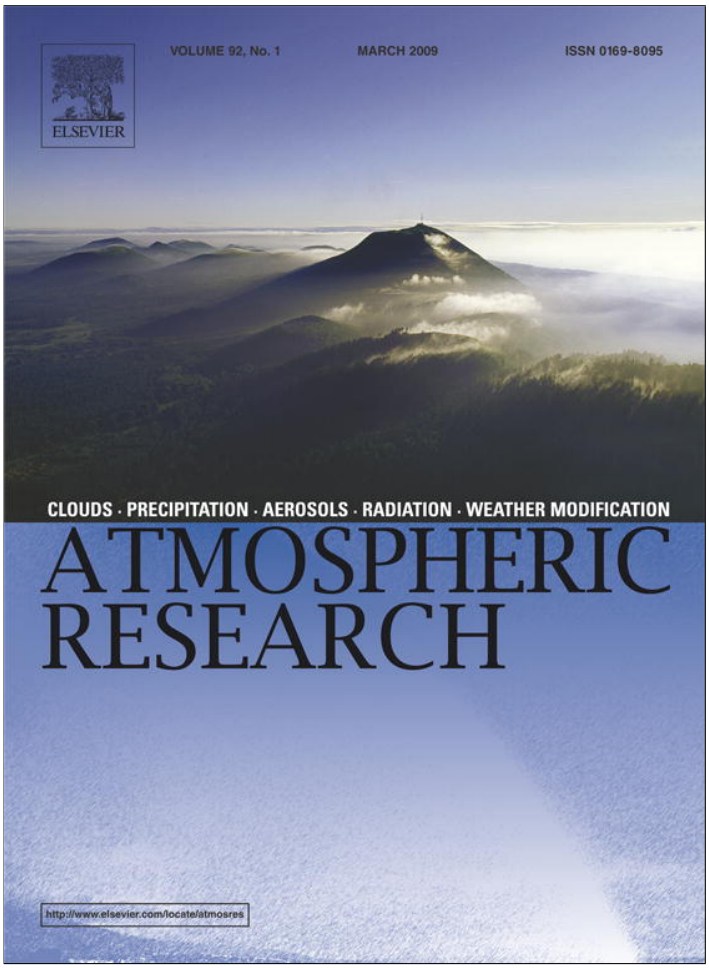

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Black Carbon (BC) in the snow of glaciers in west China and its potential effects on albedos

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ABSTRACT

Black carbon concentrations in the snow collected from some selected glaciers in west China during 2004–2006 were measured. Higher concentrations appeared at lower sites, possibly due to the topography (e.g. altitude) effect. BC concentrations in snow of Tienshan Mountains outside the Tibetan Plateau (TP) were generally higher than those inside the TP, and strong melting in spring added on more regional/local emissions from the inner TP might both contribute higher concentrations for the central TP than those on the margin of the TP. Comparison between global measured BC concentrations in snow/ice suggested the distance of the sampling site away from strong BC-emitting areas (north mid-latitudes) could be responsible for BC concentrations in snow/ice. A rough estimate for the reduced albedos in some glaciers suggested BC deposited in the surface might accelerate the melt of these glaciers in west China, e.g. HXR48 and MEG3 which were strongly contaminated by BC in their surfaces, the reduced albedos were over 5% due to the BC deposits.

1. Introduction

Black carbon, also called "soot", is an incomplete-combustion product of biofuel (e.g. wood, dung, crop residue, and etc.), fossil fuel (e.g. petroleum, diesel, charcoal, and etc.), and open biomass burning (wild fire) (Andreae and Crutzen, 1997). BC particles suspended in the atmosphere behave very complex effects on climate and a number of international campaigns (e.g. INDOEX, ACE-Asia, and etc.) have been carried out on this issue. The primary aerosol-related objectives of INDOEX were to estimate the direct and the indirect forcing of aerosols on climatologically significant timescales and space scales; link the forcing with the chemical and microphysical composition of the aerosols; and evaluate climate model estimates of aerosol forcing (Ramanathan et al., 2001). And the goal of ACE-Asia was to determine and understand the properties and controlling factors of the aerosol in the anthropogenically modified atmosphere of east Asia and the Northwest Pacific and to assess their relevance for radiative forcing of climate (Huebert et al., 2003).

In recent years, a highlight on BC's climatic effects is drawing more and more attention from scientists, i.e. BC deposited in the surfaces of snow and ice (e.g. snowpack, glacier, ice sheet, sea ice, and etc.) could enhance solar radiation absorption, reduce the albedos intensively, and thus accelerate the melting of ice. It was found that a concentration of 15 μg kg^{-1} of BC in snow may reduce the snow albedo by ~1% (Warren and Wiscombe, 1980). Light et al. (1998) calculated that 150 μg kg^{-1} of BC embedded in sea ice could reduce the albedo of sea ice by ~30% at its maximum. Hansen and Nazarenko (2004) used a model (GISSE) to simulate the solar absorption of BC in snow and ice, suggesting it may be

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responsible for ~0.17 °C of the observed global warming in the past century (accounting for ~25% of the 20th-century warming); for the same purpose, Jacobson (2004) used a different model (GATOR-GCMOM) to calculate the global warming caused by BC in snow and ice, suggesting the global mean of BC concentrations in snow and ice was ~5 μg kg^{-1} and this level of concentration could reduce the albedos of snow and sea ice by ~0.4% and thus could contribute the global warming by +0.06 °C per decade. IPCC AR4 (2007) reported the radiative forcing caused by BC in snow and ice was 0.10±0.10 W m^{-2} of global mean. And a new result from another model (SNICAR) revealed from 1906 to 1910 when the maximum BC concentration appeared in an Arctic ice core, estimated surface climate forcing in early summer from BC in Arctic snow was ~3 W m^{-2}, which was eight times of the typical preindustrial forcing value (McConnell et al., 2007). And using the same model, a north-hemisphere-based simulation suggested the greatest instantaneous forcing by BC in snow appeared on the Tibetan Plateau (TP), exceeding 20 W m^{-2} in some places during spring (Flanner et al., 2007); in particular, the mean forcing by BC deposited in the ice of the middle Himalayas exceeded 2 W m^{-2} after 2000 (Ming et al., 2008). These results indicated the solar absorption by BC in snow and ice on the TP might have significant impact on the mass balance of the glaciers.

