An Overview of the Studies on Black Carbon and Mineral Dust Deposition in Snow and Ice Cores in East Asia

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ABSTRACT

Black carbon (BC) is the most effective insoluble light-absorbing particulate (ILAP), which can strongly absorb solar radiation at visible wavelengths. Once BC is deposited in snow via dry or wet process, even a small amount of BC could significantly decrease snow albedo, enhance absorption of solar radiation, accelerate snow melting, and cause climate feedback. BC is considered the second most important component next to CO_2 in terms of global warming. Similarly, mineral dust (MD) is another type of ILAP. So far, little attention has been paid to quantitative measurements of BC and MD deposition on snow surface in the midlatitudes of East Asia, especially over northern China. In this paper, we focus on reviewing several experiments performed for collecting and measuring scavenging BC and MD in the high Asian glaciers over the mountain range (such as the Himalayas) and in seasonal snow over northern China. Results from the surveyed literature indicate that the absorption of ILAP in seasonal snow is dominated by MD in the Qilian Mountains and by local soil dust in the Inner Mongolian region close to dust sources. The detection of BC in snow and ice cores using modern techniques has a large bias and uncertainty when the snow sample is mixed with MD. Evidence also indicates that the reduction of snow albedo by BC and MD perturbations can significantly increase the net surface solar radiation, cause surface air temperature to rise, reduce snow accumulation, and accelerate snow melting.

Key words: black carbon, mineral dust, ice core, seasonal snow, radiative forcing, Tibetan Plateau

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1. Introduction

Black carbon (BC) plays an important role in the earth system through its climate effects (Bond et al., 2004; Bond and Bergstrom, 2006). BC comes from anthropogenic sources related to biomass burning, fossil fuel, and biofuel. Being an important insoluble light-absorbing particulate (ILAP), BC can significantly influence the absorption of solar radiation by warming the high-latitude regions (Rosen et al., 1981; Baumgardner et al., 2004; Jacobson, 2004a, b; Flanner et al., 2007, 2009; Flanner, 2013; Koch et al., 2009), thus altering the radiative balance of the earth system (Hansen and Nazarenko, 2004; Hansen et al., 2005) and contributing to both regional and global climate change (Hansen et al., 1980; Charlson et al., 1992; Penner et al., 1992; Shindell and Faluvegi, 2009). Emission of BC in the atmosphere has a long life of days to weeks in urban areas, and may be transported over long distance from its sources (Heintzenberg, 1982; Clarke et al., 2004; Hendricks et al., 2004; Quinn et al., 2008; Kopacz et al., 2011). Deposition of BC via snow could significantly decrease snow surface albedo, cause snow albedo feedback (Clarke and

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Noone, 1985; Krinner et al., 2006; Flanner et al., 2007, 2009; Doherty et al., 2013; Ming et al., 2013b), accelerate snow melting (Hansen and Nazarenko, 2004), and enhance the solar radiation absorbed at the snow surface (Warren and Wiscombe, 1980; Chýlek et al., 1983). Aged BC in the air may acquire hydrophilic coating and act as cloud ice nuclei to alter cloud formation processes (Jacobson, 2001b; Dusek et al., 2006). Early studies found that 40 ppb BC in new snow or 10 ppb coarse-grained BC in aged snow could reduce 1%–3% of the snow's spectrally averaged reflectance at the visible wavelength (Warren and Wiscombe, 1980, 1985). Conway et al. (1996) showed that a reduction of 0.21 in snow albedo and an increase of 50% in ablation rate of natural snow were attributed to 500 ppb BC contamination. That means that even a small reduction of snow albedo is enough to cause climate change. Several modeling studies demonstrated that BC in snow via precipitation and dry deposition could significantly alter snow albedo (Hansen and Nazarenko, 2004; Jacobson, 2004a; Hansen et al., 2005; Flanner et al., 2007, 2009), and the reduction of snow albedo is important for climate change (IPCC, 2013).

Recent studies indicated that mineral dust (MD) is another important ILAP affecting the earth climate during its transport to the downwelling area from dust sources (Huang et al., 2006, 2007, 2008; Huang et al., 2010; Wang et al., 2010; Zhou et al., 2013). MD is mixed with snow or ice via precipitation and dry deposition (Ming et al., 2008, 2009; Xu et al., 2009a, b, 2012; Huang et al., 2011). Early observations and model simulations demonstrated that the surface radiative forcing (RF) of snow and ice melting by the ILAP such as BC and MD could accelerate snow melting and has a negative impact on glacier mass balance (Warren and Wiscombe, 1980; Clarke and Noone, 1985; Chýlek et al., 1987; Hansen and Nazarenko, 2004; Wang et al., 2006a, b; Painter et al., 2007, 2010; Flanner et al., 2009; Ming et al., 2009; Qian et al., 2009; Xu et al., 2009a; Menon et al., 2010; Grenfell et al., 2011). Flanner (2013) indicated that imposed forcing of BC causes very strong Arctic surface warming of 2.8 K W^{-1} m^{-2}. Radiative forcing of MD also causes faster and earlier peak snowmelt outflow with daily-mean snowpack outflow doubling under the heaviest dust condition. On average, snow cover at a tower is lost 2.5 days after peak outflow in dusty conditions, and 1–2 weeks after peak outflow in clean conditions (Skiles et al., 2012). Liao and Seinfeld (1998) showed that atmospheric dust exerts a positive RF over bright surface. The high dust loading in the atmosphere can induce significant warming over snow-covered regions (Harvey, 1988; Overpeck et al., 1996). The model experiment by Harrison et al. (2001) suggested that the radiative impact of increased glacial dust loading in the atmosphere was of the same sign and magnitude of the RF of low glacial CO_2 levels.

