Variability in individual particle structure and mixing states between the glacier snowpack and atmosphere interface in the northeast Tibetan Plateau

Zhiwen Dong a, b, *, Shichang Kang a, c, Yaping Shao b, Sven Ulbrich b, Dahe Qin a

a State Key Laboratory of Cryosphere Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China;
b Institute for Geophysics and Meteorology, University of Cologne, Cologne D-50923, Germany;
c CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China.

* Corresponding Author. E-mail Address: dongzhiwen@lzb.ac.cn (Z. Dong).

Abstract

Aerosol impurities affect the earth’s temperature and climate by altering the radiative properties of the atmosphere. Changes in the composition, morphology structure and mixing states of aerosol components will cause significantly varied radiative forcing in the atmosphere. This work focused on the physicochemical properties of light-absorbing impurities (LAIs) and their variability through deposition from the atmosphere to the glacier/snowpack surface interface based on large-range observation in northeastern Tibetan Plateau and laboratory transmission electron microscope (TEM) and laboratory energy dispersive X-ray spectrometer (EDX) measurements. The results showed that LAI particle structures changed markedly in the snowpack compared to those in the atmosphere due to black carbon (BC)/organic matter (OM) particle aging and salt-coating condition changes. Considerably more aged BC and OM particles were observed in glacier/snowpack surfaces than in the atmosphere, as the proportion of aged BC and OM varied in all locations by 4%-16% and 12%-25% in the atmosphere, respectively, whereas they varied by 25%-36% and 36%-48%, respectively, in the glacier/snowpack surface. Similarly, the salt-coated particle ratio of LAIs in the snowpack is lower than in the atmosphere. Albedo change contribution in the Miaoergou, Yuzhufeng and Qiyi Glaciers
is evaluated using the SNICAR model for glacier surface distributed impurities. Due to
salt-coating state change, these values decreased by 30.1%-56.4% compared to that in the
atmosphere. Such great change may cause more strongly enhanced radiative heating than
previously thought, suggesting that the warming effect from particle structure and mixing
change of glacier/snowpack LAIs may have markedly affected the climate on a global
scale in terms of direct forcing in the cryosphere.

Keywords: light absorbing aerosols; atmosphere-snowpack interface; BC/OM particle
structure aging; salt-coating change; particle internal mixing

1. Introduction

Aerosols affect the earth's temperature and climate by altering the radiative properties of
the atmosphere (Jacobson, 2001; 2014). Snow cover and glaciers in cryospheric regions
play an important role in global climate change because of their large areas of distribution
on the earth’s surface, especially in the Northern Hemisphere, e.g., in the Alpine
Mountains, the Tibetan Plateau, northern hemisphere snowpack and the Polar Regions.
Individual pollutant aerosols, e.g., black carbon (BC, or soot), organic carbon (OC) or
organic matter (OM), mineral dust and various salts, deposited on glacier/snowpack
surfaces cause enhanced surface heat absorption, acting as light absorbing impurities
(LAIs), and they thus impact radiative forcing in the cryosphere. Moreover, changes in
composition, morphology structure and mixing states of different LAIs components will
cause significant variability in individual particle radiative heating with largely varied
surface albedo due to the changes in a single particle’s mixing states (Cappa et al., 2012;
Peng et al., 2016).