Neighboring west China, there are two strong BC-emitting regions, South Asia and East Asia, respectively (Bond et al., 2004). BC emission from China (concentrated in east China) and India alone accounts for 25–35% of global emissions (Ramanathan and Carmichael, 2008). West China as a less developed hinterland has relatively weaker emissions (Bond et al., 2004; Cao et al., 2006), compared with South Asia and east China. And due to the dynamic transport by westerly in winter and monsoon in summer, its air quality would suffer the invasion of the pollutants emitted from above heavily polluted regions. The monitoring for BC aerosol as an air pollutant in west China is necessary not only for its environmental purpose but also for its climatic significance. However, observing networks are scarce in this area. Remote glaciers in west China are excellent carriers for accepting and preserving the deposited BC aerosol. And investigating BC on these glaciers could provide us a good approach to understand the spatial distribution of BC concentrations in west China. An earlier study provided some results of BC concentrations in surface snow of some glaciers collected in 2001 and 2004 on the TP (Xu et al., 2006), in which the data was very limitedly reported. This work aims to describe the spatial distribution and seasonal variation of BC concentrations in the surface snow of some selected glaciers in west China and discuss the potential effect of BC on the albedos.

2. Methodology

2.1. Sampling and pre-treatment

Snow samples were collected from seven selected glaciers in the TP and Xinjiang, in which the Miao'ergou No.3 glacier (MEG3) and the Haxilegen River No.48 glacier (HXR48) of Tienshan Mountains are located in Xinjiang away from the north of the TP, the Laohugou No.12 glacier (LHG12) and the Qiyi glacier (QY) of Qilian Mountains are on the northeast margin of the TP, the La'nong glacier (LN) and the Zhadang glacier (ZD) are in the central part of the TP, and the East Rongbuk glacier (ER) of the Himalayas is on the south margin of the TP (Fig. 1). In west China, during summer when precipitation is rich, glaciers are in

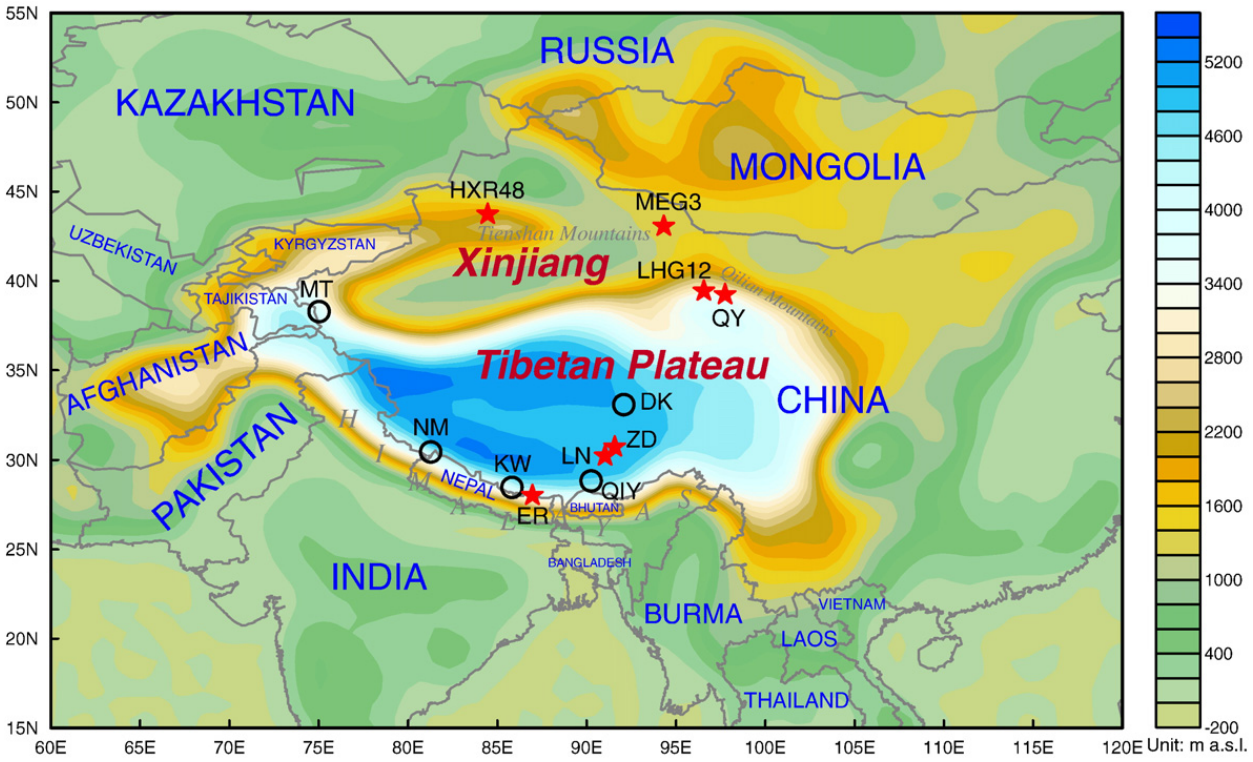

Fig. 1. The topography map surrounding the TP and the distribution of sampling glaciers. Red stars were the sampling sites in this work and black hollow circles were the sampling sites in Xu et al. (2006).

their accumulation; while during spring when precipitation is less and dust events prevail, glaciers are in their melting. Sampling site was located at the accumulation zone of the relevant glacier, and generally the zone was called the "pass" of the mountain ridge.

