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

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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

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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).

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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 LAIs between the glacier/snowpack and atmosphere interface over the northeastern Tibetan Plateau based on aerosol sampling (TSP and microscope filter samples) and the surface-distributed impurity samples of glaciers/snowpack, collected in the northeast 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 Miaoergou 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'

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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,

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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).

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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

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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

265 cell-core with organic matter particles (also sometimes including some salts) surrounded.
266 In one study the mixing state was found to affect the BC global direct forcing by a factor
267 of 2.9 (0.27 Wm^{-2} for an external mixture, +0.54 Wm^{-2} for BC as a coated core, and
268 +0.78 Wm^{-2} for BC as well mixed internally), as shown in Cappa et al. (2012), Jacobson
269 et al. (2000, 2001) and He et al., 2015. (iv) In addition to the heat-absorbing from the
270 above particle structure change, the absorbing property of some components in the
271 atmosphere and cryosphere (snow and ice) also show a large variability, as most mineral
272 and OM (or OC) particles show negative radiative forcing in the atmosphere while
273 showing positive forcing in the glacier/snowpack surface, as indicated from IPCC AR5
274 (2013), Yan et al. (2016), Zhang et al. (2018), and Hu et al. (2018). Thus, the
275 heat-absorbing of LAIs as a whole will increase greatly in glacier/snowpack surface
276 environments.

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

288

289 ## 4. Conclusions

290 The results showed that the impurities' particle structure changed greatly in snowpack
291 compared to that in the atmosphere, mainly due to particle aging (mainly BC and organic
292 matter), and the salt coating reduction process through the impurity particle's atmospheric
293 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.

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378 Tables

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

Sites	Glacier	Mountains	Locations	Altitude (m a.s.l.)	Sampling Date	Number Snow/Aerosols	Particles Calculated
MG	Miaoergou Glacier	Tianshan Mountains	42.59N,94.16E	3800-4200	12-13June 2017	8/6	>1200
LG12	Laohugou Glacier No.12	Qilian Mountains	39°20N, 96°34E	4300-4700	10-25July, 2016, 3-8June, 10-21 August 2017	20/16	>1200
QG	Qiyi Glacier	Qilian Mountains	39.14°N, 97.45°E	4200-4750	10-12June 2017 20-22August 2017	11/8	>1200
DS	Daban Snowpack	Daban Mountains	37.21°N,101.24°E	3500-3700	3-4June 2017	8/4	>1200
LG	Lenglongling Glacier	Qilian Mountains	37.51N,101.54E	3558-3990	5-7June 2017	12/5	>1200
SG	Shiyi Glacier	Qilian Mountains	38°21N, 99°88E	3900-4400	3-4June 2017	9/6	>1200
YG	Yuzhufeng Glacier	Kunlun Mountains	35.41N, 94.16E	4300-4720	12 June 2017	12/8	>1200
GS	Gannan Snowpack	Gannan Plateau	34.2N, 103.5E	2900-3200	4-8 May 2017 6-9August 2017	6/4	>1200
DG	Dagu Glacier	Hengduan Mountains	33N, 101E	3200-390	20-22 Sept 2017	2/3	>1200
HG	Hailuogou Glacier	Hengduan Mountains	31N,101E	2900-3500	11-12August 2017	6/4	>1200

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389 Figure Captions

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

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

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

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

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

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

412 **Figure 7** Salt-coating proportion changes of individual impurity particles between glacier
413 snowpack and atmosphere in various locations of northeast Tibetan Plateau

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414 **Figure 8** Internal mixing states of BC (soot), OM and mineral dust particles, in the
415 various glacier snowpack in northeast Tibetan Plateau