The Tibetan Plateau, acting as the “The Third Pole” region, is one of the largest
cryosphere regions with a large ice mass besides the Polar Regions (Qiu et al., 2008).
Large amounts of LAIs particles deposited on the glacier/snowpack surface can
significantly impact surface radiative forcing, and induce increased heat absorption of the
atmosphere interface in lower and middle troposphere (Anesio et al., 2009; Kaspari et al.,
2011; Dong et al., 2016, 2017), thereby causing rapid glacier melting in the region (Xu et
al., 2009; Zhang et al., 2017).
Aerosols and climate interaction has become a major concern in the Tibetan Plateau region (Dong et al., 2016, 2017). For example, the long-range transport and deposition of BC (soot), various types of salts (e.g., ammonium, nitrate and sulfate), and aerosols, and their climate significance on the Tibetan Plateau glaciers have recently become heavily researched topics (Ramanathan et al., 2007; Flanner et al., 2007; McConnell et al., 2007; Zhang et al., 2018). However, to date, notably limited studies have focused on the composition, mixing states, and change process of LAIs particles in the atmosphere-snowpack interface of the Tibetan Plateau glacier basins. Moreover, current modeling on cryospheric snow/ice radiative forcing’s impact on climate change have rarely considered such influences from changes to a single particle’s structure and mixing states (Ramanathan et al., 2007; Hu et al., 2018). Because of glacier ablation and LAI accumulation in summer, the concentration of distributed impurities in glacier/snowpack surface is often even higher than that of the atmosphere (Zhang et al., 2017; Yan et al., 2016).

Therefore, this study aimed to provide a first and unique record of the individual LAIs particle’s physicochemical properties, components, composition, and mixing states of Tibet Plateau based on aerosol sampling (TSP and microscope filter samples) and the surface-distributed impurity samples of glaciers/snowpack, collected in the northeastern Tibetan Plateau from June 2016 to September 2017, to determine the individual LAIs particle’s structure aging and mixing state changes through the atmospheric deposition process from atmosphere to glacier/snowpack surface, thereby helping to characterize the LAIs’ radiative forcing and climate effects in the cryosphere region of Tibetan Plateau. Moreover, the albedo change contributions in several glacier surfaces (e.g., Miaoergou, Yuzhufeng and Qiyi Glaciers) were evaluated using a SNICAR model for the salt mixing states of surface- distributed impurities of the observed glaciers.

2. Data and Methods

The main methods of the study include fieldwork observations and laboratory transmission electron microscope (TEM) and laboratory energy dispersive X-ray
spectrometer (EDX) instrument analysis. Atmospheric LAIs samples (including the atmospheric TSP and TEM filter samples) and the glacier/snowpack surface distributed impurity samples were both collected across the northeastern Tibetan Plateau region in summer between June 2016 and September 2017. Figure 1 shows the sampling locations and their spatial distribution in the region, including the Miaogou Glacier (abbreviated MG) in the eastern Tianshan Mountains; Laohugou Glacier No.12 (LG12), Qiyi Glacier (QG), Lenglongling Glacier (LG), Shiyi Glacier (SG) and Dabanshan Snowpack (DS) in the Qilian Mountains; Yuzhufeng Glacier (YG) in the Kunlun Mountains; the Gannan snowpack (GS), Dagu Glacier (DG), and Hailuogou Glacier (HG) in the Hengduan Mountains, where large-range observations were conducted (as shown in Table 1). During the fieldwork sampling, we used the middle-volume-sampler (DKL-2 with a flow rate of 150 L/min) for TEM filter sampling in this study. In total, 65 aerosol samples were collected directly on the calcium-coated carbon (Ca-C) grid filter. Additionally, 88 glacier/snowpack surface samples were collected on the glacier/snowpack surface for comparison with the deposition process. The detailed TEM sampling method is similar to the previous study in Dong et al. (2017).

Laboratory TEM-EDX measurements were performed directly on the Ca-C filters grids (Dong et al., 2016). Ca-C grids were used as filters with the advantage of clear and unprecedented observation for single-particle analyses of aerosols and snowpack samples (Creamean et al., 2013; Li et al., 2014; Semeniuk et al., 2014). Analyses of individual particle observations were conducted using a JEM-2100F (JEOL) transmission electron microscope operated at 200 kV. Detailed information of TEM-EDX measurements was similar to that shown in our previous study (see Dong et al., 2016, 2017). In general, more than 400 particles were analyzed per grid; thus, more than 1200 particles were analyzed from the three grid fractions per sample. Moreover, as the snow samples’ melting will affect the individual particle composition during the measurements, especially for various types of salts, the snow/aerosol samples were directly observed under the TEM instrument and measured before it melted. Most samples were measured in frozen states.