1-L glass bottles pre-cleaned first with a mixing liquid (H_2O–$K_2Cr_2O_2$–H_2SO_4) and then with ultrapure water (Milli-Q, 18.2 MΩ) were used for sampling. When sampling, the collector stood facing into the wind, wore the dust-proof garment with a head-and-mouth mask and gloves, and scooped snow into the bottle carefully with a stainless steel spoon. Detailed description for sampling and the sites was presented in Table 1. Sampling proceeded continuously from the snow surface to the first dust layer without intervals during 2004/2005, and in 2006 finer sampling proceeded in snow pits with intervals of 5 or 10 cm in depth, covering the deposition from spring (when dust storm prevails) to summer (when precipitations are relatively cleaner) in the same year. Empty bottles were taken to the field as blanks during each sampling course. The bottles with samples and as blanks were stored in the freezer (−20 °C) and transported to the State Key Laboratory of Cryospheric Sciences (Chinese Academy of Sciences, Lanzhou 730000, China) and kept frozen at −20 °C until the pre-treatment.

The pre-treatment included processes of melting, ultra sounding, and filtering. Warm water bath (below 30 °C) was used to shorten the time of melting, and melting process was limited within 4 h to avoid developing extra bacteria. Immediately after complete melting and prior to filtration, the bottles with samples were submitted to ultra sounding for 15 min in order to avoid loss of particles which might have attached to the inner walls of them. Samples were weighed with a cylinder (±1 mL) and then filtered through quartz-fiber filters with a pore size of 1 μm (Whatman® QMA). These filters were 25 mm in diameter and were preheated for 24 h in an oven at 600 °C. Filtration was performed using a glass unit and resulted in a circular sample-loaded spot of a 12-mm diameter in the center of the filter. A hand vacuum pump was used to accelerate filtering. Removing the pump after filtration, hydrochloric acid (2–4%) was added in the unit and passed through. Acidification step lasting for 15 min at least was necessary to remove carbonates which might if any, overestimate BC contents. The containers were rinsed four times with ultra pure water (Milli-Q, 18.2 MΩ) to ensure transferring the carbonaceous particles to the filter. Following the above processes, the attachment of particles on the glassware walls was found to be less than 5% and the fiber filter efficiency for

Table 1
Detailed description for some sampling sites and BC concentrations

Glacier	Sampling time	Location	Top–bottom (cm)	Sample code	Volume (ml)	Load (μg)	BC (μg kg^{-1})
Miao'ergou No.3	Aug. 2005	43.06°N, 94.32°E, 4510 m a.s.l.	0–70	MEG3-1	344	47.98	139
			0–70	MEG3-2	164	18.54	113
			0–70	MEG3-3	474	38.24	81
				Mean			107
				Std. Ev.			29
Haxilegen River No.48	Oct. 2006	43.73°N, 84.46°E, 3755 m a.s.l.	0–10	HXR48-1	515	5.46	11
			10–20	HXR48-2	422	9.40	22
			20–30	HXR48-3	416	12.00	29
			30–40	HXR48-4	383	31.00	81
			40–50	HXR48-5	456	28.40	62
			50–60	HXR48-6	427	14.80	35
			60–70	HXR48-7	192	16.80	88
			70–80 (dust layer)	HXR48-8	97	95.20	981
			80–90 (dust layer)	HXR48-9	71	44.80	631
				Mean			87
				Std. Ev.			330
Laohugou No.12	Oct. 2005	39.43°N, 96.56°E, 5045 m a.s.l.	0–30	LHG-1	67	2.59	39
			0–30	LHG-2	78	2.46	32
				Mean			35
				Std. Ev.			5
Qiyi	Jul. 2005	39.23°N, 97.06°E, 4850 m a.s.l.	0–34	QY-1	400	8.20	21
			0–34	QY-2	244	5.76	24
				Mean			22
				Std. Ev.			2
La'nong	Jun. 2005	30.42°N, 90.57°E, 5850 m a.s.l.	0–28	LN-1	203	16.76	83
			0–28	LN-2	234	22.58	97
			0–28	LN-3	215	4.64	22
				Mean			67
				Std. Ev.			40
Zhadang	Jul. 2006	30.47°N, 90.5°E, 5800 m a.s.l.	0–5	ZD-1	93	4.60	45
			5–10	ZD-2	67	12.61	181
			10–15	ZD-3	47	7.06	142
			15–20	ZD-4	48	1.89	32
			20–25	ZD-5	92	3.75	37
			25–30 (dust layer)	ZD-6	38	7.60	600
			30–35 (dust layer)	ZD-7	40	8.00	575
			35–40	ZD-8	35	7.00	354
				Mean			114
				Std. Ev.			236
East Rongbuk	Oct. 2004	28.02°N, 86.96°E, 6465 m a.s.l.	0–100	ER-1	205	3.71	18

capture of the particles was better than 97% (Cachier and Pertuisot, 1994). The filters would be moved into the clean Petri-slides (Millipore®) and set in the laminar flow cabinet (class 100) to let them dry. Hydrochloric acid and the rinsing solution after washing the blank bottles with ultra pure water would pass through clean filters (25 mm) for making blanks.

2.2. BC measurement

Filters were analyzed at the Laboratoire des Sciences du climat et de l'Environnement (CEA-CNRS-University Versailles St Quentin, Gif-sur-Yvette 91198, France). Pre-combustion was necessary to eliminate organic carbon (OC) and minimize any "cross-over" effect between OC and BC. BC and OC separation was obtained following the analytical protocol set up for aerosols (Cachier et al., 1989) and adopted for snow and ice samples (Cachier and Pertuisot, 1994). Sample-loaded filters were punched with a pre-cleaned stainless steel unit (14 mm of the diameter) to remove the outer sample-free loops. Before moving the filters into the analyzers, they were put in an oven for around 20 min at 70 °C to eliminate water vapor and volatile organic compounds likely adhered when they were between pre-combustion and analysis. The filters with samples and as blanks were submitted to a coulometric titration-based analysis (using the Ströhlein Coulomat 702C® with the detection limit of 3 μgC and the precision of 0.02 μgC) for measuring their BC mass. Acidification of the solution by CO_2 activated back-electrolysis to recover the initial pH value (9.8) and the quantity of electricity needed for operation could be directly related to the amount of CO_2 that had entered the solution. The pH value was readjusted to its initial prior to each analysis. More detailed description for the carbon analysis with this instrument could be seen in a previous study (Cachier and Pertuisot, 1994). The area-average BC mass density of the blank filters was 0.245 (±0.012) μgC per cm^2, yielding an average BC loading for each blank filter (14 mm) was 0.38 (±0.019) μgC, which would be subtracted from the measuring results of the samples. The weighted average BC concentration in the snow at each site was calculated, taking sample volume as weight.