In order to better understand the climate effect by BC and MD via snow and ice cores, several field campaigns were carried out to measure BC deposited on the snowpack over the Northern Hemisphere since the 1980s (Warren and Wiscombe, 1980; Clarke and Noone, 1985; Ming et al., 2009; Xu et al., 2009a, b, 2012; Doherty et al., 2010; Hegg et al., 2010; Yasunari et al., 2010; Huang et al., 2011; Ye et al., 2012; Wang X. et al., 2013). Most of the field campaigns were conducted in Europe (Heintzenberg, 1982; Covert and Heintzenberg, 1993), and near Point Barrow in northern Alaska (Clarke and Noone, 1985; Grenfell et al., 1994, 2011; Doherty et al., 2010; Hegg et al., 2010). Little attention was given to scavenging BC in seasonal snow in the midlatitude regions, except for a few sites over the Tibetan glacier on the Himalayas where field campaigns on collecting BC and MD in seasonal snow were conducted (Wang et al., 2006a, b; Ming et al., 2008, 2009, 2013b; Xu et al., 2009a, b, 2012; Ye et al., 2012; Wang X. et al., 2013). The possible climate effect of MD and BC deposition via snow in the Himalaya and northern China is barely known due to lack of observations. Furthermore, quantitative measurement of scavenging BC in snow/ice is still a challenge. The methods used to measure ILAP in snow or ice cores are seldom illustrated, and most of the optical instruments are typically designed to measure light absorption by ILAP based on the content of BC deposited on a filter (Hansen, 1984; Doherty et al., 2010). The purpose of this paper is to illustrate recent progress in measuring the mixing ratio of BC and MD in snow/ice cores and their radiative forcing to regional and global climate.

2. Review of field snow samplings and measuring techniques

Since the 1980s, seasonal snow has been collected from most high-latitude regions across the Northern Hemisphere, such as the polar region (Warren and Wiscombe, 1980; Clarke and Noone, 1985; Doherty et al., 2010), Greenland (Warren and Wiscombe, 1980; Doherty et al., 2010), Canada, and Russia (Clarke and Noone, 1985; Doherty et al., 2010). Only a few experiments focused on scavenging BC in the seasonal snowpack over the midlatitude regions. Since 2004, several samples of snow and ice cores were collected in the Tianshan Mountains and Tibetan Glacier across northwestern China (Wang et al., 2006a, b; Ming et al., 2009, 2013b; Xu et al., 2009a, b), and BC and MD in seasonal snow were collected in northern China (Huang et al., 2011; Ye et al., 2012; Wang Z. W. et al., 2013; Zhang et al., 2013). Generally, the locations for collecting the data were selected to be 50 km away from villages or cities, and 1 km away from freeways or roads, so the snow samples were not contaminated by local sources of pollution.

Typically, the snow samples were collected from every 5-cm layer of the snowpack, if there were not any significant polluted layers, to obtain the vertical profile of snow depth (Doherty et al., 2010; Wang X. et al., 2013), and the snow samples were stored in a plastic bag. The snow samples were kept frozen before they were analyzed in the laboratory or the temporal lab during the survey. In order to minimize possible loss of BC to the glass container's walls, all snow samples were thawed in a microwave oven immediately and filtrated through Nuclepore filters (with a 0.4-μm pore size).

In recent years, several methods have been developed for measuring ILAP in snow, which are listed in Table 1. However, there are only three kinds of effective methods on measuring BC and other ILAPs in snow, such as the filter-based method (Clarke and Noone, 1985; Clarke et al., 1987; Horvath, 1995; Doherty et al., 2010; Wang X. et al., 2013), the thermo-optical technique (Chýlek et al., 1987; Cachier and Pertuisot, 1994; Lavanchy et al., 1999; Jenk et al., 2006; Hagler et al., 2007a, b; Ming et al., 2008; Hadley et al., 2010), and the single particle soot photometer (SP2) method (Stephens et al., 2003; Baumgardner et al., 2004; McConnell et al., 2007; McConnell and Edwards, 2008; Schwarz et al., 2012). The filter-based techniques are an indirect method for the determination of the scavenged BC on snow, and all of the techniques are based on measuring light transmission changes on the filters following Beer's law (Clarke et al., 1987). Nonetheless, most of the filter-based techniques cause large uncertainties because the aerosol scattering does affect the solar radiation despite the careful design of the instruments (Clarke et al., 1987; Horvath, 1993; Petzold et al., 1997; Bond et al., 1999). In order to avoid the problem, the ISSW spectrophotometer system were designed by incorporating as integrating sandwich together with an integrating sphere to analyze the concentration of BC in snow (Grenfell et al., 2011, see Section 3 of this paper for exact abbreviation of ISSW). Although this technique is considered as precise and reliable in measuring the ILAP deposited onto suitable filters (Doherty et al., 2010; Grenfell et al., 2011), the total uncertainty associated with the ISSW on measuring the concentration of BC has still been estimated as approximately 40% for ambient snow (Doherty et al., 2010; Grenfell et al., 2011).

