g⁻¹, 24 ng g⁻¹, and 28 ng g⁻¹, respectively. We found that the ILAPs in the ice samples was decreased from the top to the bottom in XD glacier due to the scavenging effect during the non-monsoon season, while a opposite trend due to the washing effect by high temperature during the monsoon season.
- BC played a dominant role in particulate light absorption with average values ranging from \sim 44%-54% in these glaciers, while \sim 25%-46% for OC. By using a PMF receptor model, we found that the ILAPs across the northern glaciers is heavy polluted due to human activities, but the major emissions of the light absorption by insoluble particles in TP
- 20 glaciers originated from the local mineral dust and industrial pollution sources, followed by the biomass burning source. Therefore, the natural mineral dust source and anthropogenic emission source are both non-negligible to the ILAPs in the TP glaciers.

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5 Data availability

5 All datasets and codes used to produce this study can be obtained by contacting Xin Wang (wxin@lzu.edu.cn).

Competing interests. The authors declare that they have no conflicts of interest.

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Region	Latitude	Longitude		C_{BC}^{equiv}	C_{BC}^{max}	C_{BC}^{est}	f_{non-BC}^{est}	Ŀ
	(N)	(E)		(ng g ⁻¹)	(ng g ⁻¹)	(ng g ⁻¹)	(%)	
Qiyi glacier	39°14'28"	97°45'27"	average	414	299	238 (116, 313)	42 (15, 66)	2.:
			median	176	128	94 (29, 124)	41 (17, 70)	2.
			minimum	26	29	25 (13, 35)	21 (, 53)	0.
			maximum	2651	2230	1877 (1182, 2109)	73 (41,—)	3.
Qiumianleiketage	36°41'47"	90°43'44"	average	421	296	238 (139, 402)	44 (24, 81)	2.
			median	307	215	172 (64, 218)	44 (24, 81)	2.
			minimum	139	93	62 (19, 93)	37 (12, 64)	2.4
			maximum	995	662	558 (143, 678)	56 (27, 86)	3.
Meikuang glacier	35°40'24"	94°11'10"	average	493	328	260 (119, 331)	42 (15, 37)	2.
			median	197	156	133 (76, 153)	44 (16, 69)	2.
			minimum	24	23	19 (17, 24)	16 (, 17)	1.
			maximum	4696	2817	2292 (109, 2938)	62 (23, 85)	3.
Yuzhufeng glacier	35°38'43"	94°13'36"	average	457	312	233 (94, 295)	51 (-, 37)	2.
			median	317	201	160 (116, 204)	48 (26, 87)	2.
			minimum	52	35	24 (8,35)	15 (-, 37)	1.
			maximum	2630	1608	1169 (72, 1603)	110 (6, 49)	3.
Hariqin glacier	33°08'23"	92°05'34"	average	476	327	256 (100, 385)	48 (26, 82)	2.
			median	54	37	23 (9,30)	48 (26, 82)	2.
			minimum	36	24	13 (4, 22)	19 (-, 41)	1.
			maximum	3990	2702	2131 (682, 2784)	64 (32, 84)	3.
Xiaodongkemadi	33°04'08"	92°04'24''	average	253	171	152 (76, 177)	37 (15, 63)	2.2
Region	Latitude	Longitude		C_{BC}^{equiv}	C_{BC}^{max}	C_{BC}^{est}	f_{non-BC}^{est}	A
	(N)	(E)		(ng g ⁻¹)	(ng g ⁻¹)	(ng g ⁻¹)	(%)	
			median	62	47	53 (37, 65)	36 (13, 59)	2.
			minimum	13	12	9 (6, 18)	8 (-, 19)	1.
			maximum	2770	1849	1637 (596, 2031)	86 (25,90)	3.
Gurenhekou glacier	30°11'17"	90°27'23''	average	382	292	247 (212, 591)	46 (16,71)	2.4
			median	61	46	30 (19, 44)	48 (18,75)	2.4
			minimum	28	23	15 (10, 24)	27 (7, 52)	1.
			maximum	4674	3634	3080 (1876, 3884)	61 (26, 85)	2.

Table 1. Statistics of the ILAPs in each glacier measured using an ISSW spectrophotometer

 associated with the chemical analysis.

Glacier	Sampling	Season	Altitude/	BC	OC	MD	Sample type	References
name	time		m a.s.l.	(ng g ⁻¹)	(ng g ⁻¹)	(µg g ⁻¹)		
Qiyi	2005.7	Monsoon	4850	22±2			Snow pit	Ming et al., 2009
	2001.7-8	Monsoon	4600	6.65 <u>±</u> 3.3	87.52 <u>+</u> 37.59		Fresh snow	Xu et al., 2006
	2001.7-8	Monsoon	4600	52.64±17.83	195.5 <u>±</u> 85		Aged snow	Xu et al., 2006
	2013.8-9	Monsoon	4700	238 <u>+</u> 349	1210±2023	1.42±1.17	Ice	This study
Qiumianleiketage	2014.5	Non-monsoon	5300	238±168	1431±1130	2.92±2.09	Ice	This study
Meikuang	2001.7-8	Monsoon	5200	446	124		Surface snow	Xu et al., 2006
	2015.10	Monsoon	5050	290±241	3745±5100	5.27±6.81	Ice	This study
	2015.5	Non-monsoon	5050	250 <u>±</u> 468	1718±3639	1.85±2.38	Ice	This study
Yuzhufeng	2014,2015.10	Monsoon	5350	265 <u>+</u> 270	1596±2052	2.93±3.19	Ice	This study
	2014.5	Non-monsoon	5350	213±188	1421±1173	1.9±1.77	Ice	This study
Hariqin	2015.10	Monsoon	5650	91±126	930 <u>±</u> 1880	1.23±1.77	Ice	This study
	2015.5	Non-monsoon	5650	1077 <u>+</u> 1489	4860±6759	8.38±10.59	Ice	This study
Xiaodongkemadi	2014.8-2015.7	Monsoon	5400-5750	41.77±6.36	157.97±42.3	1.89±0.92	Fresh snow	Li et al., 2017
		Monsoon	5400-5750	246.84±118.3	611.45±467.7	39.43±24.35	Aged snow	Li et al., 2017

Table 2. Statistics of the ILAPs in snow and ice in the studied TP glaciers and other related glaciers.