3. Results and discussion

3.1. Spatial and temporal distribution of BC concentrations and its transport

In general, these glaciers where samples were collected could be divided into three types based on their geographic

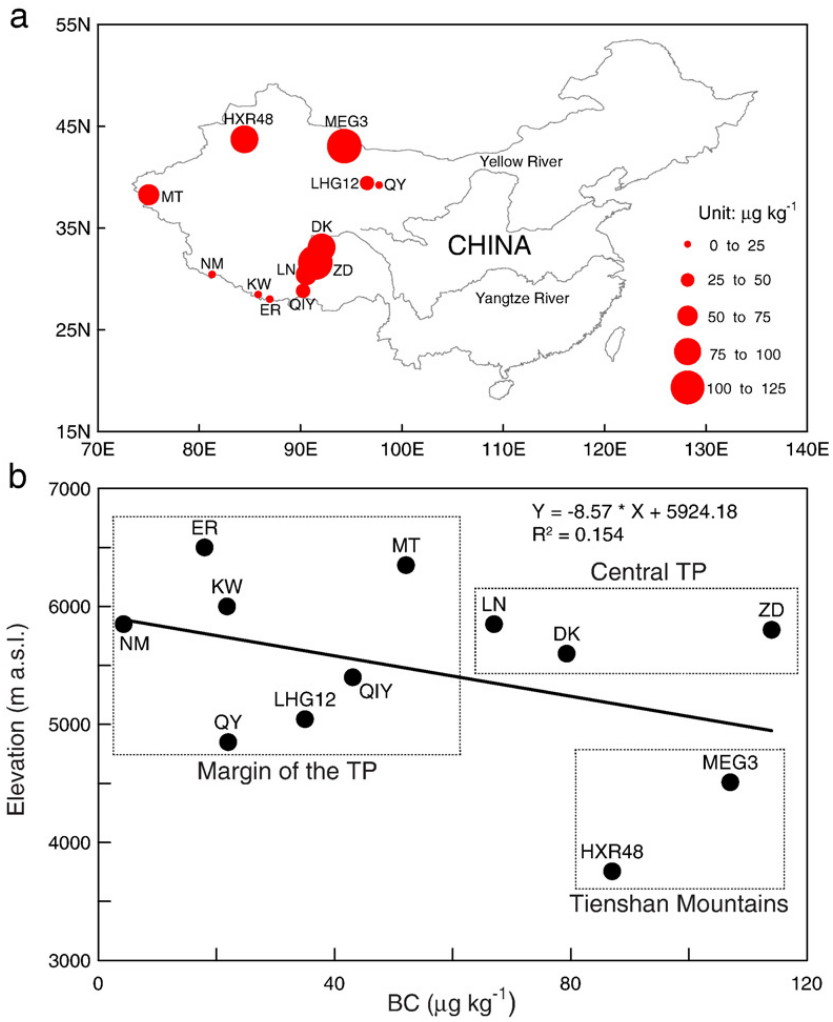

Fig. 2. a) Spatial distribution of BC concentration in snow of west China; b) BC concentrations in snow vs. elevations, where the solid line was the linear fit and different BC concentration levels were shown in three squares.

locations: one type is those located in the central TP (e.g. DK, ZD, and LN), another is those on the margin of the TP (e.g. MT, LHG12, QY, QIY, NM, ER, and KW), and the other is those on Tienshan Mountains outside the TP (e.g. HXR48 and MEG3). The TP with an average elevation over 4000 m a.s.l., is a huge terrain plumped in the north mid-latitudes and an efficient barrier restricting pollutant's invasion transported by general or regional atmospheric circulation system (westerlies and monsoons) from its outside. Previous studies suggested BC emissions from Tibet and Qinghai provinces were very weak (e.g. Streets et al., 2001; Bond et al., 2004), so the contributions from the TP to atmospheric BC could be less.

The spatial distribution for BC concentrations in the snow of the glaciers was depicted in Fig. 2, and the distribution of BC concentrations depended on the topography of west China. Compared with the glaciers on the TP with a total population over 7.5 million, the glaciers on Tienshan Mountains are more influenced by human activities due to their lower elevations and more populated surroundings (Xinjiang Autonomous Region has a population over 19 million). In general, BC concentration level in the glaciers of Tienshan Mountains (HXR48 and MEG3) was higher than that in the glaciers located on the TP (Fig. 2); and roughly, BC concentrations and their elevations showed a weak negative relationship, i.e., higher BC concentrations appeared at lower sites, and vice versa (Fig. 2b). Seasonal variation of the BC concentrations in HXR48 showed higher concentrations in spring and lower concentrations in summer, and the striking concentration variance between seasons indicated there could be strong melting taking place in spring (Fig. 3).

For the glaciers on the TP, BC concentrations in the glaciers of central TP (e.g. LN, DK, and ZD) were higher than that in those on the margin of the TP (e.g. ER, QY, and NM). On the TP, BC emissions could be found in some specific places, e.g. Lhasa (the biggest city in Tibet, owning a population larger than 450,000). A previous study suggested BC particles due to biomass burning of religious activities in Lhasa could be widely transported to the outer area of the city (Zhang et al., 2001), and another study supported this result because it found the similar phenomenon for other five cities of Tibet (Okada et al., 1999). A more recent study on aerosol near ZD and LN (the distance between these two glaciers is about 20 km) during 2005–2006 reported the ions of SO_4^{2-}, NO_3^-, and NH_4^+ had local biogenic sources, such as dung burning for