The principles of the SP2 instrument are based on the light scattering and absorbing to derive the diameter and mass concentration of individual particles of diameters ranging from 0.15 to 1 μm (Stephens et al., 2003). Schwarz et al. (2012) indicated that the SP2 can be used to measure BC mass concentration in snow with a substantial 60% systematic uncertainty, which is dominated by calibration process and the uncertainty of the size distribution of BC in snow or ice cores. Cachier et al. (1989) pointed out that the thermo-optical method satisfactorily distinguishes between organic and soot carbon and allows reliable soot carbon determination at the μg level in the atmospheric samples from a wide variety of environments.

Table 1. Methods for measuring BC in snow and ice

Instrument	Filter type	Method	Reference
Integrating plate (IP) method	Whatman QM-A Quartz fiber; Pallflex Tissuquartz 2500QAT-UP	Light transmission	Lin et al., 1973; Clarke, 1982; Horvath, 1997
Integrating sandwich (ISW) method	Whatman QM-A Quartz fiber; Pallflex Tissuquartz 2500QAT-UP	Light transmission	Clarke, 1982; Clarke et al., 1987
Integrating sphere (IS) method	Polycarbonate filters	Integrating sphere	Fischer, 1970; Heintzenberg, 1982; Clarke, 1982, Clarke et al., 1987
Integrating sphere/ integrating sandwich (ISSW) method	Whatman Nuclepore filters, 0.4-μm pore size	Integrating sphere/ integrating sandwich	Doherty et al., 2010, 2013; Grenfell et al., 2011; Wang X. et al., 2013
Thermo-optical (TOT) method	Whatman QM-A Quartz fiber; Pallflex Tissuquartz 2500QAT-UP	Thermal optical; Two-step thermal	Cachier et al., 1989; Jenk et al., 2006; Xu et al., 2006, 2009b; Hagler et al., 2007a, b; Ming et al., 2009; Kondo et al., 2011
Single particle soot photometer (SP2)	Liquid samples (without filter-based)	Intense intra cavity laser to heat the refractory EC/OC to vaporization	Schwarz et al., 2006, 2010, 2012; Slowik et al., 2007; McConnell et al., 2007; McConnell and Edwards, 2008

Actually, visual estimate is still well recognized as another effective method to estimate the BC loading in snow, although visual estimates of equivalent BC concentrations only agree with those derived from the integrating-sandwich spectrophotometer within a factor of approximately two (Grenfell et al., 2011; Wang X. et al., 2013).

3. BC and MD in the Tibetan glacier

Recently, much attention was paid to the Tibetan Plateau (TP) because the ice there was melting away fast (Ding et al., 2006; Liu et al., 2006, 2009; Yao et al., 2007, 2012; Qiu, 2008). Several field campaigns for measuring BC in snow and ice cores were carried out over the TP at an altitude higher than 4000 m. In the past half century, 82% of the plateau's glaciers retreated. In the past decade, 10% of its permafrost degraded (Qiu, 2008). Therefore, it is important to reveal the mechanism behind the faster melting of snow and ice cores there than that in the Arctic and Antarctic regions. Liu and Chen (2000) indicated that a statistically significant warming trend over the TP since the mid 1950s was detected, especially in cold season, although no obvious change was found in the temperature variability. A nearly 900-yr record of the Malan ice core was reconstructed, which revealed that the 1770s–1880s was a prolonged period of high dust ratio, indicating that dust events occurred frequently from the late 18th century through the 19th century over northern TP (Wang et al., 2006a, b). They also found that dust events were more frequent in the cold and dry periods than in the warm and wet periods. A recent study demonstrated that the satellite-derived RF of MD in snow has a large forcing value over the Himalaya, based on the Moderate Resolution Imaging Spectroradiometer (MODIS) data (Painter et al., 2012a). The higher BC emission in the Himalayan glacier regions significantly affected the snow darkening that decreased the snow surface albedo (Flanner et al., 2007, 2009; Aoki et al., 2011; Yasunari, 2011) and caused the glacier retreat (Menon et al., 2010; Qian et al., 2011; Ming et al., 2012). Xu et al. (2009a) extracted ice core record from five locations on the TP, which indicated that the mass concentration of BC increased significantly during the last 20 years and the variation of BC deposited on the Tibetan glacier was a significant factor affecting the rapid glacier retreat (Liu et al., 2006, 2009; Yao et al., 2007, 2012; Xu et al., 2009a, b, 2012). As shown in Fig. 1, the relatively high concentration of BC in the TP glacier ice cores occurred in the 1950s and 1960s, which may be related to the air pollution from European sources at that time, and the concentration of BC decreased in

