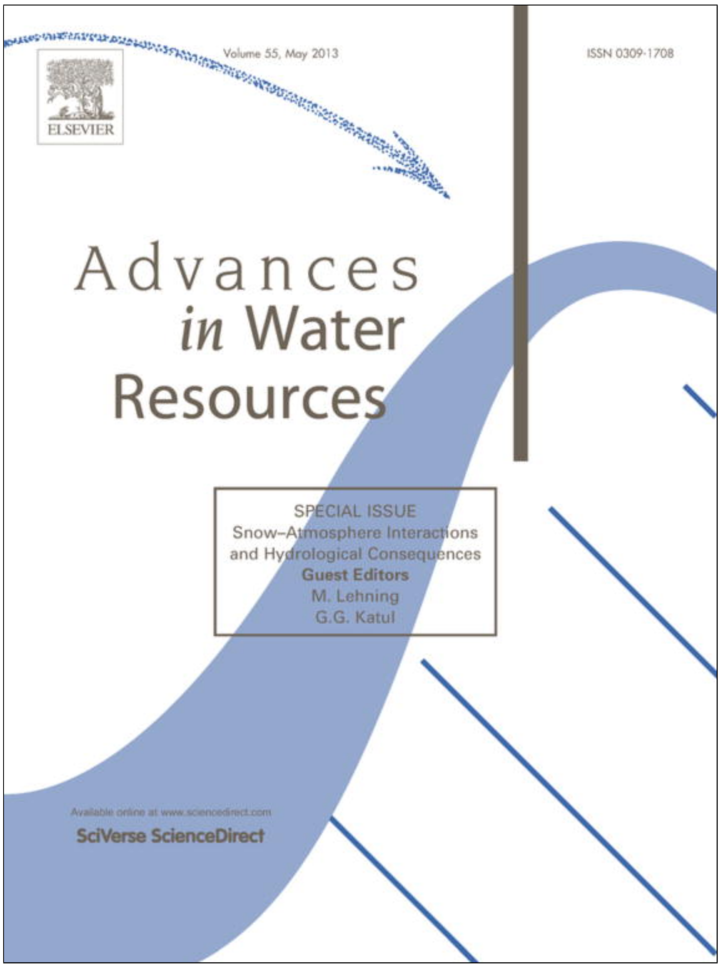
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An overview of black carbon deposition in High Asia glaciers and its impacts on radiation balance

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ABSTRACT

Since 2000, 18 High Asia glaciers have been surveyed for black carbon (BC) deposition 22 times, and numerous snow samples and ice cores have been collected by researchers. However, most of the results were interpreted individually in papers. Here, we assemble the data and discuss the distribution of BC deposition and its impacts on the melting of the glaciers through radiative forcing. We find that BC distribution on the surfaces of High Asia glaciers primarily depends upon their elevations (i.e., higher sites have lower concentrations) and then upon regional BC emissions and surface melting conditions. BC concentrations in High Asia glaciers are similar to the Arctic and western American mountains but are significantly less than heavy industrialized areas such as northern China. Although Himalayan glaciers, which are important due to their water resources, are directly facing the strong emissions from South Asia, their mean BC is the lowest due to high elevations. A new finding indicated by ice core records suggested that great valleys in the eastern Himalayan section are effective pathways for BC entering the Tibetan Plateau and make increasing BC trends in the local glaciers. On average, BC deposition causes a mean forcing of ~6 W m^{-2} (roughly estimated 5% of the total forcing) in High Asia glaciers and therefore may not be a major factor impacting the melting of most glaciers.

1. Introduction

Black carbon (BC) aerosols deposited on the surface of snow and ice could reduce the albedo and accelerate melting [11]. The IPCC AR4 report showed that global mean radiative forcing caused by BC in snow and ice was 0.1 ± 0.1 W m^{-2} from 1750 to 2005 [9], while the discrepancy between different regions was very significant due to their emitting intensities, ocean-land distributions, topography, regional atmospheric circulations, and other factors.

More recent studies have suggested that the impact of BC deposition in snow and ice cannot be ignored as an element of climate forcing. An ice core from Greenland revealed that industrial BC emissions had altered 20th century Arctic climate forcing by eight times compared with that of typical preindustrial ages [15]. Flanner et al. [8] suggested that BC emitted from the Northern Hemisphere in 1998 caused a radiative forcing of 0.2–0.6 W m^{-2} in the Arctic snow and ice, and it reduced the snow albedo by 0.13 in northeastern China; whereas the greatest radiative forcing in the Northern Hemisphere was over the snow and ice cover of the Tibetan Plateau (TP) with an average of 1.5 W m^{-2}. A numerical model showed that approximately 0.9% of Himalayan snow and ice cover disappeared from 1990 to 2000 due to aerosols, of which approximately 36% was caused by BC [16]. These results lead to an impression that BC deposition in the global snow and ice surfaces could be accelerating melting.