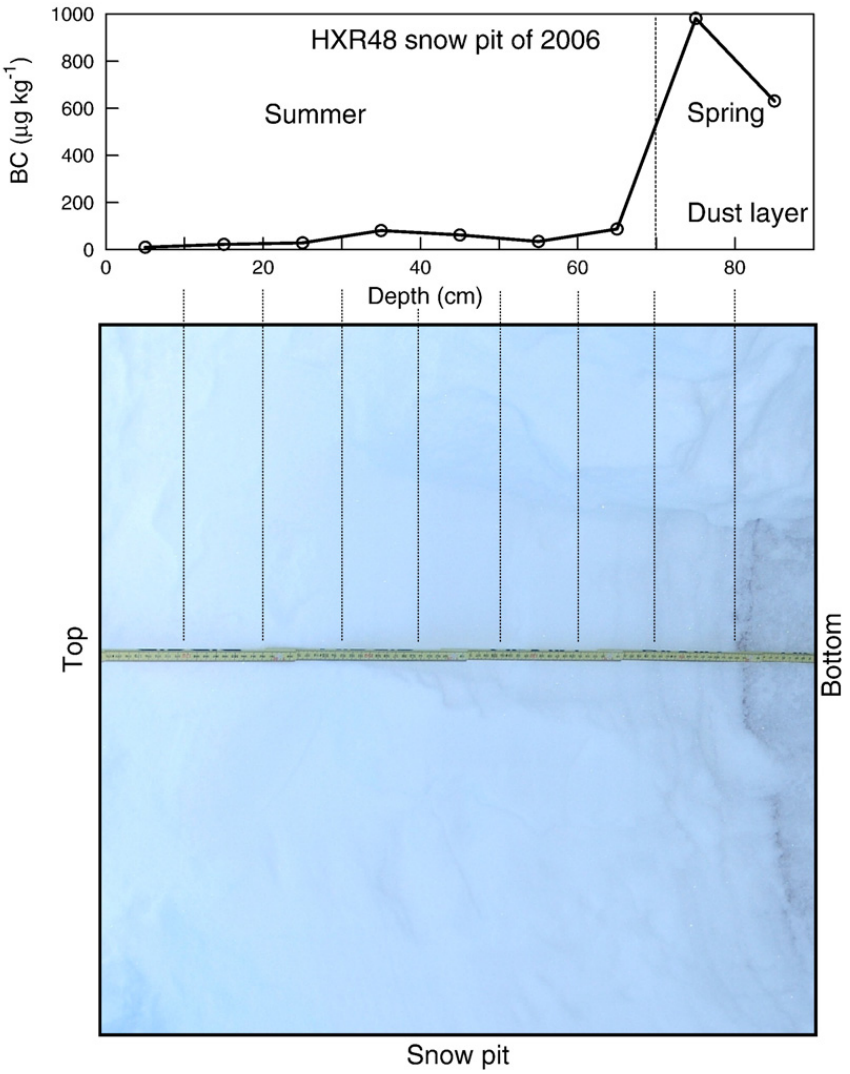

Fig. 3. BC concentrations (upper) measured in the snow pit (bottom) of the HXR48 glacier. Dust layer at 80 cm indicated the spring (melting season) of 2006.

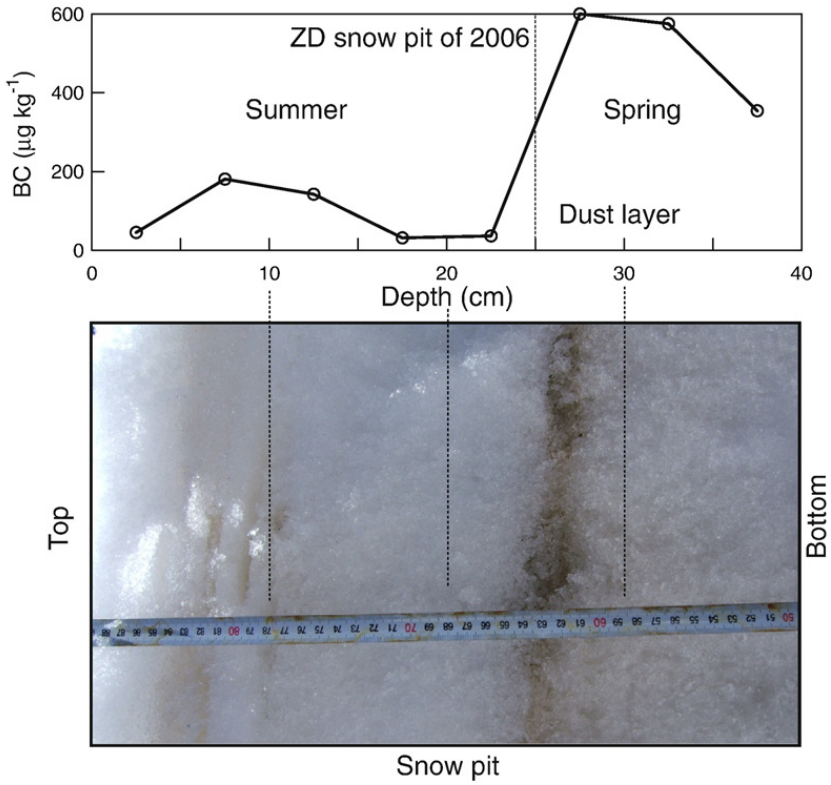

Fig. 4. BC concentrations (upper) measured in the snow pit (bottom) of the ZD glacier. Dust layer at 30 cm indicated the spring (melting season) of 2006.