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

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

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

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

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441 **Figure 1**

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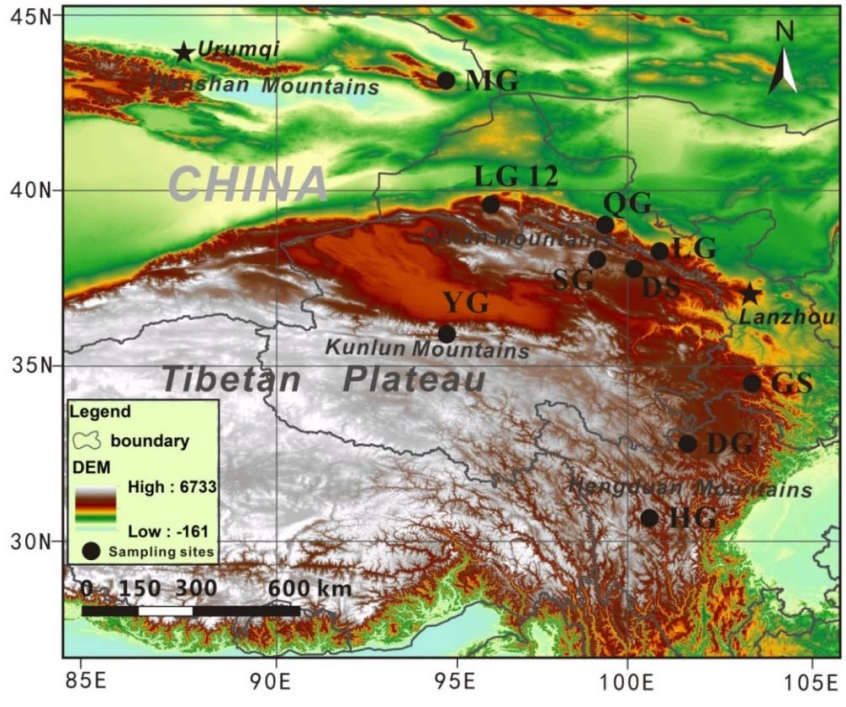

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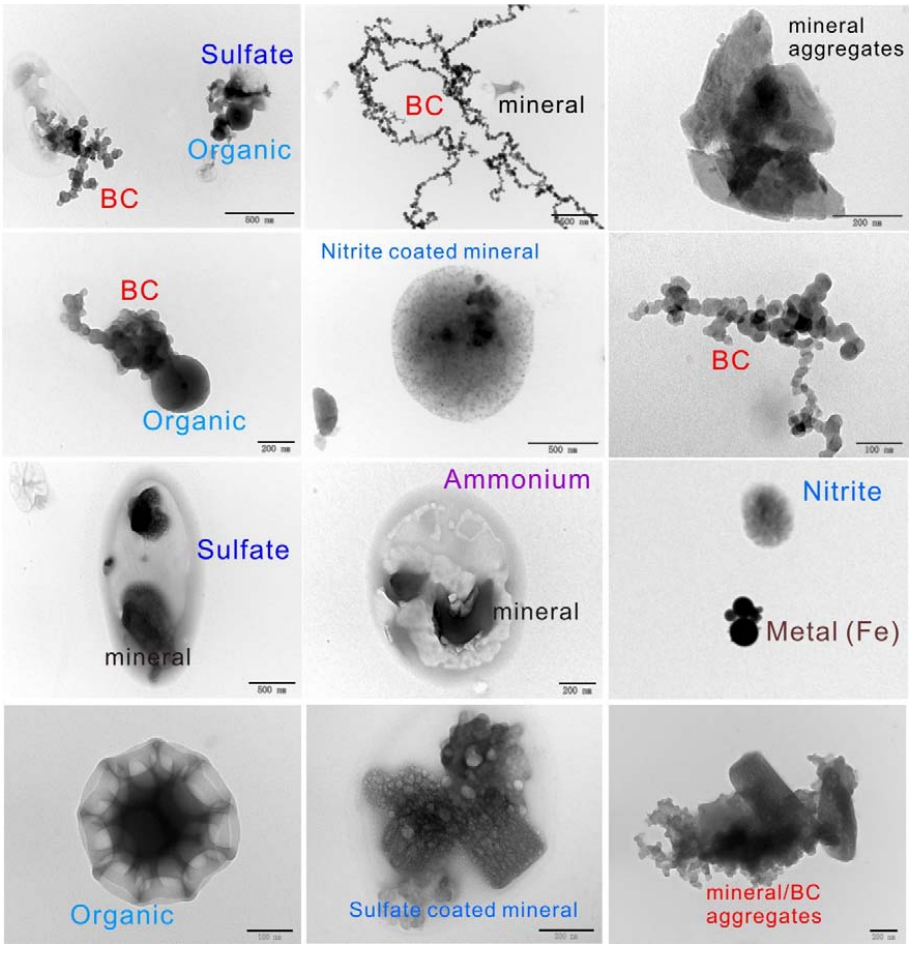
455 **Figure 2**