The preceding conclusion was primarily based on BC emission-transport-deposition modeling work [16,35,21,13]. However, during 1998 and 2005–2009, Doherty et al. [5] collected ~1200 snow samples in Arctic regions for comparison with the 1983–1984 survey of Clark and Noone [4]; the measured results showed that the BC concentration level for Arctic snow was lower than (or comparable to) that approximately 20 years ago. Warren's group then suggested it was doubtful to claim BC in Arctic snow had contributed to the rapid decline of Arctic sea ice in recent years [5]. The results of this study hinted that the impact of BC deposition on the snow and ice should also be reconsidered in other regions of the world.

High Asia is the wide mountainous interior of Asia including the Tibetan Plateau, the Pamirs, the Himalayas, and Tianshan Mountain. Western China is home to High Asia glaciers, where water resources are extremely important for more than one billion residents of these regions (Central, East, and South Asia). Closely neighboring High Asia, BC emissions of South Asia and Eastern China doubled from 1950 to 2000 [2]. Some previous studies suggested BC might be

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the second factor, next to greenhouse gases, that were heating the glaciers in this region [23,16].

Nevertheless, the impact of BC deposition, and the resulting melting of High Asia glaciers, is still a question to be answered from the view of measurement. Since 2000, Chinese researchers have investigated 18 glaciers for BC in Western China, where snow and ice core samples were collected and BC concentrations were measured [30,18–20,31,32]. The data and results were based purely on the measurements in the field and the laboratory; however, they were published separately in individual papers, and no comprehensive discussions on BC impact on melting were made until now. Here, we collect the BC data together from the previous investigations, simulate the forcing of BC deposition, and estimate its impact on glacier energy balance assisted by in situ radiation measurements.

2. Data and methods

2.1. BC data collection

The BC data used here are mainly cited from previous studies with few unpublished data and are listed in Table 1. In total, there are 18 glaciers that have been investigated 22 times altogether since 2000. The glaciers span from 75°–100°E, 25°–45°N and are located in seven different mountain ranges in High Asia, including the Tianshan, Pamirs, Qilian, Kunlun, Tanggula, Nyainqentanglha, and Himalayas (northern slopes inside China) (Fig. 1). The samples from these sites include 72 snow samples and six ice cores. Snow samples were collected mostly from snow pits, and some were collected from surface snow; and their sampling sites were all located in the accumulative areas. Here, we use the BC concentration data averaged for each site. Usually, the snow-pit samples represented the snow deposited across one year, at least, and the surface snow samples were deposited within the year when the sample was collected. Ice cores span over a longer period of time, and their BC concentrations are averaged in Table 1. What should be noticed here is that only surface snow is relevant to the radiation balance, although during melt some BC from deeper layers will regularly re-surface. And therefore, the calculated radiative forcings caused by BC refer to annual averages, but not real-time values. Taking into account the sample-filtering method follows Cachier and Pertuisot [3] and is similar to Huang et al. [12], we estimate that the BC concentrations are approximately 8–15% less than the values they should be.

2.2. In situ radiation measurements on the snow surfaces

We do not have in situ radiation measurements at all sites; however, we set up radiation observation systems on the glacier-accumulation-area surfaces of ER in 2005 and LHG12 in 2006 (Fig. 1, Table 1). Both of the sites use the same type of sensors (CNR-1, Kipp&Zonen) with a sensitivity of 5–35 μV m^2 W^{-1} to measure the downward incidence and upward reflectance of the glacier surfaces. They were fixed on iron weather towers, and measurements were recorded, except when the battery failed due to very low temperatures. At the ER site, we had successful radiation records in the summer of 2005 and the winter of 2007–2008, and at the LHG12 site, a complete annual cycle was recorded during 2008–2009 (Table 2).

Table 1
Dataset of averaged BC in snow and ice samples in some High Asia glaciers primarily based on previous investigations with few unpublished data.