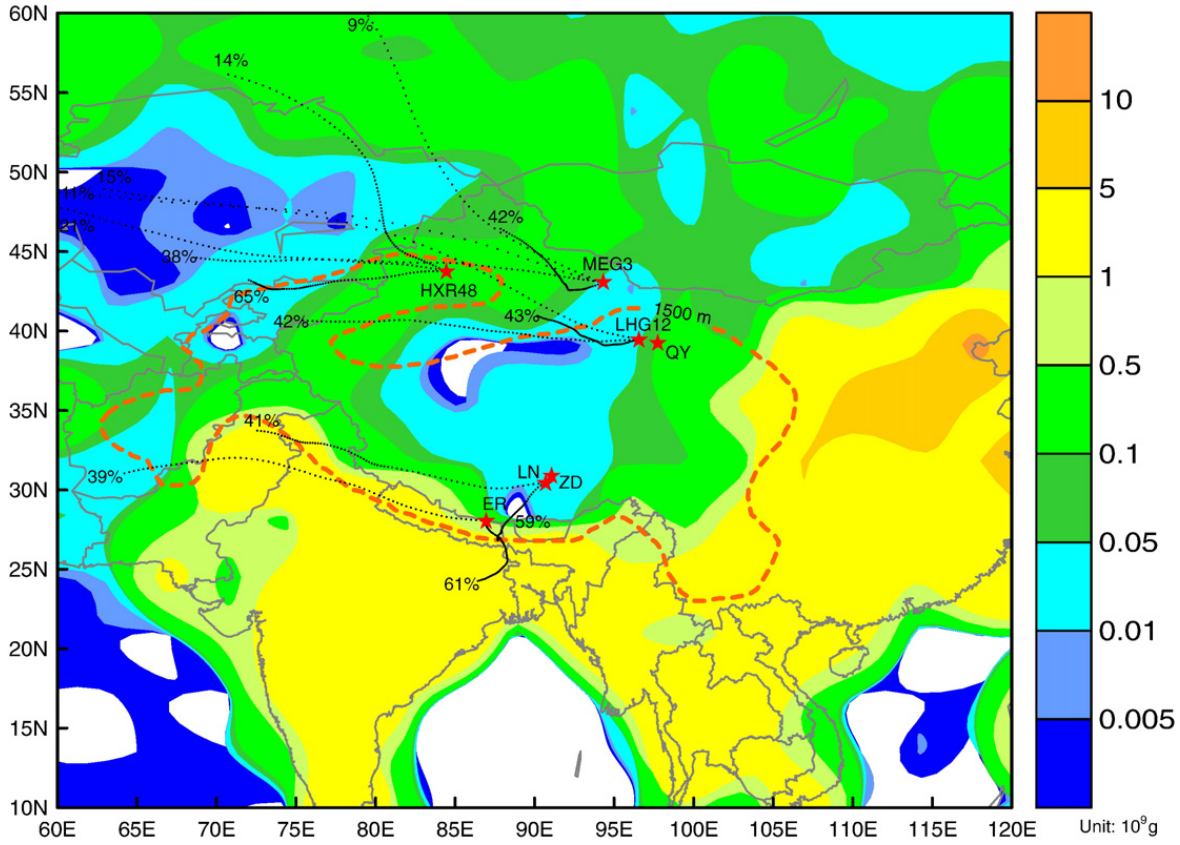

Fig. 5. Clustered mean trajectories (black dotted lines) ending at the sampling sites with sharing percentages marked beside. BC emission data (Bond et al., 2004) was plotted as the background. Orange dashed line was the contour line of 1500 m above sea level.

heating and cooking (Li et al., 2007). And these glaciers in central TP were neighboring the largest zone of human residences on the TP (Qinghai–Tibet highway), so more regional and/or local BC emissions (e.g. religious activities, transportation, heating and cooking, and etc.) could contribute more BC deposited on these glaciers. A study reported the mass balance of ZD during 2005/2006 was around −1500 mm water equivalent (Zhou et al., 2007), indicating very strong melting on ZD in recent years. And strong melting in spring could also lead to very high BC concentration in snow of these glaciers. Through a snow pit profile in ZD, significant seasonal variation of BC concentrations was observed. In summer average BC concentration in the snow of ZD was around 100 μg kg^{-1}, while it exceeded 400 μg kg^{-1} strikingly in spring (Fig. 4).

Trajectory analysis could be used to investigate the potential sources and the transport pathways of the BC deposited in the sampling sites. Daily backward trajectory traveling 3 days before ending at each sampling site (500 m above the real sampling elevation) was calculated using the HYSPLIT model (Version 4.8 with FNL data of 1.87°×1.87°) (Draxler and Hess, 1998). The mean trajectory of those ending at the site from May (when dust events prevail every year in west China) to the sampling time was calculated by clustering and shown in Fig. 5. And in the north TP and Tienshan Mountains, emissions from Xinjiang and Central Asia transported by westerlies could be the most important source for BC deposited in the glaciers, and the contribution of regional emissions carried by short-range transports shared a fairly big portion (around 40%). And in the Himalayas, BC emissions from South Asia could have impact on atmospheric environment through long-range transport by monsoons and westerlies. And in the central TP, trajectories showed similar transports as those in the Himalayas, which indicated the air quality was also influenced by westerlies and monsoons, and emissions from Indo-Gangetic basin could influence the atmospheric environment, as well as the emissions from the big cities in south TP.

3.2. A simple comparison between BC concentrations in snow and ice

Since the 1980s, measurements for BC concentrations in snow and ice have been carried out in the Arctic, north mid-latitudes, and Antarctica (Table 2). Although the methods applied for BC measurements in these studies were various, the results should be possible for a rough comparison, and worldwide measured BC concentrations in snow and ice were shown in Fig. 6. It was complex to interpret the reason that BC concentration at a specific site was higher than that at another site, but the discrepancies between the BC concentrations for snow and ice collected from different areas could be understood in a global scale. The distance of the sampling site away from the strong BC-emitting areas (north mid-latitudes) could