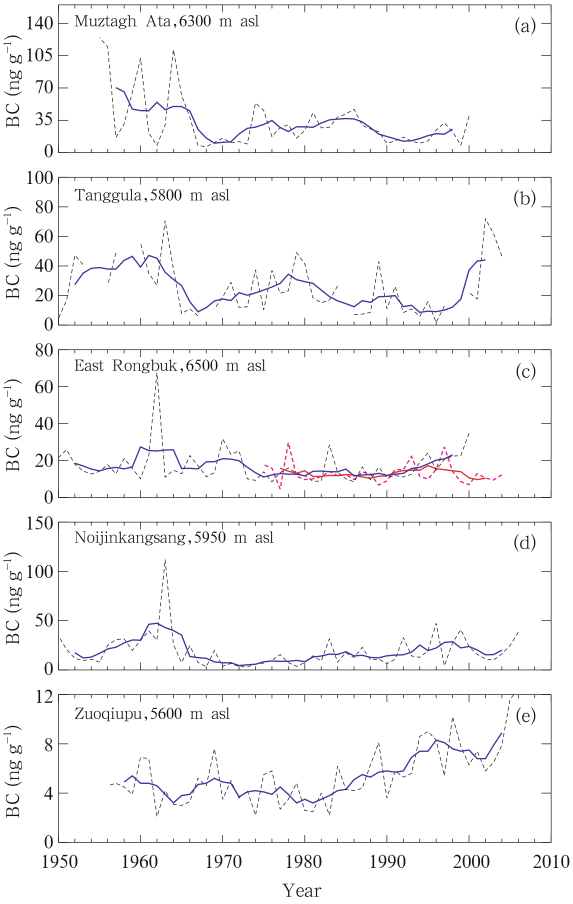

Fig. 1. Black carbon in the five ice cores collected over the Tibetan Plateau. The dashed line is annual concentration (ng g^{-1}), and the solid line is 5-yr running mean. After Xu et al., 2009a. The pink dashed line and red solid line in (c) shown for comparison are the results of Ming et al. (2008) for the East Rongbuk glacier.

the 1970s and 1980s. Note that all the ice core samples revealed a significant increase trend of BC since the 1990s, which is consistent with the glacier retreat and the increasing industrial activities (Xu et al., 2009a). The surface concentration increase of BC could increase snow/ice melting more effectively.

By analyzing the dust layers in the Malan ice core from northern TP, Wang (2005) proposed that the decreasing trend in the dust event frequency might be caused mostly by natural processes, including increasing precipitation and weakening westerly, which is possibly related to global warming. Other studies indicated that the BC in the snow and ice cores in the TP was really lower than that in the other regions (Streets et al., 2001; Bond et al., 2004; Xu et al., 2009a; Ming et al., 2013b). The site-integrated concentration of BC in seasonal snow across the TP was in the range of 20–120 ppb. Ming et al. (2009, 2013b) demonstrated that the higher concentration of BC in snow appeared at some lower sites over the TP. For Zhadang (ZD) glacier, the authors also indicated that there was a significant seasonal variation of BC in snow of around 100 ppb, while it exceeded 400 ppb in spring, with a dust layer inside. The important notion is that the Asian emission was still increasing after 2003 based on the Zuoqiupu's ice core data (Xu et al., 2009a).

4. Measuring BC and MD in seasonal snow across northern China

Although the properties of BC in snow and ice cores have already been studied all over the world, measurements of BC in seasonal snow were seldom illustrated across the midlatitudes, especially over northern China. To better understand the geographical distribution and spatial and temporal variability of snow cover over northern China in winter, we analyze in this study the MODIS/Terra Snow Cover Monthly L3 Global 0.05 Deg CMG (MOD10CM) dataset version 5 (V005) from February 2001 to February 2013, and the results are given in Fig. 2. Generally, most areas of northern China are covered with snow during the whole winter season. More than 80% of northeastern China is covered with snow in February. Moreover, a few regions in the central Inner Mongolian grassland (IMG) region, except for the border of Mongolia and Siberia, show a snow cover extent of approximately 85%. Huang et al. (2011) indicated that the IMG region has thin and patchy snow in winter because of strong wind. For the high mountains over western China and the TP, the extent of snow cover is nearly 10%–30%. The extent of the snow cover in Xinjiang Region of China is higher than that in other regions (Fig. 2), which could be as high as 85% across northern Xinjiang; however, it is lower than 10% near the Taklimakan basin in winter.

Ye et al. (2012) indicated that the seasonal snow depth could be more than 50–60 cm in some areas over

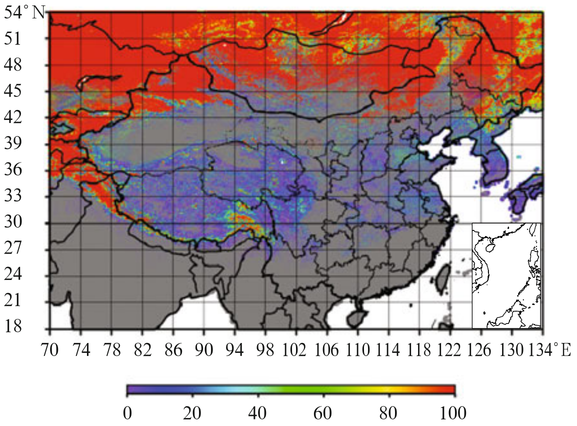

Fig. 2. Average extent (%) of snow cover across northern China derived from the MODIS/Terra monthly data in winter season (February) from 2001 to 2013.