Mountain area	Glacier name	Glacier ID	Sampling time	Latitude (°N)	Longitude (°E)	Altitude (m)	Sample type (#)	Deposition time	Ave. BC (ng g^{-1})	Source
Tianshan	Haxilegen Riverhead No. 48	HXR48	Oct. 2006	43.73	84.46	3755	Snow pit (9)	2005–2006	87	[19]
	Urumqi Riverhead No.1	UR1	Nov. 2006	43.10	86.82	4050	Snow pit (2)	2005–2006	141	[20]
	Miao'ergou No. 3	MEG3	Aug. 2005	43.06	94.32	4510	Snow pit (3)	2003–2005	107	[19]
Qilian	Laohugou No. 12	LHG12	Oct. 2005	39.43	96.56	5045	Snow pit (2)	2004–2005	35	[19]
	Qiyi	QY	Jul. 2005	39.23	97.06	4850	Snow pit (2)	2004–2005	22	[19]
Kunlun	Meikuang	MK	Nov. 2005	35.67	94.18	5200	Snow pit (2)	2004–2005	81	[20]
Tanggula	Tanggula	TGL	~2004	33.11	92.09	5800	Ice core (32.5 m)	~1950–2004	26	[32]
	Dongkemadi	DK	2001	33.10	92.08	5600	Snow pit (4)	~2001	79	[30]
			2005	33.10	92.08	5600	Surface snow (1)	~2005	36	unpublished before
Nyainqentanglha	La'nong	LN	Jun. 2005	30.42	90.57	5850	Snow pit (3)	2004–2005	67	[19]
	Zhadang	ZD	Jul. 2006	30.47	90.50	5802	Snow pit (8)	2005–2006	114	[19]
Pamirs	Muztagh Ata	MT	2001	38.28	75.02	6350	Snow pit (6)	~2001	52	[30]
			~2001	38.28	75.10	6300	Ice core (40 m)	~1955–2001	33	[32]
Himalayas	Namunani	NM	2004	30.45	81.27	5900	Surface snow (7)	~2004	4	[30]
	Kangwure	KW	2001	28.47	85.82	6000	Surface snow (1)	~2001	22	[30]
	East Rongbuk	ER	Sep. 2006	28.02	86.96	6500	Snow pit (20)	Summer, 2006	9	Unpublished before
			Oct. 2004	28.02	86.96	6500	Snow pit (1)	2003–2004	18	[19]
			Sep. 2002	28.02	86.96	6500	Ice core (40 m)	1951–2001	16	[18]
	Noijin Kangsang	NK	~2006	29.04	90.20	5950	Ice core (23.5 m)	~1950–2006	20	[32]
	Qiangyong	QIY	2001	28.83	90.25	5400	Surface snow (1)	~2001	43	[30]
	Palong-Zanbu No. 4	PLZ4	2006	29.21	96.92	5500	Ice core (29 m)	1998–2005	9	[31]
	Zuoqiupu	ZQP	~2006	29.21	96.92	5600	Ice core (97 m)	1956–2006	5	[32]