We also evaluated the albedo change contributed by individual particle mixing states’
variability of LAIs. The SNICAR model can be used to simulate the albedo of snowpack by the combination of the impurity of the contents (e.g., BC, dust and volcanic ash), snow effective grain size, and incident solar flux parameters (Flanner et al., 2007). Details for running the SNICAR model are similar to that of Zhang et al. (2018). In the model simulation, mineral dust (93.2 ug/g), BC (854 ug/g) and OC (974 ug/g) average concentration data, as well as other parameters, such as effective grain size, snow density, solar zenith angle, and snow depth on the glaciers, are considered, and mass absorption cross-sections (MAC) for salt-coated BC is referred to the average situation derived from the northern Tibetan Plateau glaciers (Zhang et al., 2017, 2018; Yan et al., 2016).

3. Results and Discussion

3.1 Composition of Various LAIs Components between the Atmosphere and Snowpack Interface in the Glacier Basins

Figure 2 shows the component types of an individual haze particle in northwestern China. Based on the above microscope observations, aerosols were classified into eight components: NaCl salt, mineral dust, fly ash-BC (soot), sulfates, ammonium, nitrates, and organic matter (OM). Figure 3 shows the comparison of individual LAIs particle composition (e.g., mineral dust, BC, organic matter, sulfate and various salts) between glacier/snowpack and atmosphere interface in northeast Tibetan Plateau region. We found that the impurity components show large differences between the snowpack and atmosphere in all locations, implying significant change through the aerosols' deposition processing in the interface (Figure 3). LAIs components have a large change of proportion in the interface, probably due to different atmospheric cleaning rates and atmospheric processing with dry/wet aerosol deposition. Sulfates and other salts in the atmosphere act as salt-coating forms to other particles with aggregated states and will be dissolved and taken away with precipitating snow and meltwater in the snowpack, which will cause reduced salt components (e.g., sulfate, nitrate, NaCl, and ammonium) in the glacier/snowpack surface compared to those in the atmosphere. Therefore, we can observe obvious changes in composition and mixing states of the impurities between the atmosphere and glacier/snowpack surface in Figure 3, as the ratio of BC, organic matter,
and mineral dust components in the snowpack increased greatly during this process, whereas the ratio of various salts in the snowpack decreased significantly (Figure 3). Such change will undoubtedly cause a significant variability of impurities’ heat absorbing property in both the atmosphere and the glacier/snowpack surface. Meanwhile, the deposition flux and processing of various types of aerosol particles are different, causing the changes in composition and mixing states of impurities between the atmosphere and cryosphere. Moreover, such aerosol change processes (especially through deposition with precipitating snow) will also lead to large variability of individual LAIs particle structures and morphology; for example, the particle’s aging, salt-coating and mixing states changes of BC and organic matter (internal or external mixing), as shown below, which will cause further influences on the radiative forcing of the glacier/snowpack surface.