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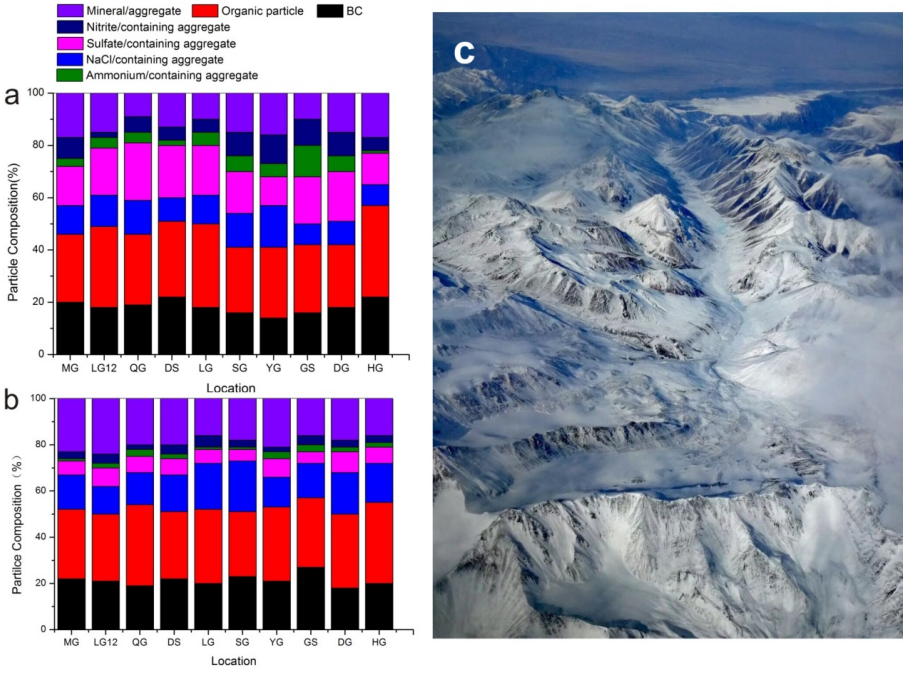
460 **Figure 3**