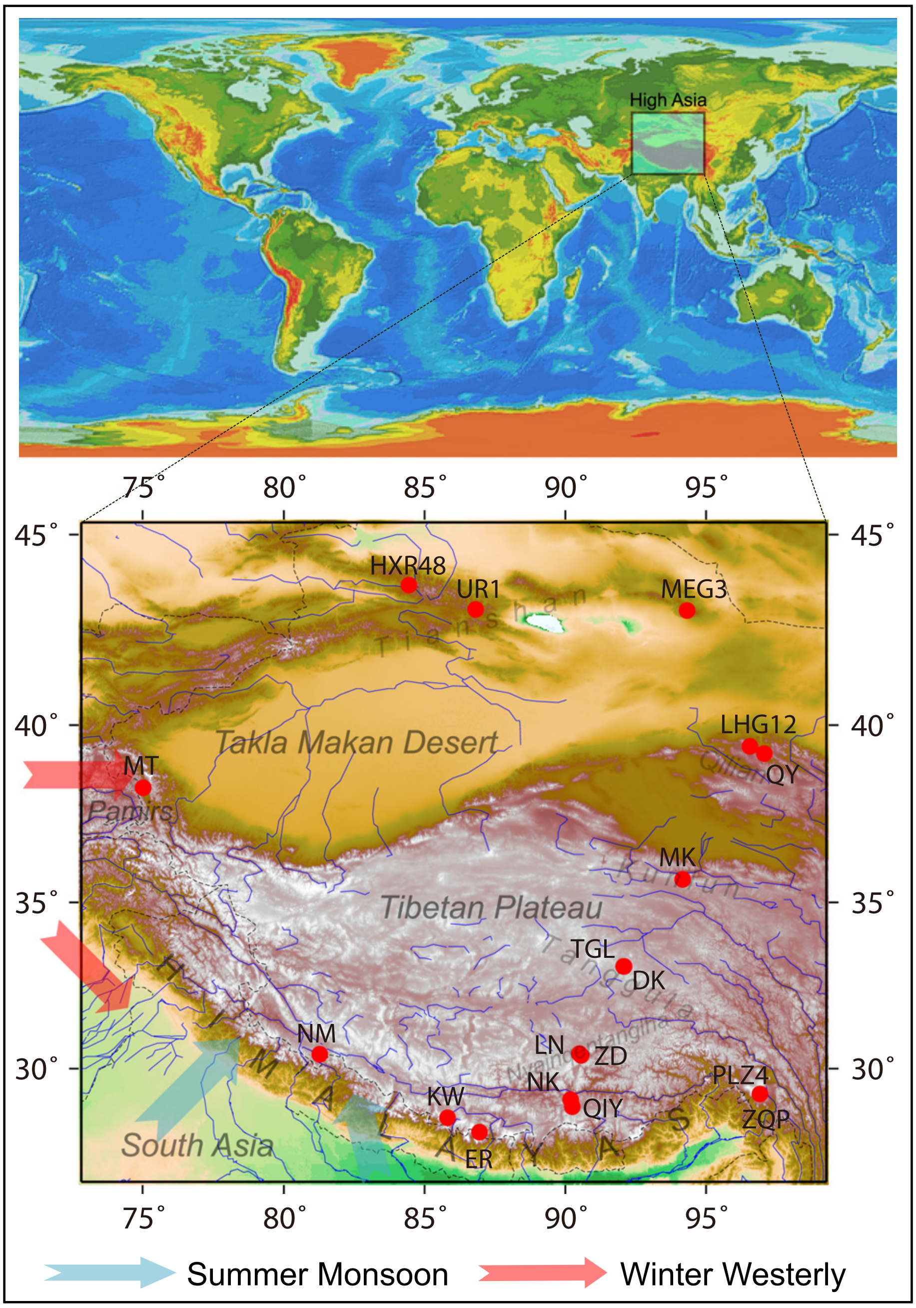

Fig. 1. Location map of the surveyed glaciers in High Asia.

Table 2
Surface radiation balances on the ER and LHG12 glaciers.

Glacier ID	Observing time period	Ave. R_d (W m^{-2})	Ave. R_u (W m^{-2})	Net Flux (W m^{-2})	Source
ER	2005 summer & 2007–2008 winter	556	389	167	[33]
LHG12	2008–2009 annual cycle	220	162	58	[28]

Note: R_d denotes the downwelling radiation, and R_u denotes the upwelling radiation.

2.3. The model description

The model used for simulating the radiative forcing caused by BC deposition in the snow surface is a SNow-ICe-Aerosol Radiative (SNICAR) model developed by Flanner et al. [8]. Although we had calculated the forcing of BC deposition for some glaciers in a previous work [20], the results did not include the data of all known sites and were very conservative for only assuming a fine-grain snow case (snow grain effective radius of 150 μm and density of 150 kg m^{-3}). However, the effects of BC deposition on the albedo of different types of snow are quite different, and a certain concentration of BC could reduce more albedo for the snow with greater grain size [29]. Here, we run the model by inputting the average BC concentration at each site and simulate their forcings in the snow surfaces in both maximum (coarse-grain: grain effective radius of 1000 μm and density of 500 kg m^{-3}) and minimum (fine-grain) cases. Thus, uncertainty ranges of BC forcing in glacier surfaces are derived, and the forcing values could be more confident.

3. Results and discussion

3.1. BC emissions surrounding High Asia glacial regions

The regions surrounding High Asia, such as South Asia, Eastern China and Central Asia, are rapidly developing regions. Hence, BC emissions in these regions are increasing dramatically. For example, an inventory study suggested that the BC emission in India had increased 61% from 1991 to 2001 [25]. Ming et al. [20] showed that there are several strong-emitting regions surrounding High Asia glacial areas, i.e., Indo-Gangetic Basin in Northern India, Sichuan Basin in Central China, Pakistan, Bangladesh, and Central Asia.

Consequently, aerosol loading in the atmosphere over these regions was thicker than elsewhere. An aerosol optical depth (AOD) map, derived from the data of the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite, describes the mean atmospheric aerosol-loading status in 2003 (Fig. 2). As showed in Fig. 2, strong emission areas lead to heavy aerosol loadings, except the desert regions that are strongly influenced by natural sand emissions. It is generally believed that the westerly wind and the monsoon dominate the synoptic system over the Tibetan Plateau during winter and summer, respectively [27]. Industry-related pollutants, including sulfate and mercury, had been detected in the glaciers of high Mt. Qomolangma [17,14]. Thus, the glacial covers of High Asia areas can be affected by the surrounding BC emissions.

3.2. Regional BC distribution in the High Asia glaciers and a global view

BC concentrations were averaged in the mountain ranges to interpret their regional distribution in the surfaces of the High Asia glaciers (Fig. 3). BC concentrations range from 16 to 112 ng g^{-1} with the average of ~50 ng g^{-1}. The glaciers with the highest BC concentration are in the Tianshan Mountains. The Himalayan glaciers have the lowest BC concentration (16 ng g^{-1}), compared with others.