3.2 BC/OM Particle Structure Aging Variability between Atmosphere and Snowpack Interface

Figure 4 shows how the particle’s structure changes during the individual particle aging process when deposited from the atmosphere into the glacier snowpack surface. Figure 4a-4d is representative of that in atmosphere, whereas Figure 4e-4h is that in the glacier/snowpack surface. It is clear that abundant aerosol particles were observed with relatively fresh structure in the atmosphere, similar to previous studies (e.g., Li et al., 2015; Peng et al., 2016). As shown in Figure 4a-4d, the fresh aerosol particles of BC and OC (or organic matter, OM) appeared very common in the atmosphere as the main parts, whereas as shown in Figure 4e-4h, more aged particles were found deposited in the glacier/snowpack surface. This process is characterized by initial transformation from a fractal structure to spherical morphology and the subsequent growth of fully compact particles. Previous work has indicated the structure and mass absorption cross (MAC) section change of BC particles in the atmosphere but has not discussed such change phenomena of OM particles’ change during the structure-aging process. This study reveals clearly the structure and morphology change of BC and OM particles’ structure aging through the transport and deposition process to the glacier snowpack from the atmosphere (Figure 4).
Based on TEM-EDX observations, we evaluated the aged BC/OM particle composition ratio (%) in the snowpack and the atmosphere, respectively. Figure 5 shows the aging of BC/OM individual particles and their composition ratio (%) change with the deposition process from the atmosphere to the glacier/snowpack surface. The proportion of aged BC/OM particles varied from 4%-16 % and 12%-25% in atmosphere, respectively, and varied from 25%-36% and 36%-48% in the glacier/snowpack surface, respectively. The amount of aged particles in snowpack is 2-3 times higher than that in the atmosphere. We can demonstrate that in the atmosphere the BC/OM both showed high ratios of fresh structure particles (fractal morphology), while in the glacier/snowpack surface more particles indicated aged structure (spherical morphology), although there were a small portion of particles still fresh (Figure 5). The change proportion of BC/OM particle aging is very marked between the interfaces. Large amount of fresh particles varied to aged particles throughout the deposition process between the transition at atmosphere and glacier/snowpack interfaces (Figure 5). The particle structure is a very important factor influencing radiative forcing as shown in previous studies (Peng et al., 2016); thus, such changes in BC/OM particles’ structure aging between the glacier snowpack and atmosphere will actually influence the total radiative absorbing of the mountain glacier/snowpack, even affecting that of the whole cryosphere on earth’s surface.

3.3 Changes in Salt-Coating Conditions and BC/OM Mixing States between the Atmosphere and Snowpack Interface

Using TEM-EDX microscope measurements, we can easily derive the salt-coating conditions based on the advantage of the transmission micro-observation of the single particle structure. In addition to particle structure aging, we find evident variability in particle salt-coating conditions between the atmosphere and glacier/snowpack interface during the observation period. Figure 6 demonstrates the different salt-coating examples for individual aerosol particles (including BC, OM, and mineral dust) in the atmosphere in various glacier basins in the northeast Tibetan Plateau. We found that the salt-coating form is very common for impurity particles in the atmosphere, which will of course cause significant influence on radiative forcing of the atmosphere. A large part of fresh BC/OM (with fractal morphology) and mineral dust particles were coated by various salts, such as...
sulfate, nitrates, and ammonium. Such obvious salt-coating conditions will cause reduced atmospheric radiative forcing, due to the increase of albedo (IPCC, 2013).

Similarly, we also evaluated the salt-coated particle ratio for BC/OM and its change between glacier/snowpack and atmosphere. Figure 7 shows the salt-coating proportion of impurity particles and its difference between the glacier/snowpack and atmosphere interface at those locations. The proportion of salt-coating particles varied largely from the atmosphere to the glacier/snowpack surface (2-4 times more in the atmosphere than that in snowpack). We can demonstrate that in the atmosphere impurity particles showed higher ratios with salt coating, while in the snowpack, only a small part of them indicate salt-coating. The change proportion of salt-coating particles is very marked, and this change will cause very complicated changes in a particle’s mixing states and structure, as many particles without salt-coating will change to internally mixing with BC/OM particles as a core, or external mixing with BC/OM, which will also significantly influence the total radiative forcing (RF) of the mountain glaciers/snowpack in the cryosphere.

Figure 8 shows the situation of internal mixing states of BC (soot), organic matter (OM) and mineral dust particles in various glacier snowpacks in the region, which demonstrates the influence of the transport and deposition process to a particle’s structure change. Most salts in the salt-coated particles will disappear when deposited into the glacier/snowpack surface, and the mixing states change largely to the internal and external mixing forms with BC/OM as the core, in which the internal mixing of BC and OM particles will cause strongly enhanced radiative forcing as indicated in previous work (Jacobson et al., 2001). The proportion change of an internally mixed BC particle with other particles is presented in Figure 9, showing great increases in internal mixing after deposition among the locations in the whole northeast Tibetan Plateau region. We find that with the salt-dissolution, a large part of LAIs particles changed to the internally mixed BC/OM particle with other aerosol particles. As a large number of particles lose the salt coating in the snowpack compared with those in the atmosphere, the whole process will certainly increase the heating absorption proportion of the LAIs. Moreover, as shown in Figure 10, average conditions of single, internally and externally mixed BC/OM individual particles
in the glacier/snowpack of the northeast Tibetan Plateau changed greatly with the
diameter of the particle. With the increase in particle size, most BC/OM particles (PM>1
um) showed internal mixing conditions, which will influence the RF of the glacier
snowpack.