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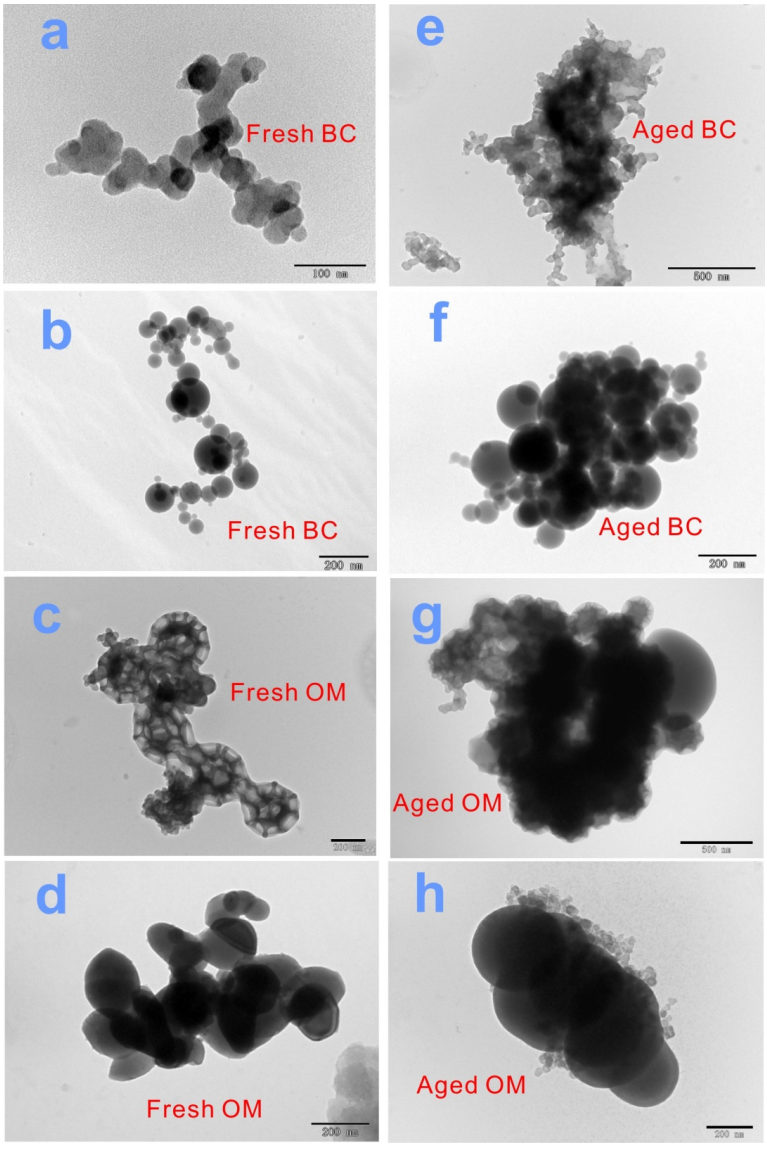
472 **Figure 4**



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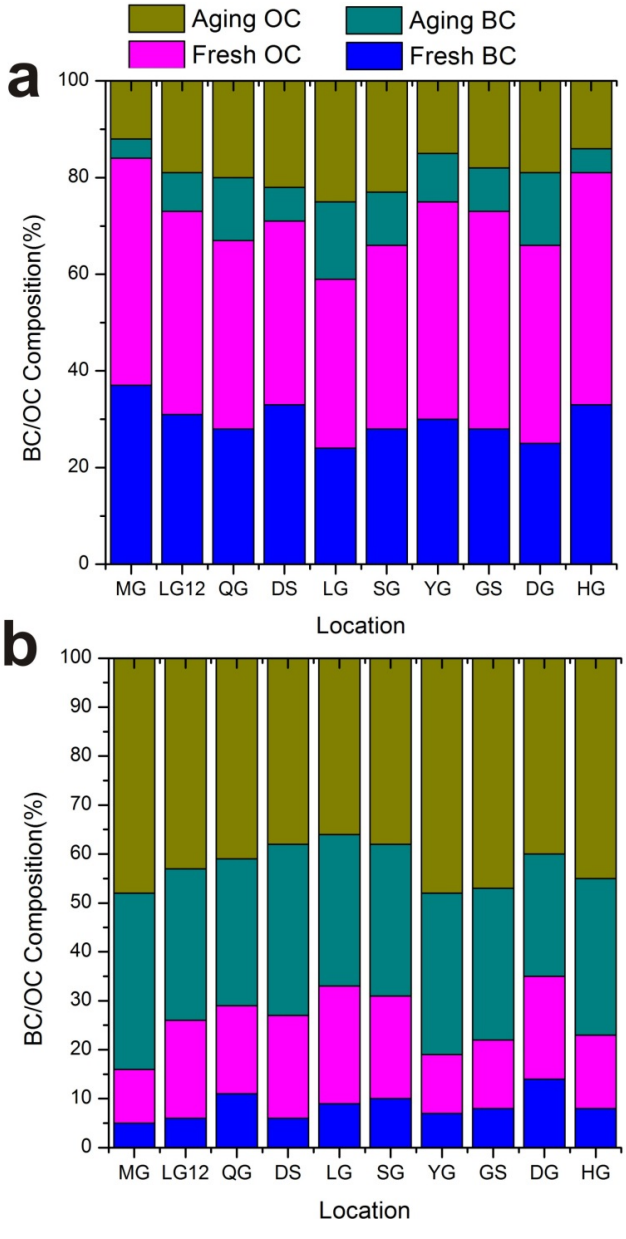
475 **Figure 5**