In a previous investigation [19], it was suggested that the elevations where glaciers were located was the dominant factor influencing BC levels. After assembling all data together, the previous conclusion seems to not only work here that higher glaciers have lower BC concentrations in their surfaces, but also make the correlation between elevation and BC more robust after adding six new points (the R^2 increases from 0.15 to 0.36) as shown in Fig. 4. It is notable that the glaciers in the hinterland of the Tibetan Plateau

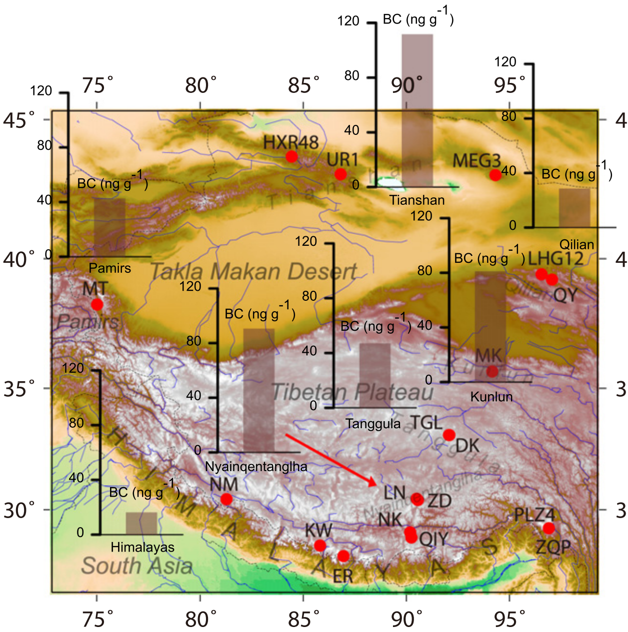

Fig. 3. Mountain-averaged BC concentrations deposited in the surfaces of the investigated glaciers.

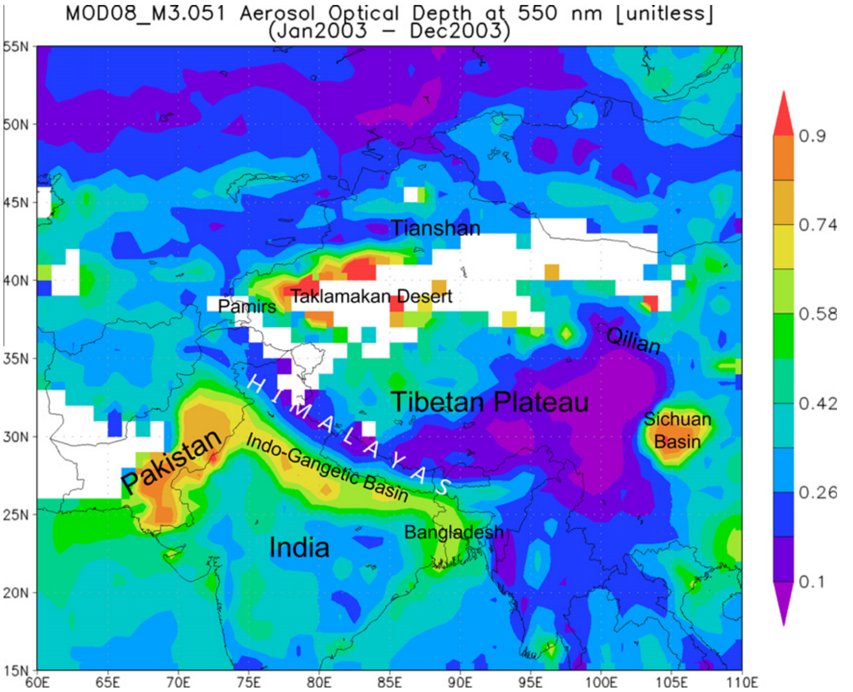

Fig. 2. Annual mean aerosol optical depth in the High Asia region in 2003, recorded by MODIS sensor aboard the Terra satellite.

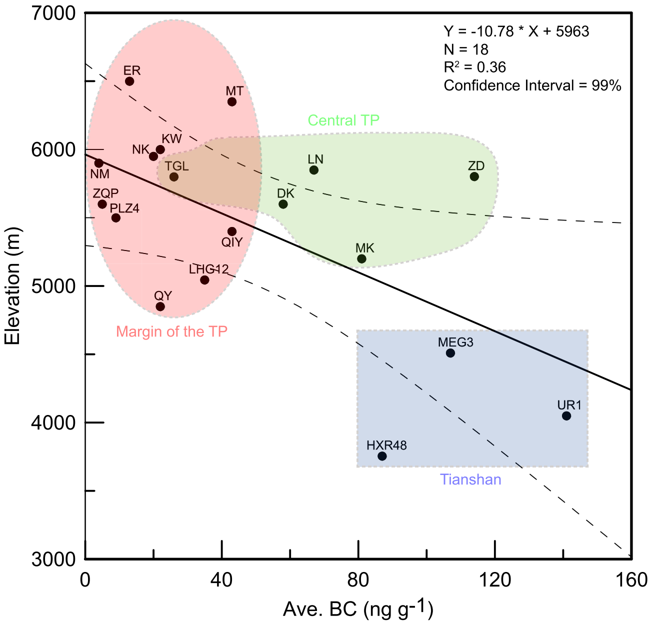

Fig. 4. Distribution plot of BC concentrations of High Asia glaciers varying with elevation. The black solid line is the fit of the data points, beside which two dashed curves represent the confidence interval of 99%.