3.4 Discussion of Particle Mixing States Variability and Its Contribution to
Radiative Forcing Enhancement

Figure 11 shows the schematic diagram model for the explanation of the particle structure
aging and salt-coating changes, and a comparison of its influence to the radiative forcing
between the atmosphere and glacier/snowpack interface on the Tibetan Plateau. From the
above discussion, we find a large variability in LAIs particles’ mixing forms between the
glacier/snowpack surface and atmosphere, mainly originating from the morphologic
changes of the LAIs particle’s structure (e.g., aging of BC/OM), and salt-coating changes
from increased internal mixing of BC/OC particles. Moreover, due to glacier ablation and
accumulation of various types of impurities, the concentration of impurities in the
snowpack surface is often even higher than that of the atmosphere (Zhang et al., 2017;
Yan et al., 2016).

In general, as shown in Figure 11, (i) more fresh structure BC/OM particles were
observed in the atmosphere, whereas more aged BC/OM particles were found on the
glacier/snowpack surface. Aged BC/OM particles often mean stronger radiative forcing
in the snowpack than in the atmosphere (Peng et al., 2015). (ii) More salt-coated
particles were found in the atmosphere of the glacier basin, whereas reduced salt coating
was found in the glacier/snow surface. With thick salt coating, the LAIs’ light- absorbing
properties may not be that much stronger than the particles without coating, as most salts
(sulfate, nitrates, ammonium and NaCl) did not have strong forcing because of their light-
absorbing property and hygroscopicity in the mixing states (IPCC, 2013; Li et al., 2014),
especially for sulfate/nitrate aggregated particles. (iii) With the salt-coating decrease,
more internally mixed particles of BC/OM surrounded by a well-mixed salt-shell were
observed from the individual particles of LAIs in the snow-ice of the cryospheric glacier
basin, when compared to that of the atmosphere. Internally mixed particles of BC/OM
have showed the strongest light absorption in previous modeling studies, as BC acts as a
cell-core with organic matter particles (also sometimes including some salts) surrounded.

In one study the mixing state was found to affect the BC global direct forcing by a factor of 2.9 (0.27 Wm$^{-2}$ for an external mixture, +0.54 Wm$^{-2}$ for BC as a coated core, and +0.78 Wm$^{-2}$ for BC as well mixed internally), as shown in Cappa et al. (2012), Jacobson et al. (2000, 2001) and He et al., 2015. (iv) In addition to the heat-absorbing from the above particle structure change, the absorbing property of some components in the atmosphere and cryosphere (snow and ice) also show a large variability, as most mineral and OM (or OC) particles show negative radiative forcing in the atmosphere while showing positive forcing in the glacier/snowpack surface, as indicated from IPCC AR5 (2013), Yan et al. (2016), Zhang et al. (2018), and Hu et al. (2018). Thus, the heat-absorbing of LAIs as a whole will increase greatly in glacier/snowpack surface environments.

Additionally, the extent of influence of such particle mixing state changes are also important and need to be evaluated for radiative forcing. The SNICAR model is often employed to simulate the hemispheric albedo of snow and ice for a unique combination of LAIs contents (e.g., BC, dust, and volcanic ash), snow effective grain size, and incident solar flux characteristics (Flanner et al., 2007). We also evaluated the influence on albedo caused by individual particle structure and mixing state changes in the glaciers of the northeast Tibetan Plateau region. As shown in Figure 12, the albedo changes in MG, YG and LG12 is evaluated using the SNICAR model for glacier/snowpack surface-distributed impurities, which decreased by 30.1%-56.4%, caused by salt-coating changes, when compared to that of the hypothetical similar situation of glacier surface impurities’ composition as in the atmosphere.