the northern Xinjiang Region. Qin et al. (2006) used a multiple linear regression analysis to show the interannual variations of snow cover. Their results indicated that long-term variability of snow cover exhibited a small increasing trend, and did not experience a continuous decrease during the great warming period of the 1980s and 1990s. Since 2006, several field campaigns on scavenging BC in snowpack and ice cores were conducted over the Tibetan Glacier in high Asia (Ming et al., 2008, 2009, 2012, 2013b; Xu et al., 2009a, 2012) and northern China (Huang et al., 2011; Ye et al., 2012; Wang X. et al., 2013). Zhang et al. (2013) reported that the ILAP in Qilian Mountains was dominated by local soil dust, which was related to the dust sources nearby, such as the Taklimakan Desert (Zhang et al., 1997, 2003; Wang et al., 2008). However, the snow sampling sites in northern Xinjiang Region were much different from those in other regions. The seasonal snow was very thick and the mixing ratio of BC was relative low without melting snow, compared to the situation in the other regions. The mixing ratio of BC could be representative of large-scale transport (Ye et al., 2012). In comparison with the snow samples collected in the Arctic or Greenland (Doherty et al., 2010; Hegg et al., 2010), the difference was that the field operations of collecting seasonal snow were complicated across northern China, as demonstrated by Wang X. et al. (2013). Shortly, the insoluble light-absorbing impurities were dominated not only by BC and organic carbon (OC) (Hegg et al., 2009, 2010); they also included heavy MD and local soil that might be originated from dust sources (Zhang et al., 1997, 2003; Wang et al., 2008, 2010; Che et al., 2009, 2013).

Figure 3 shows a box plot of BC concentration in the snow across northern China. The north border area (NB) of northeastern China and the Xinjiang Region (XJ) are two relative clean regions, with the average values of BC of 110 and 90 ppb and the medium values of 80 and 70 ppb, respectively. Although the 90th percentile of the BC mixing ratio data could reach 400 and 700 ppb, the results indicate that the extent of BC in the snow of these regions barely shows high variations for each snowfall, and the average and medium values are representative of the regional average of BC in snow. The highest average and medium values of BC are 900 and 770 ppb, which appear in the industrial regions of northeastern China (IN). This is consistent with the previous study by Wang X. et al. (2013), who reported that those industrial regions were heavily polluted with abundant BC and other ILAPs during winter, and the main absorber was dominated by BC (Streets et al., 2001; Cao et al., 2007; Han et al., 2009; Zhang et al., 2013). In comparison, the 90th percentiles of the BC mixing ratio data reach 3700

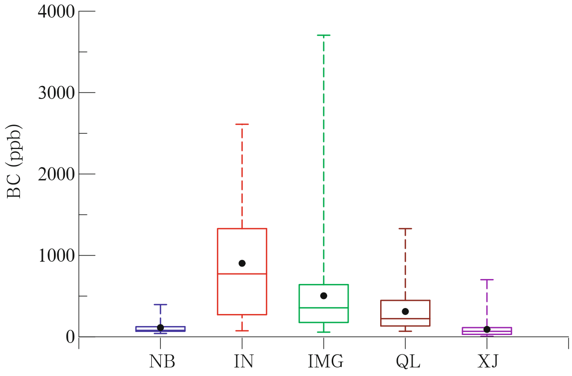

Fig. 3. Box plot of medium concentration of BC in snow in the five regions across northern China (NB: North Border of northeastern China; IN: Industrial Northeast; IMG: Inner Mongolian Grassland; QL: Qilian Mountains; XJ: Xinjiang Region). The black dot denotes regional average, and the error bars represent the 10th, 25th, 50th (medium), 75th, and 90th percentiles of the data.

and 1300 ppb in the snow over the IMG and the Qilian Mountains (QL), much higher than the average and medium values of BC. The large discrepancy could be mainly due to the mixed MD and local soil dust in the snow brought by strong local winds in winter. The QL are located at the northern border of the TP, and the sampling sites are covered with thin and patchy snow. The local soil and the remote MD can be lifted by strong winds and deposited on the snow surface by both dry and wet deposition. For the high difference of BC in the snow between both regions (NB and XJ vs. IMG and QL), we consider medium value more representative of the local average than the average value. The medium values of BC in snow are 360 and 220 ppb, respectively, for the IMG and QL. Although the ILAPs in both IMG and QL could be dominated by local soil and MD, the snow cover condition may be more complicated and snow is more extensive in the IMG, and local winds there are also much stronger than over the QL. Therefore, drifting snow is supposed to collect over the IMG.