Table 2
Comparison between measured BC concentrations in snow and ice

Site	Longitude	Latitude	Altitude (m)	BC (μg kg^{-1})	Sampling time	Method/instrument	REF.
Cascade, Washington	121.00°W	46.00°N		59	Mar. 1980	Integrating plate	a
Alert	62.50°W	83.50°N		45.5	Nov.–Dec. 1983	Integrating plate	b
Eureka	86.00°W	80.00°N		52	1983–1984	Integrating plate	b
Greenland sea	4.23°W	79.75°N		38.7	Jul. 1983	Integrating plate	b
Spitzbergen	12.00°E	79.00°N	~500	31	May 1983	Integrating plate	b
Mould Bay	120.40°W	76.30°N		52	1983–1984	Integrating plate	b
Sea ice, Arctic	/	75.00°N		25	1983–1984	Integrating plate	b
Resolute	94.85°W	74.70°N		52	1983–1984	Integrating plate	b
Barrow	156.60°W	71.30°N		22.9	Apr. 1983, Mar. 1984	Integrating plate	b
Abisko	18.50°E	68.30°N		33	Mar.–Apr. 1984	Integrating plate	b
Dye-3, Greenland	43.80°W	65.20°N	4300	3.5	May 1983	Integrating plate	b
Hurricane Hill	123.50°W	48.00°N	1500	14.7	Mar. 1984	Integrating plate	b
Camp Century, Greenland	61.10°W	77.20°N	1886	2.4	~1985	Carbon thermal analysis	c
West Texas/New Mexico	106.00°W	32.00°N		20	1982–1985	Carbon thermal analysis	c
Ross Ice Shelf, Antarctica	175.00°W	81.50°S	657	2.5	1982–1985	Carbon thermal analysis	c
South Pole	102.00°W	90.00°S	2841	0.2	Jan.–Feb. 1986	Integrating plate	d
Summit, Greenland	37.63°W	72.57°N	3240	2.5	1988–1989	Ströhlein Coulomat 702C®	e
Vostok	106.9°E	78.5°S		0.6	Dec. 1990–Feb. 1991	Integrating plate	f
Alps	7.88°E	45.93°N	4450	128	~1982	Integrated optical and thermal method	g
Central Arctic	165.00°E	76.00°N		4.4	Mar.–Apr. 1998	Integrating plate	h
MT glacier	75.02°E	38.28°N	6350	52.1	2001	Two-step heating–gas chromatography	i
DK glacier	92.08°E	33.1°N	5600	79.3	2001	Two-step heating–gas chromatography	i
QIY glacier	90.25°E	28.83°N	5400	43.1	2001	Two-step heating–gas chromatography	i
KW glacier	85.82°E	28.47°N	6000	21.8	2001	Two-step heating–gas chromatography	i
NM glacier	81.27°E	30.45°N	5850	4.3	2004	Two-step heating–gas chromatography	i
MEG3 glacier	94.32°E	43.06°N	4510	107	Aug. 2005	Ströhlein Coulomat 702C®	This work
LHG12 glacier	96.56°E	39.43°N	5045	35	Oct. 2005	Ströhlein Coulomat 702C®	This work
QY glacier	97.06°E	39.23°N	4850	22	Jul. 2005	Ströhlein Coulomat 702C®	This work
LN glacier	90.57°E	30.42°N	5850	67	Jun. 2005	Ströhlein Coulomat 702C®	This work
ER glacier	86.96°E	28.02°N	6500	18	Oct. 2004	Ströhlein Coulomat 702C®	This work
HXR48 glacier	84.46°E	43.73°N	3755	87	Oct. 2006	Ströhlein Coulomat 702C®	This work
ZD glacier	90.50°E	30.47°N	5802	125	Jul. 2006	Ströhlein Coulomat 702C®	This work

Note: a—Grenfell et al. (1981); b—Clarke and Noone, (1985); c—Chylek et al., (1987); d—Warren and Clarke (1990); e—Cachier and Pertuisot, (1994); f—Grenfell et al., (1994); g—Lavanchy et al., (1999); h—Grenfell et al., (2002); i—Xu et al., (2006).

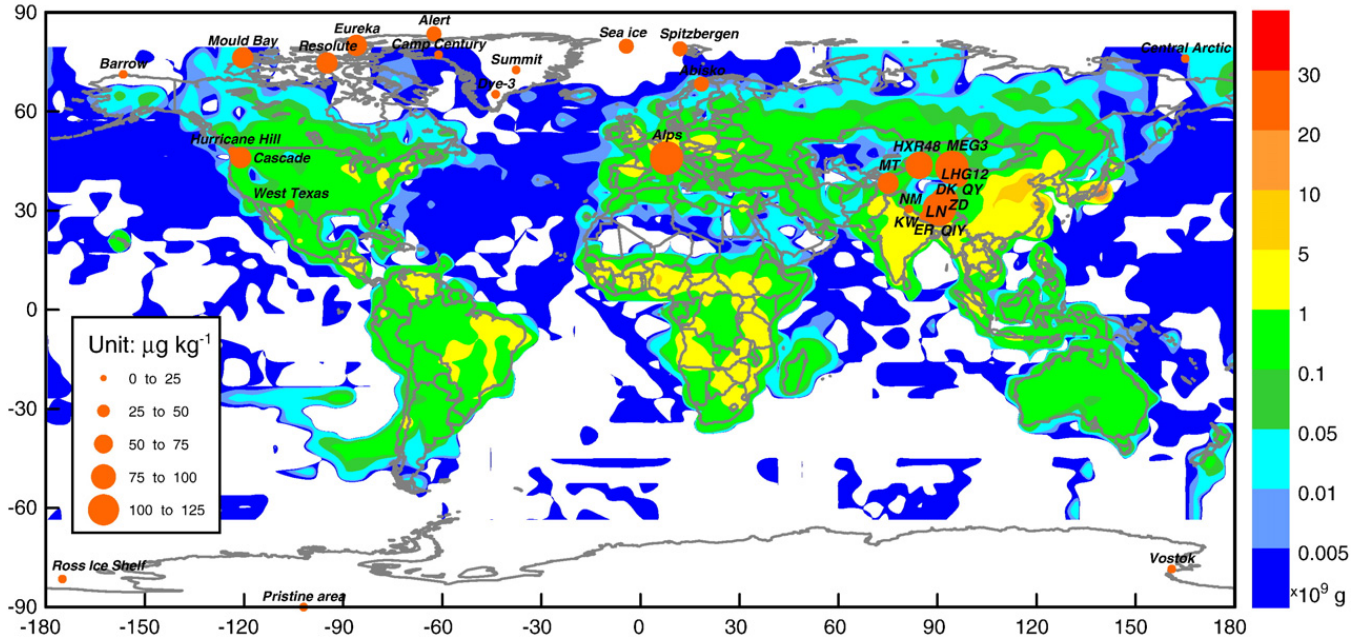

Fig. 6. BC concentrations in snow and ice measured in the globe with the background of BC emissions based on Bond et al. (2004).

be responsible for the distribution of BC concentrations in snow and ice. For example, among BC concentrations in snow/ice of Antarctica, of Arctic, and of north mid-latitudes, BC concentration in Antarctica were the lowest for the long distance away from human residences; in north mid-high latitudes, BC concentrations at sampling sites were generally high due to stronger emissions; while in Greenland and other Arctic regions, BC concentrations in snow/ice were not as high as the former due to weaker emissions and their remote sites. The turn for the sites based on BC concentration level in snow/ice could be aligned as Central Asia>Europe>North America>Arctic>Antarctica.