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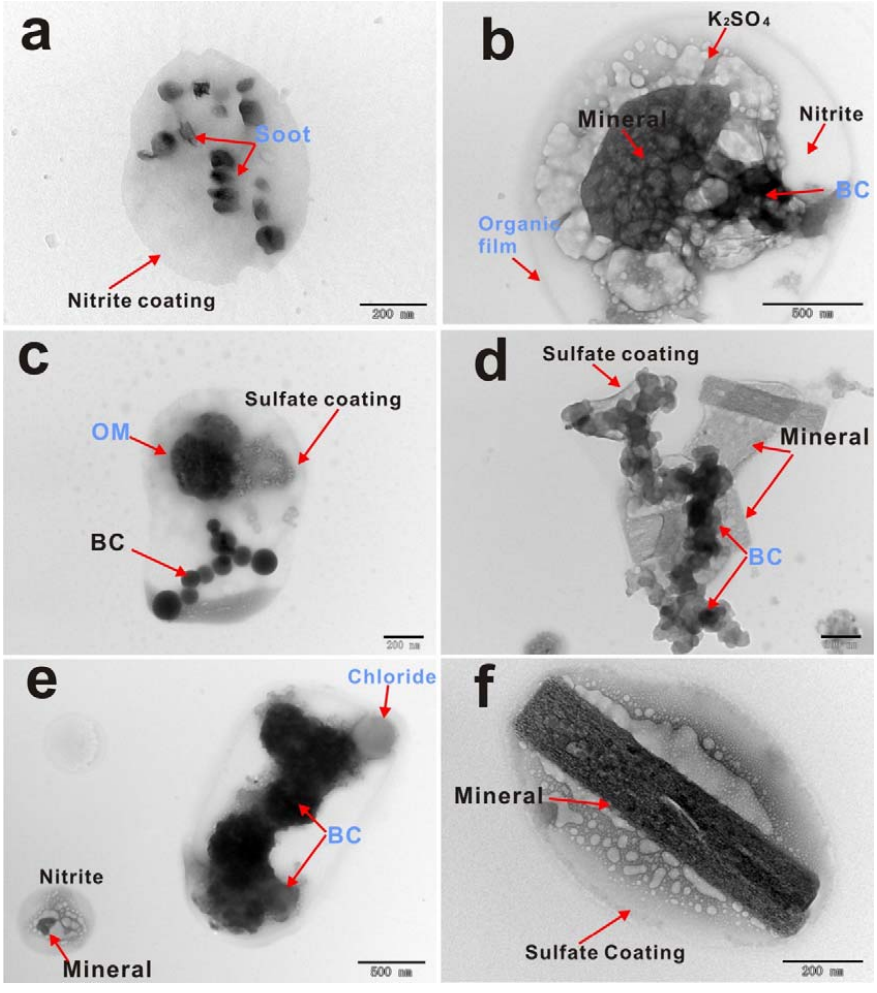
479 **Figure 6**