5. Comparing BC in snow between model simulation and observation

In recent years, BC and other insoluble light-absorbing impurities in snow have been simulated in numerical models so as to investigate their impacts as RF estimate on climate change. Although Flanner and Zender (2005) indicated that SNow, ICe, and Aerosol Radiative model (SNICAR) could improve our understanding of the phenomena related to snow cover across the TP, matching modeled BC in snow with the measurement is still a challenge. The combination of observations and modeling provides a comprehensive distribution of BC in snow over the Arctic, which suggests that the albedo reduction due to BC deposition could reach as high as 1.25% in the Russian Arctic, a much larger value than those in the other Arctic regions (Dou et al., 2012). Qian et al. (2011) reported a large simulated BC content in snow over the TP, especially over the southern slope. They suggested that this was due to the high aerosol content in snow, large incident solar radiation in the low latitude, and high elevation. However, their model simulation still had a large bias to the observation. A comparison of a SNICAR model simulation and the observation of BC in surface 5-cm snow using an integrating sandwich together with an integrating sphere (ISSW) spectrophotometer, was described in Wang X. et al. (2013) (their Fig. 13b).

Figure 4 from Wang X. et al. (2013) indicates that there is a good relationship between the simulation and observation of BC in snow over northeastern China from January to February 2010. The concentrations of surface BC in snow at sites 20–40 were higher than the model simulation, except for 4–5 lower sites (Wang X. et al., 2013). Using the chemical method, Zhang et al. (2013) found that BC is the main absorber across northeastern China. Therefore, the observed surface BC in snow can represent the regional average, and the model simulation is comparable with the observation, where the ILAPs in snow are mainly dominated by BC. Note, Flanner et al. (2007) also showed that the estimate of BC deposition in snow between model estimates and observations is in a good agreement with that over Greenland, the Arctic, and Antarctica regions, with a correlation coefficient of 0.78.

6. Snow albedo

It is well known that snow is the most reflective natural surface on earth at the ultraviolet and visible wavelengths. However, even a trace amount of BC can

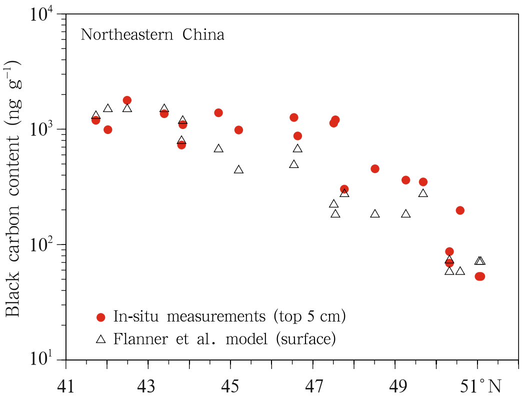

Fig. 4. Comparison of measured (red dots) and modeled (black triangles) snow BC concentrations over northeastern China as a function of latitude. After Wang X. et al., 2013.

significantly change snow albedo by absorbing more solar radiation and lead to the acceleration of snow melting. Comparing all the aerosol particulates that can reflect the solar radiation back to the space finds that only a few can absorb light, which include BC (Jacobson, 2001b; Moosmüller et al., 2009; Hadley and Kirchstetter, 2012), MD (Sokolik and Toon, 1996; Alfaro et al., 2004; Fialho et al., 2006; Derimian et al., 2008; Bi et al., 2011; Liu et al., 2011), and OC (Jacobson, 2001a; Chen and Bond, 2010). However, BC is considered as the most effective ILAP that are produced by the burning of biofuel, fossil fuel, and biomass. Flanner et al. (2007) indicated that BC warms the earth system two to three times more than CO_2 for the same instantaneous values (in W m^{-2}) of RF estimate.

In this section, we employ the climate model called the SNICAR developed by Flanner et al. (2007, 2009) to simulate the reduction of surface snow reflectance caused by BC contamination, and compare the results with other model simulations. The SNICAR is a multi-layer two-stream model based on Wiscombe and Warren (1980) and Toon et al. (1989); it treats snow as a collection of ice spheres (Wiscombe and Warren, 1980; Toon et al., 1989). Snow albedo is estimated by using the theory of Wiscombe and Warren (1980) and Warren and Wiscombe (1980); these authors validated their model for cases of both pure snow and the snow containing aerosols. We ran the SNICAR model with a solar zenith angle of 60° under the winter clear sky condition at the midlatitudes of northern China. The average parameters of snowpack density, snow grain radius and thickness are matched with the field experimental values (Wang X. et al., 2013). The visible and near-infrared reflectance of underlying ground is 0.2 and 0.4 μm, respectively, based on the MODIS data. We simulate the snow reflectance with BC concentration ranging from 0 to 3000 ppb, which is comparable to the concentration of BC during the 2-yr field campaigns across northern China (Huang et al., 2011; Ye et al., 2012; Wang X. et al., 2013).

Figure 5 indicates that the snow reflectance without BC can reach 0.95 or higher at the visible wavelength. However, just 50 ppb BC could reduce snow albedo by about 3%–4%. The result is consistent with the previous studies (Warren and Wiscombe, 1980; Grenfell et al., 2002; Hansen and Nazarenko, 2004; McConnell et al., 2007; Ming et al., 2008, 2009; Hadley and Kirchstetter, 2012). For some heavily polluted regions with mixing ratio of BC ranging from 1000 to 3000 ppb (Wang X. et al., 2013), snow albedo could be reduced by as much as 10%–20%, depending on the snow grain size (Warren and Wiscombe, 1985). This indicates that the BC is a main kind of insoluble light-absorbing impurities, which could significantly reduce snow albedo and accelerate snow melting. Furthermore, the size of snow grain is also an important parameter affecting light absorption by BC in snow (Schwarz et al., 2013). A modeling simulation on the albedo of snowpack in central Tibet indicated that BC, dust, and grain growth in the winter snowpack could reduce the snow albedo by 11%, 28%, and 61%, respectively (Ming et al., 2013a).