have considerably high BC concentrations (exceeding 80 ng g^{-1}), such as those in the Kunlun and Nyainqentanglha mountains. Strong melting often occurs in these glacier surfaces [37] and caused BC enriching and forming some dirty layers, which may be a possible reason leading to high BC levels, suggested by snow-pit observations [19]; on the contrast, relatively low temperature in the highly elevated Himalayas could preserve glaciers' snow well from strong melting and conserve the initial BC concentrations. The glaciers in Tianshan may be impacted by both strong surface melting and local BC emissions, leading to the highest BC level in their surfaces. This implies that the snow surface BC particles in some glaciers of High Asia may be concentrated and cause high concentrations in their surfaces due to melting.

We collected three other studies on in situ snow sampling and laboratory measurements of BC and list the results, including ours, in Table 3. These other three studies were implemented in the Arctic [5], Sierra Nevada [10], and Northern China [12], respectively. The four groups of samplings were mostly carried out after 2000, which makes the results comparable in some way. Remote sites (Arctic, Sierra Nevada, and High Asia glaciers) have BC concentrations lower than 50 ng g^{-1}. However, in Northern China, which is well known for heavy industry activities, the average BC is an order of magnitude higher than the other three. This indicates that BC concentrations on High Asia glaciers could represent a less contaminated level, although these glaciers are surrounded by strong BC-emitting regions.

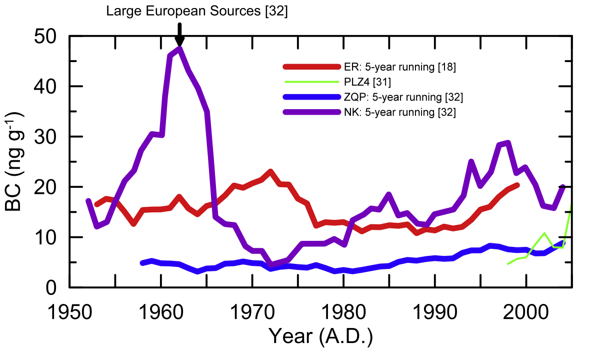

Fig. 5. BC records in the ice cores drilled from the ER, NK, PLZ4, and ZQP glaciers in the middle and eastern Himalayan parts.

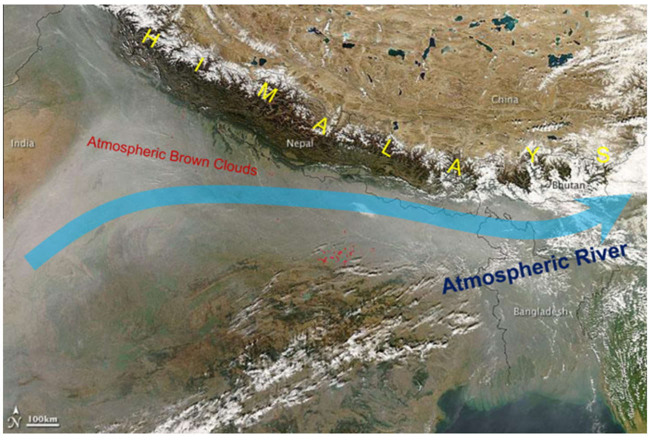

Fig. 6. The MODIS image from Dec. 11, 2008, indicating the narrow corridor of water vapor transport (Atmospheric River) along with the Himalayas. Grey smog is mainly composed of water vapor, black carbon particles, dust, and other aerosol species.

3.3. BC depositing history in Himalayan glaciers and its implications

The Himalayas is the closest mountain range to South Asia, which is a rapidly developing and strong BC-emitting region. Himalayan glaciers are drawing attention with their rapid melting in the recent decades [26], and some studies stated that BC could be responsible for the melting [23,16]. However, our investigation showed that the BC level in Himalayan glaciers is low and is comparable to that in the Arctic. BC emissions from South Asia were not consistent with the BC record in the ER ice core, while dynamic transport indicated by trajectories showed a close relationship with BC [20]. We suggest that extremely high elevation, over 6000 m, is the dominant factor restricting BC deposits on the northern side of the Himalayas.

Table 3
Comparison between BC depositions in snow and ice measured in different areas since 2000.