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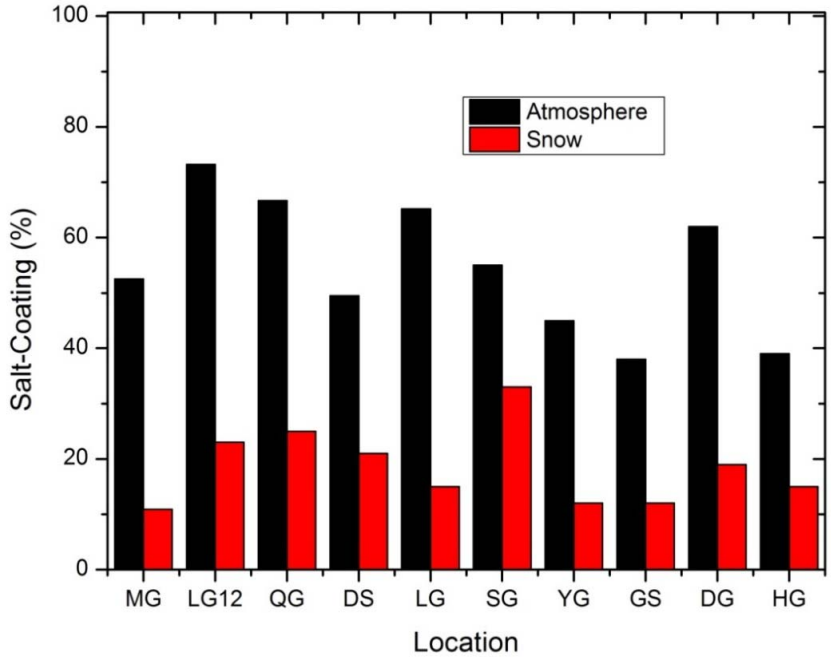
484 **Figure 7**



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499 **Figure 8**

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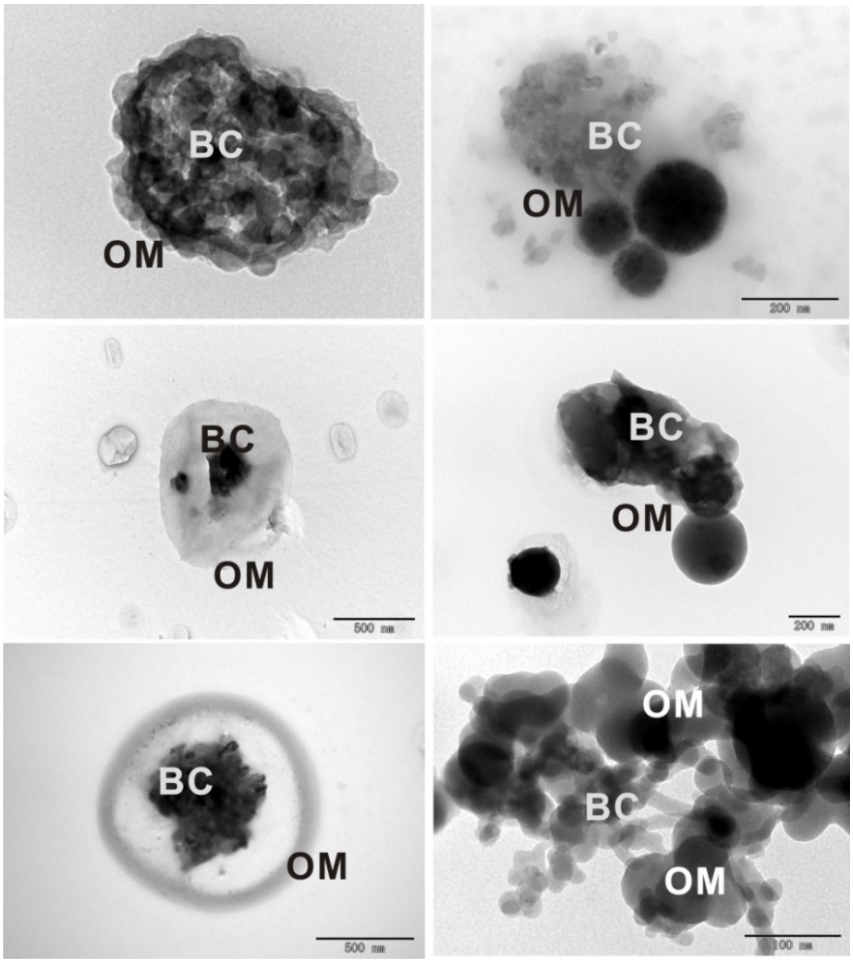