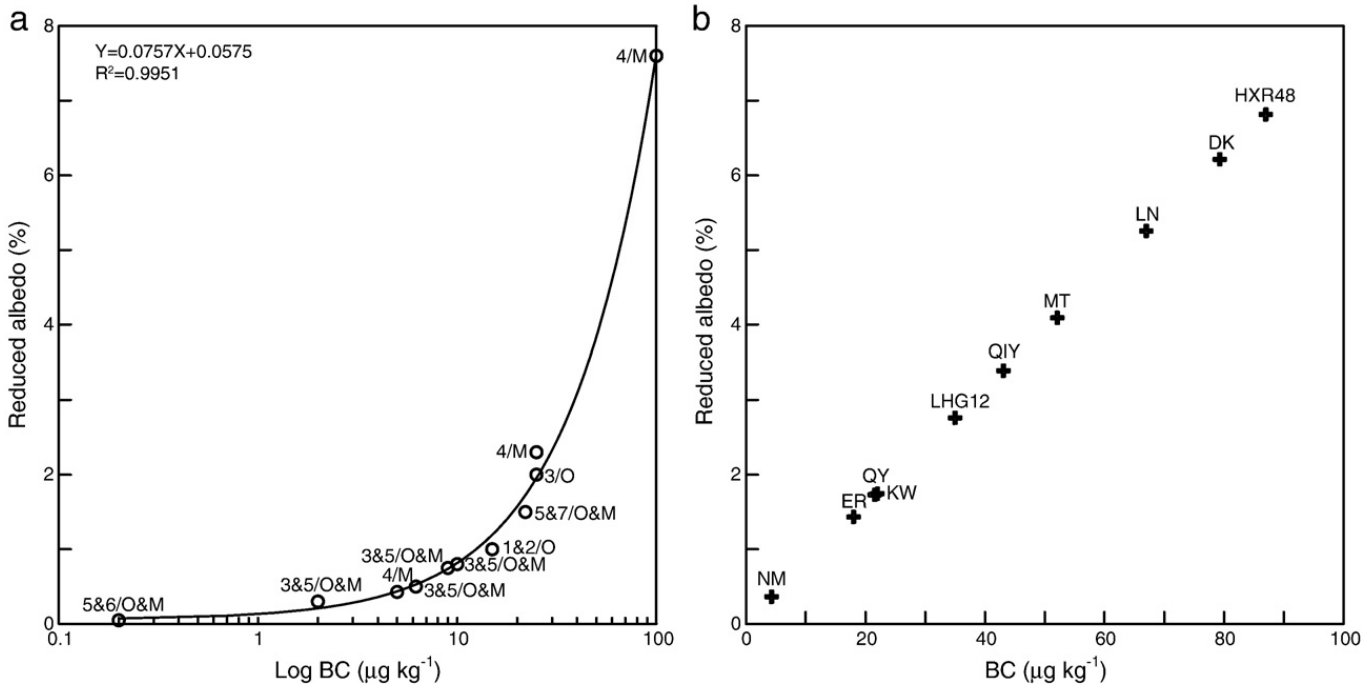

Fig. 7. a) Logarithmic scatter plot for BC concentrations and the reduced albedos (hollow circles) in snow and ice based on the observed and/or modeled results in previous studies, and the simple linear relationship (equation with R^2) possibly existed between them. Beside the hollow circles, "O" refers to Observed, "M" to Modeled, and Arabic numerals to references: 1-Warren and Wiscombe (1980), 2-Grenfell et al. (1994), 3-Clarke and Noone (1985), 4-Jacobson (2004), 5-Hansen and Nazarenko (2004), 6-Warren and Clarke (1990), 7-Grenfell et al. (1981); b) The reduced albedos due to BC in the surface of some glaciers calculated using the equation in Fig. 7a.

3.3. Potential effects on the albedos of the glaciers

A recent review provided evidence that over 80% of China's glaciers (including the glaciers in this work) were in their retreats (Xiao et al., 2007). Albedo of glacier is a very important factor to impact its mass balance besides net accumulation, air temperature, and flow dynamics. BC in snow/ice could yield significant radiative forcing, reduce albedo, and thus contribute global warming that could not be negligible. We summarized the measured and modeled BC concentrations in snow/ice versus the relevant reduced albedos from the previous studies, and thus a simple linear relationship could be derived between the BC concentrations and the reduced albedos (Fig. 7a). Using the equation in Fig. 7a, we made a rough and arbitrary calculation for the reduced albedos only due to BC for the glaciers where we sampled. The estimated results showed the significant decreases of the albedos took place in some strong BC-contaminated glaciers, e.g. albedo reduced by ~6% in HXR48 and MEG3, by ~5% in LN, and by ~4% in MT (Fig. 7b). These results were only a theoretical estimate, and needed field measurements to validate in future.

4. Summary and conclusions

BC concentrations in snow samples collected from glaciers in west China during 2004–2006 were measured. The concentrations showed a weak negative relationship with the sampling elevations, i.e., higher concentrations appeared at lower sites, and vice versa. BC concentrations in snow collected from Tienshan Mountains were generally higher than those from the TP. Strong melting in spring and more regional/local emissions from the inner TP (as indicated by trajectory analysis) might both contribute higher concentrations for the glaciers in central TP than those on the margin of the TP. Comparison between global measured BC concentrations in snow/ice suggested the distance of the sampling site away from strong BC-emitting areas (north mid-latitudes) could be responsible for BC concentrations in snow/ice. The turn for the sites based on BC concentration level in snow/ice could be aligned as Central Asia>Europe>North America>Arctic>Antarctica. A rough estimate for the reduced albedos in some glaciers suggested BC deposited in the surface might accelerate the melt of these glaciers in west China.

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