		Monsoon	5400-5750	3335±3767	9857±10923	880±1038	Granular ice	Li et al., 2017
	2015.10	Monsoon	5600	57 <u>±</u> 37	250±233	0.68±0.3	Ice	This study
	2013-2015.5	Non- monsoon	5600	178 <u>+</u> 381	1174 <u>±</u> 2014	2.18±6.15	Ice	This study
Gurenhekou	2015.10	Monsoon	5610	85 <u>±</u> 177	330±648	1.17±1.49	Ice	This study
	2014.5	Non-monsoon	5610	1116±1700	2148±2668	7.7 <u>+</u> 9.99	Ice	This study
Palong-Zanbu-	1998-2005	Monsoon	4800-5600	5.27 <u>±</u> 2.23	70.8±39.3		Ice core	Xu et al., 2009a
No. 4		Non-monsoon	4800-5600	11.51 <u>+</u> 4.7	97.5 <u>±</u> 49.9		Ice core	Xu et al., 2009a
Zuoqiupu	1956-2006	Monsoon	5100-5400	2.37±1.55	11.55±11.5		Ice core	Xu et al., 2009b
		Non-monsoon	5100-5400	8.33±3.29	26.71±13.74		Ice core	Xu et al., 2009b
Zhadang	2012.8	Monsoon	5500-5800	51.9±7.2		6.38±1.54	Snow pit	Qu et al., 2014
	2014.6	Monsoon	5800	79	515.08		Snow pit	Li et al., 2016
	2015.5	Non-monsoon	5790	303	822		Snow pit	Li et al., 2018
	2015.6-9	Monsoon	5570-5790	281	743		Surface snow	Li et al., 2018
Urumqi No.1	2004.7-8	Monsoon	4130	500	1200		Surface snow	Xu et al., 2012
	2013.8	Monsoon	3800-4100	30±5		17 <u>±</u> 6	Fresh snow	Ming et al., 2016
Muji	2012.6-10	Monsoon	4700-5500	375 <u>+</u> 3	175±15		Snow pit	Yang et al., 2015
Qiangyong	2001		5400	43.1	117.3		Surface snow	Xu et al., 2006
Kangwure	2001		6000	21.8	161.1		Surface snow	Xu et al., 2006
Namunani	2004		5780-6080	4.4±2.1	51.1±20.6		Surface snow	Xu et al., 2006
Demula	2014.5	Non-monsoon	5404	17	185		Snow pit	Li et al., 2016
Yulong	2015.5	Non-monsoon	4400-4800	372 <u>±</u> 58	2003±308	9.47±2.36	Aged snow	Niu et al., 2017
	2015.8	Monsoon	4400-4800	2309±125	3211±168	97.12±50.78	Aged snow	Niu et al., 2017
Laohugou No. 12	2015.8	Monsoon	4400-4800	2198±1004	2190±1203	114 <u>±</u> 67	Aged snow	Zhang et al., 2017
	2015.10	Non-monsoon	4400-4800	1218 <u>+</u> 212	504 <u>±</u> 50	63±2	Aged snow	Zhang et al., 2017



Figure 1. Geographical locations of (a) Qiyi glacier (97.76° E, 39.24° N), (b) Qiumianleiketage glacier (90.73° E, 36.70° N), (c) Meikuang glacier (94.19° E, 35.67° N), (d) Yuzhufeng glacier (94.23° E, 35.65° N), (e) Hariqin glacier (92.09° E, 33.14° N), (f) Xiaodongkemadi glacier (92.07° E, 33.07° N), (g) Gurenhekou glacier (90.46° E, 30.19° N). The black dot is the sampling locations.



Figure 2. The equipment for collecting new snow samples in seven TP glaciers.



Figure 3. Spatial distribution of the averaged AOD retrieved from Aqua-MODIS at 500 nm over Tibetan Plateau from 2013 to 2015. The red stars are the sampling locations (see also Table 1):



Figure 4. The spatial distribution of the median absorption Ångström exponent for (a) total particulate constituents (\mathring{A}_{tot}), and (b) non-BC particulate constituents (\mathring{A}_{non-BC}) in each glacier.



Figure 5. Histograms of the frequency of \mathring{A}_{tot} (450-600 nm) for ice samples in each of the glacier region. Samples from all vertical profiles are included.



Figure 6. Box plots of the regional variations in (a) BC concentration, (b) ISOC concentration, and (c) Fe concentration of the seven glaciers. Error bars are 10^a, 25^a, median, 75^a, and 90^a percentiles of the data. The dot symbol represents the average concentrations of the ILAPs in ice samples in each glacier.



Figure 7. The median of relative contributions to total light absorption by BC, OC, and Fe for ice samples in each glacier.



Figure 8. Average enrichment factors of trace metals in surface ice samples at each region.



Figure 9. Source profiles for the three factors/sources that were resolved by the PMF 5.0 model.



Figure 10. Chemical composition and source apportionment for the seven glaciers in the TP regions. Note that the apportionment is of the light absorption by insoluble particles in the surface glaciers.

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