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506 **Figure 9**

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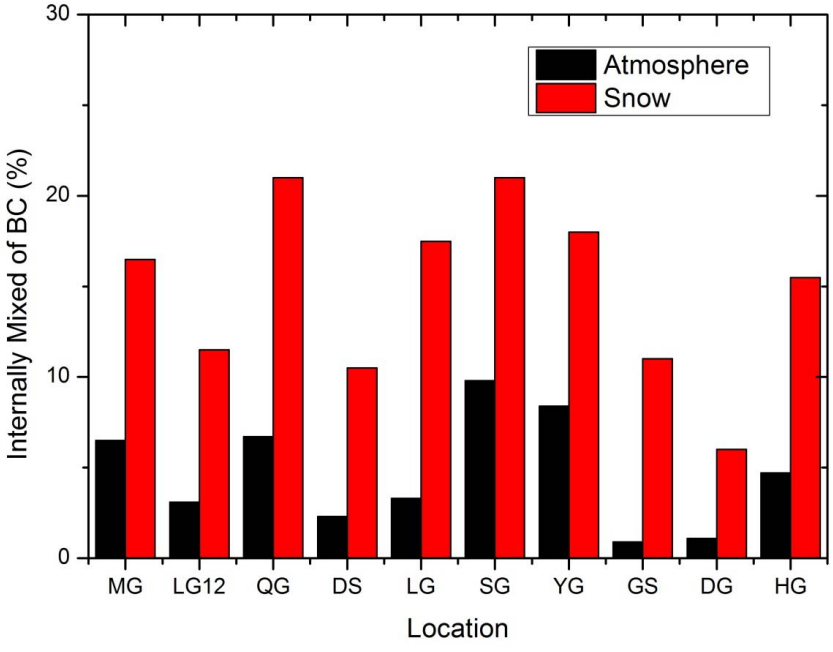