4. Conclusions

The results showed that the impurities’ particle structure changed greatly in snowpack compared to that in the atmosphere, mainly due to particle aging (mainly BC and organic matter), and the salt coating reduction process through the impurity particle’s atmospheric deposition. Many more aging BC and OM and more internally mixed BC particles were
observed in glacier snowpack than in the atmosphere during the simultaneous
observations; for example, the proportion of aged BC and OM varies from 4-16% and
12-25% in the atmosphere respectively, and varies from 25-36% and 36-48% respectively
in the snowpack of the cryosphere. In addition to the heat absorbing from the above LAIs
particle structure change, the absorbing property of dust and OC in atmosphere and
cryosphere (snow and ice) also shows a large difference.

A schematic model diagram linking the explanation the LAIs’ structure aging and
salt-coating change and comparing their influences to the radiative forcing between the
atmosphere and glacier snowpack was created in the study. Thus, the heat absorption of
the impurities as a whole will increase greatly in glacier snowpack environments.
Moreover, we also evaluated the increase in radiative forcing caused by LAIs particle
structures and mixing state changes. The albedo changes in MG, YG and LG12 were
evaluated using the SNICAR model simulation for distributed surface impurities in the
observed glaciers caused by salt coating changes, which decreased by 30.1%-56.4%
compared to glacier surface with similar conditions as in the atmosphere. We think the
modeling evaluation in this work is helpful in understanding the contribution of
individual particle structure and mixing change in atmosphere-snowpack interface.

Acknowledgments

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team (especially to Li G., Li Y. and Chen S.) in the northeast Tibetan Plateau for their
logistical work and sample collections. All the data used are contained within the paper
and tables, figures, and references.

References

China, S. et al., 2013. Morphology and mixing state of individual freshly emitted wildfire


Table 1. Sampling locations, sampling dates, and cryoconite-snow depth at mountain glaciers of the northeast Tibetan Plateau

<table>
<thead>
<tr>
<th>Sites</th>
<th>Glacier</th>
<th>Mountains</th>
<th>Locations</th>
<th>Altitude (m a.s.l.)</th>
<th>Sampling Dates</th>
<th>Number Snow/Aerosols</th>
<th>Particles Calculated</th>
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<tbody>
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<td>MG</td>
<td>Miaoergou Glacier</td>
<td>Tian Shan Mountains</td>
<td>42.59°N, 94.16°E</td>
<td>3800-4200</td>
<td>12-13 June 2017</td>
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<td>LG12</td>
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<td>Qilian Mountains</td>
<td>39°20′N, 90°34′E</td>
<td>4300-4700</td>
<td>10-25 July, 2016, 3-8 June, 10-21 August 2017</td>
<td>20/16</td>
<td>&gt;1200</td>
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<tr>
<td>DS</td>
<td>Daban Snowpack</td>
<td>Daban Mountains</td>
<td>37.21°N, 101.24°E</td>
<td>3500-3700</td>
<td>3-4 June 2017</td>
<td>8/4</td>
<td>&gt;1200</td>
</tr>
<tr>
<td>LG</td>
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<td>Qilian Mountains</td>
<td>37.51°N, 101.54°E</td>
<td>3558-3990</td>
<td>5-7 June 2017</td>
<td>12/5</td>
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<tr>
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<td>3-4 June 2017</td>
<td>9/6</td>
<td>&gt;1200</td>
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<td>Yuzhu Feng Glacier</td>
<td>Kunlun Mountains</td>
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<td>4300-4720</td>
<td>12 June 2017</td>
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<td>4-8 May 2017, 6-9 August 2017</td>
<td>6/4</td>
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<td>Hengduan Mountains</td>
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<td>20-22 Sept 2017</td>
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<td>Hengduan Mountains</td>
<td>31°N, 101°E</td>
<td>2900-3500</td>
<td>11-12 August 2017</td>
<td>6/4</td>
<td>&gt;1200</td>
</tr>
</tbody>
</table>
Figure Captions