Area	Investigation time	Domain	Elevation (m)	Industry or human activities	Sample type (#)	Ave. BC (ng g^{-1})	Source
Arctic	1998 & 2005–2009	North of 60°N	Plain and ocean (very low)	Light	Snow (~1200)	<20	[5]
Sierra Nevada	2006	36°–42°N, 120°–123° W	Mountain (<2000 m)	Light OR almost none	Snow/precipitation (29)	~15	[10]
Northern China	2010	35°–50°N, 100°–130°E	Plain (low)	Heavy	Snow (~300)	400–500	[12]
Glacial areas in High-Asia	2001–2006	25°–45°N, 75°–100°E	Mountain (>3500 m)	Almost none	Snow (72) & ice core (6)	47	This dataset

Table 4
Radiative forcing caused by BC depositions in the investigated glaciers.

Mountain Area	Glacier ID	Ave forcing (W m^{-2})	Uncertainty (W m^{-2})	Area-averaged forcing (W m^{-2})
Qilian	LHG12	4.5	1.9	3.8
	QY	3.2	1.3	
Kunlun	MK	8.9	3.6	8.9
Tianshan	MEG3	9.3	3.8	9.5
	HXR48	8.0	3.3	
	UR1	11.2	4.5	
Nyainqentanglha	ZD	12.1	5.0	10.3
	LN	8.4	3.5	
Tanggula	TGL	4.0	1.7	6.1
	DK	7.1	3.0	
PamirsHimalayas	MT	5.3	2.2	5.3
	ER	3.1	1.3	2.9
	QIY	6.3	2.6	
	KW	3.7	1.6	
	NM	0.8	0.4	
	PLZ4	1.7	0.8	
	NK	3.4	1.5	
	ZQP	1.0	0.5	

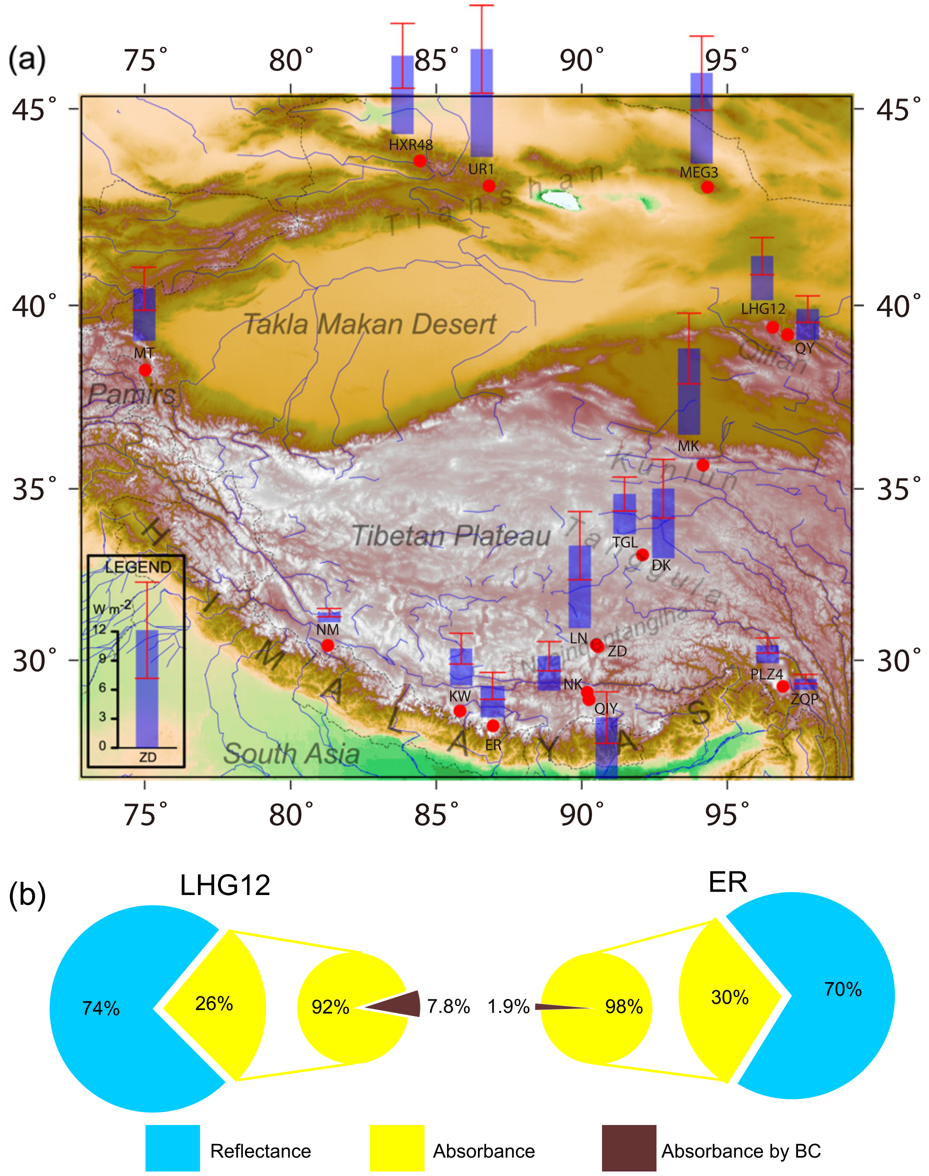

Fig. 7. (a) Radiative forcing caused by BC in the glacier surfaces, where error bars represent the forcing in the maximum and minimum cases; (b) Apportions of BC absorptions accounting for the surface net solar fluxes in the LHG12 and ER glaciers.