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516 **Figure 10**

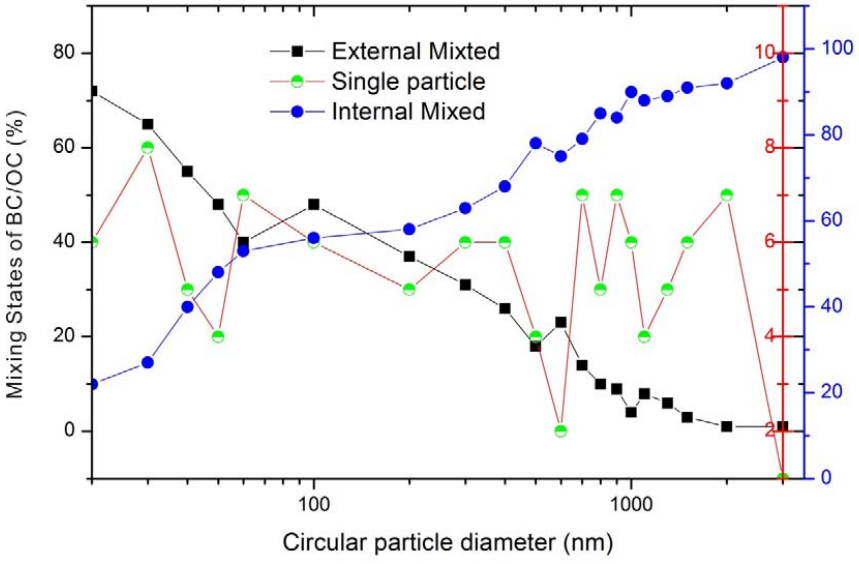

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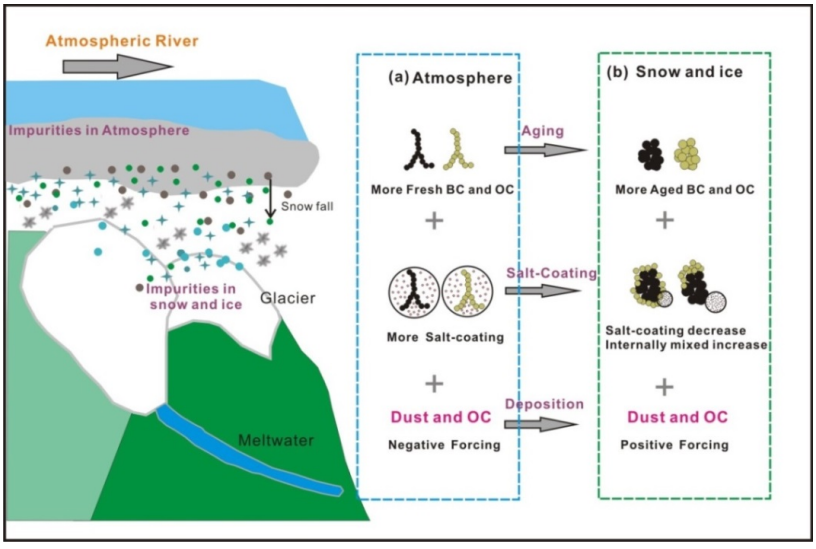
Figure 11



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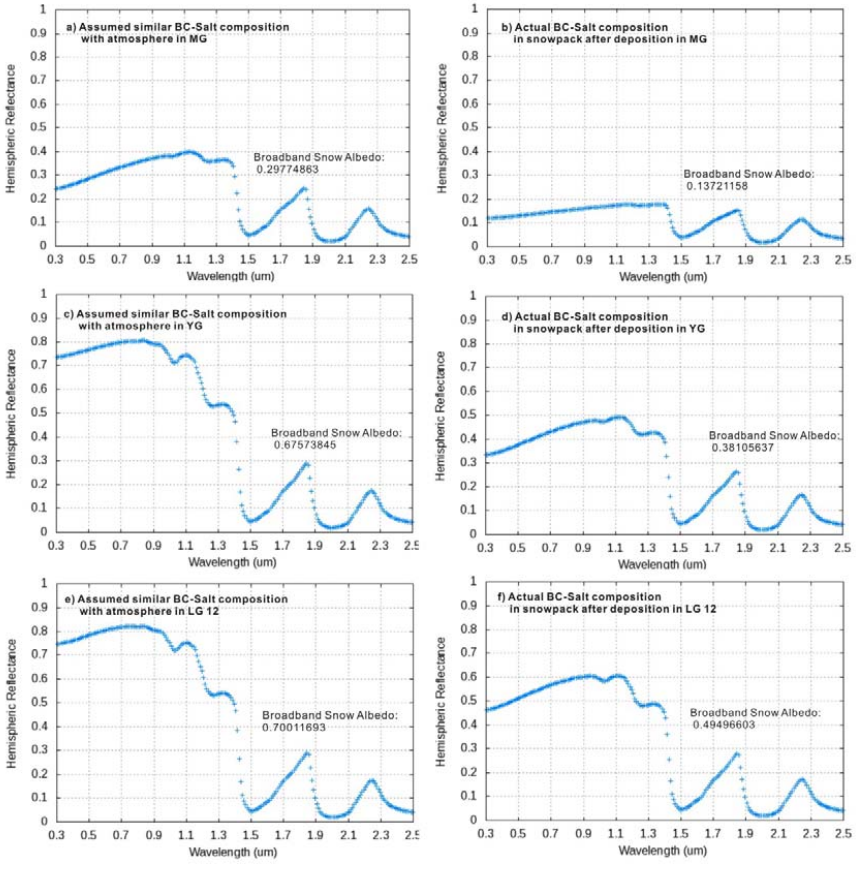

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