**Figure 1** Location map showing the sampled glaciers and snowpack in the northeast Tibetan Plateau, including the Miaogou Glacier (MG), Laohugou Glacier No.12 (LG12), Qiyi Glacier (QG), Lenglongling Glacier (LG), Shiyi Glacier (SG), Dabanshan snowpack (DS), Yuzhufeng Glacier (YG), Gannan Snowpack (GS), Dagu Glacier (DG), and Hailuogou Glacier (HG), where large-range field observations of atmosphere and glacier surface impurities were conducted.

**Figure 2** Component types of individual haze particles in northwest China. Based on the above microscope observation, aerosols were classified into seven components: NaCl salt, mineral dust, fly ash, BC (soot), sulfates, nitrates, and organic matter (OM).

**Figure 3** Comparison of individual particles’ compositions of light-absorbing impurities in the (a)atmosphere and (b) snow and ice surface of the glacier basin in Tibetan Plateau, and (c) a photo of snowpack and glaciers in the Qilian Mountains taken from flight in autumn 2017, showing large distribution of snow cover and glaciers in the north Tibetan Plateau region -round.

**Figure 4** Structure change during the aging of individual black carbon (BC) / organic matter (OM) particles when deposited from the atmosphere onto snow and ice surface. Figures 3a-3d is representative of atmosphere, while Figure 3e-3h shows the condition of snow and ice.

**Figure 5** Structure aging of BC/OC individual impurity particles and composition ratio (%) change during the deposition process from the atmosphere to glacier snowpack.

**Figure 6** Examples of different salt-coating conditions of BC, OM and dust for individual particles in the atmosphere of various glacier basins in northeast Tibetan Plateau.

**Figure 7** Salt-coating proportion changes of individual impurity particles between glacier snowpack and atmosphere in various locations of northeast Tibetan Plateau.
**Figure 8** Internal mixing states of BC (soot), OM and mineral dust particles, in the various glacier snowpack in northeast Tibetan Plateau.

**Figure 9** The proportion change of internally mixed BC particle with other particles, showing the obvious increase of internally mixed BC/OM in glacier snowpack compared with those in the atmosphere.

**Figure 10** Average conditions of single, internally and externally mixed BC/OM individual particles in the snowpack of northeast Tibetan Plateau glaciers, showing most of the BC/OM with diameter >1 μm in internally mixing conditions.

**Figure 11** Schematic diagram linking aging and salt coating change and comparing its influence to the radiative forcing between the atmosphere and snowpack of a remote glacier basin, causing markedly enhanced radiative heat absorption.

**Figure 12** Evaluation of snow albedo change of BC-salt coating change in the snowpack compared with atmosphere using SNICAR model simulation in the MG (a, b), YG (c, d), LG 12 (e, f), which shows the largely decreased albedo of snow surface impurities in snowpack compared to that of the atmosphere, implying markedly enhanced radiative forcing in the snowpack surface impurities.
Figure 1
Figure 2
Figure 3
Figure 4
Figure 5

(a) BC/OC Composition as a function of location for Aging OC, Fresh OC, Aging BC, and Fresh BC. 

(b) BC/OC Composition as a function of location for the different locations MG, LG12, QG, DS, LG, SG, YG, GS, DG, and HG.
Figure 6
Figure 7
Figure 8
Figure 9
**Figure 10**

![Graph showing mixing states of BC/OC (%) against circular particle diameter (nm) with three types of mixed states: External Mixed, Single particle, and Internal Mixed.](image-url)
Figure 12

(a) Assumed BC-Salt composition with atmosphere in WG

(b) Actual BC-Salt composition in snowpack after deposition in WG

(c) Assumed BC-Salt composition with atmosphere in YQ

(d) Actual BC-Salt composition in snowpack after deposition in YQ

(e) Assumed BC-Salt composition with atmosphere in LG 12

(f) Actual BC-Salt composition in snowpack after deposition in LG 12