BC records in the ice cores could be used to detect how much BC, emitted from South Asia, is deposited on the northern slopes of the Himalayas. We collected BC data in four ice cores, which were drilled on the northern slopes (Fig. 5). Three of them (ER, NK, and ZQP) roughly span the second half of 20th century, which was an economic boom period for South Asia, while PLZ4 has a much shorter record covering 1998–2005.

The ER glacier is located in the middle Himalayan section, and the other three are located in more eastern regions; ZQP and PLZ4 are two neighboring glaciers. The four glaciers have different dominating pathways of water and mass. For ER, the primary way for gaining mass is the Indian summer monsoon, but for the other more eastern sites, the atmospheric river provides the pathway for water vapor to arrive (Fig. 6). Atmospheric rivers (ARs) are narrow corridors of water vapor transport in the lower atmosphere that traverse long swaths of the Earth's surface [22]. Over the southern slopes of the Himalayas, the upper boundary of the water vapor layer indicated by the atmospheric brown clouds is below the crests of the mountains, as shown by the investigation [1]. BC records in the ER ice core showed that there is no significant increasing trend of BC and that there were only two fluctuations during early 1970s and late 1990s; however, there have been slightly, significantly, and dramatically increasing trends in ZQP, NK, and PLZ4 ice cores, respectively (Fig. 5), although NK has a great fluctuation likely due to a significant contribution from large European sources in the 1950s–1960s [32]. The latter three glaciers are located on the water transport pathways from the Indian Ocean to the hinterland. The trends of BC in the latter three ice cores are consistent with increasing BC emissions in South Asia from 1950s to 2000s [20]. This also implies the restriction that the high Himalayas exert on BC transported from southern slopes to the north.

3.4. Radiative forcing caused by BC in High Asia glaciers and the estimated impact on their melting

The simulation shows the radiative forcing caused by BC deposition in the High Asia glaciers varies 0.8–12.1 W m^{-2}, adopting the median of maximum and minimum forcing here (Table 4). The highest forcing is in Nyainqentanglha (10.3 W m^{-2}), but not in Tianshan, which has the highest BC in glacial surface, most likely because stronger solar radiation on the Plateau amplifies BC absorption [8], and the lowest (2.9 W m^{-2}) was in the Himalayas (Fig. 7). On average, the forcing caused by BC depositions in High Asia glaciers is 5.7 ± 3.4 W m^{-2}.

We do not have observation data to assess how much this forcing impacts the melting of the High Asia glaciers at every site. Fortunately, ER and LHG12 provide us some in situ data for a rough estimation (Table 2). Average net radiation fluxes on ER and LHG12 are 167 W m^{-2} and 58 W m^{-2}, respectively, while the absorbed radiation by BC in snow/ice only accounted for ~2% and ~8% of the total absorptions at the two sites. The annual mean albedo for the surface of the ER glacier was 70% (Table 2), and 30% of irradiance was absorbed by the glacier. BC absorbed 2% of the total absorption. The left 98% of the absorption could be attributed to ice, dust, liquid water existing in the glacier, and other factors. A simple assumption is that ice is responsible for absorbing 20% of the sunlight, if assuming pure snow has higher albedo of approximately 80% [29], and then the left 8% could be attributed to dust and the water, which will need more in-situ measurements to validate. Thus, from the view of radiation balance, the impact of BC deposition on the melting of High Asia glaciers could be minor; currently, global and regional warming is still the major factor that accelerates the melting of these glaciers, as most studies had suggested [24,36,34,6,7].

4. Conclusion

BC deposition distribution in the surfaces of High Asia glaciers primarily depends on elevation (i.e., higher sites have lower concentrations, and vice versa) and secondarily on regional emission intensities and surface melting conditions. BC concentrations in High Asia glaciers are similar to other remote sites such as the Arctic and the western American mountains but are significantly lower than heavy industrialized areas such as northern China. Although there has been strong emissions neighboring South Asia, the BC level of the Himalayan glaciers is the lowest due to very high elevations, while great valleys in the eastern Himalayan section are effective pathways for transporting BC into the Tibetan Plateau. On average, BC deposits cause a mean forcing of ~6 W m^{-2} (roughly estimated 5% of the total forcing) in High Asia glaciers and could therefore not be a major factor impacting the melting of most glaciers.

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