7. RF estimates of BC and MD in snow/ice cores

Model simulations have quantified the RF estimates of BC and MD deposited on snow/ice cores by

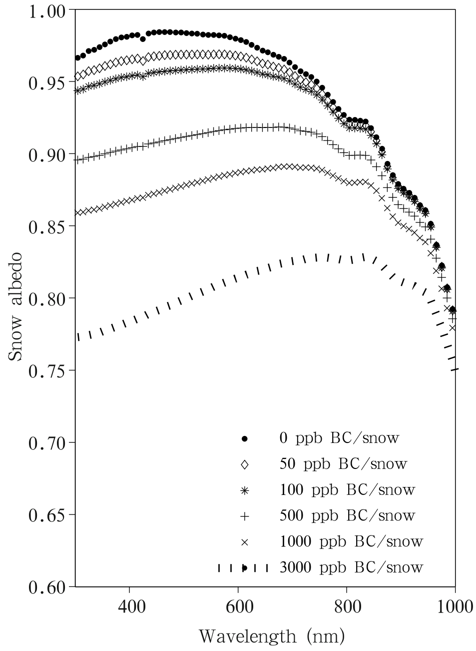

Fig. 5. Snow albedo of different BC concentrations at different wavelengths calculated by the SNICAR model.

their absorption capabilities (Hansen and Nazarenko, 2004; Flanner et al., 2007, 2009; Qian et al., 2009, 2011; Kopacz et al., 2011; Holland et al., 2012; Chen et al., 2013; Liu et al., 2013). Forster et al. (2007) demonstrated that the RF estimate of surface albedo change resulted from BC deposition in snow can be +0.1±0.1 W m^{-2}, indicating a high uncertainty in RF estimates mainly due to lack of observations. McConnell et al. (2007) estimated that the surface forcing by industrial BC emission from 1906 to 1910 was 3.2 W m^{-2} over the Arctic, where BC was transported from distant regions (Koch and Hansen, 2005; Stohl, 2006). Hansen et al. (2000) reported a global average RF of 0.10 W m^{-2} for the effect of BC on snow albedo. Estimates of the present-day global-average RF from BC in snow are approximately 0.04–0.20 W m^{-2} (Hansen and Nazarenko, 2004; Jacobson, 2004a; Flanner et al., 2007), yielding a high forcing efficacy (Hansen et al., 2005). Indeed, Hansen et al. (2005) identified BC in snow and ice as one of the largest sources of uncertainty in their comprehensive assessment of the RF related to climate change. However, Jacobson (2004a) found that the simulated concentrations of soot entering snow via wet and dry deposition were in a reasonable agreement with those from observations. The impact of BC in snow and sea ice on surface temperature calculated by Jacobson (2004a) was smaller than that by Hansen and Nazarenko (2004). The globally averaged radiative forcing by BC in snow was 0.05 W m^{-2}, while it was 3.0 W m^{-2} for the regional forcing across the Himalayas region (Flanner et al., 2007). As indicated in Fig. 6 (Flanner et al., 2009), BC and MD caused a large mean RF on snow in East Asia, especially in the TP and northeastern China. We point out a rather large mean RF of BC and MD on snow in central Asia, especially over northeastern China and the TP.

Qian et al. (2011) found that the deposition of BC in snow increased the surface air temperature by an average of 1°C across the TP because it boosted the absorption of sunlight, and BC was up to 4 times more effective at melting snowpack per degree of warming it induced than the warming of air resulted from increased atmospheric CO_2. Over Europe and North America, BC emissions from fossil fuel and biofuel decreased by 20% and 8%, respectively, during 1980–2000 (Bond et al., 2007), while simulated BC emissions from MD and biomass burning exhibited no significant trend over either continent (Flanner et al., 2009). However, the forcing in the high latitudes was estimated to be small (–0.9 to +0.2 W m^{-2}), especially when compared to nearly –20 W m^{-2} due to the reflection from extended ice sheets over unglaciated regions close to the expanded dust source region in central Asia (Claquin et al., 2003). The measurements of the mixing ratio of BC in Mt. Everest ice cores showed a summer darkening effect of 4.5 W m^{-2} in 2001 (Ming et al., 2008). Kopacz et al. (2011) indicated that the monthly RF due to the BC climate effect in the five glacier sites ranged from 0.39 to 3.5 W m^{-2}, with a global annual mean of +0.32 W m^{-2}. Bond et al. (2013) derived that the radiative forcing estimate of

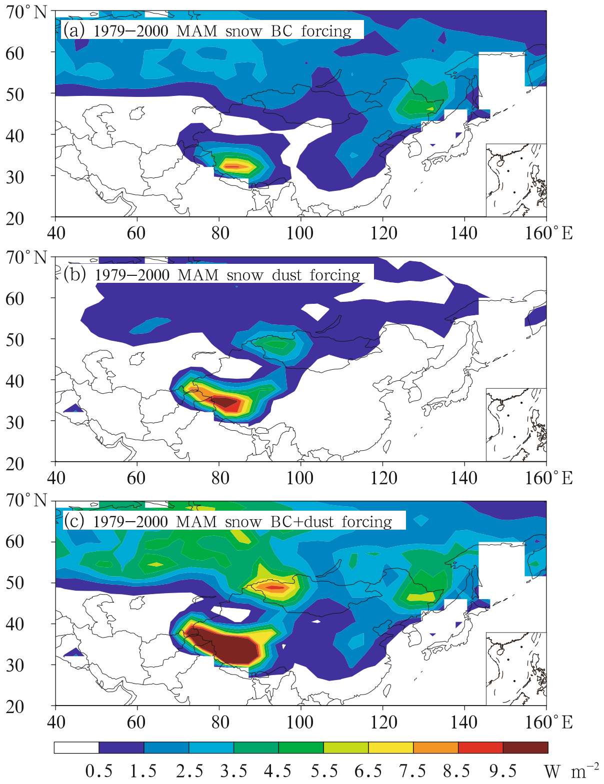

Fig. 6. March–May surface radiative forcing, averaged spatially and temporally only over snow in East Asia, caused by (a) black carbon in snow, (b) mineral dust in snow, and (c) both agents. After Flanner et al., 2009.

BC in snow and sea ice from 1750 to 2010 is +0.046 (+0.015 to +0.094) W m^{-2} by considering forcing ranges from all relevant global observational and modeling studies.

Scientists have realized that other natural and anthropogenic particles besides BC, such as MD, also deposit in snow and change the surface albedo (Painter et al., 2007, 2010, 2012b; Flanner et al., 2009). Actually, MD in snow via wet and dry deposition likely has a much greater impact than BC in snow for some regions (e.g., the southern Rockies) during a particular season (Painter et al., 2007). Lawrence et al. (2012) calculated surface RF by BC and dust on terrestrial snow to be 0.083 W m^{-2}. They also noted the impact in springtime (March–May), when the forcing was the greatest at 0.17 W m^{-2}, averaging only over the areas where snow was present. Holland et al. (2012) found that the additional shortwave energy absorbed at the surface averaged over the Arctic basin from BC and MD in sea ice always remained below 1 W m^{-2} in their 1850 equilibrium simulation. The important forcing by light-absorbing particulate impurities decreased in their doubled CO_2 experiment, as the sea ice area was reduced. Overpeck et al. (1996) suggested that heavy atmospheric dust loading during the last glacial period could have induced abrupt warming of a few degrees over snow- and ice-covered regions. Claquin et al. (2003) showed that the net RF of the last glacial maximum (LGM) dust aerosol was negative on the global scale, with positive forcing occurring only over small regions with high surface albedo.

8. Conclusions and discussion

Since BC is an important factor in the climate change, scientists realized that higher BC concentration has the potential to perturb global climate through accelerating the melting of glacier snow and ice, causing the snow reflectance to decrease, and thus affecting regional and global climate. In this paper, studies related to all snow sampling sites across northern China including the Tibetan Glacier and the Qilian Mountains were reviewed. Concentrations of BC in the ice core record from five locations show relatively high values in the 1950s and 1960s, which may be related to the air pollution from European sources at that time, and low values in the 1970s and 1980s. In addition, analysis of ice core samples revealed that the amount of BC had a significant increasing trend since the 1990s, consistent with the glacier retreat and the increasing industrial activities. For the dry and wet process of BC in seasonal snow, the cleanest sites of BC in snow were located in northern Xinjiang and the remote northeast on the border of Siberia, where the insoluble light-absorbing impurities were mainly dominated by BC. Industrial northeastern China was another region dominated by BC in snow. The highest concentration of BC in snow existed in northeastern China because of heavily polluted air during winter heating. There was a good relationship between model simulation and the observation of BC in snow over the industrial northeastern China. The ILAP in snow was dominated by local soil and MD in Qilian Mountains and Inner Mongolian grassland regions. The average snow depth in the Inner Mongolian grassland was 5–8 cm, and the snow cover there was thin and patchy; meanwhile, local soil could be lifted by strong winds and deposited on the surface snow. The snow cover over the Qilian Mountains was above sandy soil with very little vegetation, and strong winds in this region were mainly associated with spring frontal systems. Recent studies also revealed that only 50 ppb BC could reduce snow albedo by approximately 3%–4% (Warren and Wiscombe, 1980; Hansen and Nazarenko, 2004). The reduction in snow reflectance could affect regional climate via changes in radiative forcing. Climate models indicate that the altered radiative forcing estimates of BC and MD by their absorption capabilities in snow or ice cores can significantly affect regional and global climate. However, based on a combination of model results and observations from remote sensing, we point out that there are still large uncertainty and bias in the RF estimates of BC and MD deposited on snow and ice cores by model simulations.

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