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Review

# An overview of black carbon deposition and its radiative forcing over the Arctic

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**Abstract**

This paper gives an overview of the current understanding of the observations of black carbon (BC) in snow and ice, and the estimates of BC deposition and its radiative forcing over the Arctic. Both of the observations and model results show that, in spring, the average BC concentration and the resulting radiative forcing in Russian Arctic > Canadian and Alaskan Arctic > Arctic Ocean and Greenland. The observed BC concentration presented a significant decrease trend from the Arctic coastal regions to the center of Arctic Ocean. In summer, due to the combined effects of BC accumulation and enlarged snow grain size, the averaged radiative forcing per unit area over the Arctic Ocean is larger than that over each sector of the Arctic in spring. However, because summer sea ice is always covered by a large fraction of melt ponds, the role of BC in sea ice albedo evolution during this period is secondary. Multi-model mean results indicate that the annual mean radiative forcing from all sources of BC in snow and ice over the Arctic was ~0.17 W $m^{-2}$. Wet deposition is the dominant removal mechanism in the Arctic, which accounts for more than 90% of the total deposition. In the last part, we discuss the uncertainties in present modeling studies, and suggest potential approaches to reduce the uncertainties.

*Keywords:* Arctic; Black carbon; Snow; Ice; Radiative forcing

## 1. Introduction

The Arctic region widely covered with snow and ice is especially sensitive to climate change. The warming rate in this region is almost twice the global average rate (IPCC, 2013). It is believed that the Arctic snow and ice has been undergoing rapid melting in the past decades, reflecting in retreat of sea ice (Comiso et al., 2008; Stroeve et al., 2012a, 2012b; Overland and Wang, 2013), reductions in snow cover (Brown and Mote, 2009; Brown et al., 2010; Bulygina et al., 2009; Derksen and Brown, 2012) and large area ablation in Greenland ice sheet surface (Tedesco, 2007; Mernild et al., 2009; Nghiem et al., 2012). Except for the contribution of rising air temperature, the light-absorbing aerosols (called as impurities in snow and ice) are considered to be important factors leading to the rapid melting of Arctic snow and ice (Clarke and Noone, 1985; Flanner et al., 2007; Dumont et al., 2014; AMAP, 2015).

Black carbon (BC) is the most efficient atmospheric particulate species at absorbing visible light (Bond et al., 2013). It is emitted directly through incomplete combustion and

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remains in the atmosphere until it is removed by wet or dry deposition. BC-containing aerosols in the Arctic can perturb the radiation balance in a number of ways. BC aerosols absorb solar radiation and hence warm the atmosphere (Haywood and Shine, 1995). BC may also affect the distribution, lifetime, and microphysical properties of clouds through indirect and semi-direct effects (Koch and del Genio, 2010; AMAP, 2015). When deposited to snow and ice surfaces, BC can darken the surface, enhance the absorption of radiation (Warren and Wiscombe, 1980; Hansen and Nazarenko, 2004; Quinn et al., 2011), warm the lower atmosphere and accelerate snow and ice melting (Clarke and Noone, 1985). In addition, the BC snow/ice forcing mechanism can trigger the snow albedo feedback through acceleration of snow melt, giving a further warming (Flanner et al., 2009).

Here, we provide a brief review to the present field measurements of BC in snow and ice over the Arctic. We also describe the observed and modeled BC deposition, along with the models that can be applied to characterize the BC distribution and its climate impacts over the Arctic. Quantitative descriptions of radiative forcing estimates from previous literature and observations are also provided. In the last part, we discuss the uncertainties existing in present studies and give a conclusion.

## 2. Field measurements

Present field campaigns in the Arctic have provided snapshot and detailed pictures of the spatial distribution and properties of BC in snow and ice over the Arctic. The earliest campaign was performed over the western Arctic in the 1980s by Clarke and Noone (1985). Later, snow samples were gathered across the Arctic Ocean for composition analysis including BC during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment (Grenfell et al., 2002). The measurements of BC in snow and ice were greatly expanded during 2005–2009 (Doherty et al., 2010), which involve the sites in Russian Arctic, Arctic Ocean, the Canadian and Alaskan Arctic and few points in Greenland. Another campaign took BC measurements in Scandinavia and the European Arctic (Forsström et al., 2013). In summer 2010, a dozen of snow samples were gathered over the Canada Basin and Arctic Ocean center, enriching the measurements over the Arctic Ocean during summer time (Dou et al., 2012). The locations of present BC observations are shown in Fig. 1.

## 3. Observed BC in snow and ice

The average concentrations in different Arctic regions are shown in Fig. 2. There exhibits significant spatial variation over each sector in spring, with the higher mean value in the Western Russia (33.7 ng $g^{-1}$), followed by the Eastern Russia (21.4 ng $g^{-1}$) and the Canadian and Alaskan Arctic region (7.9 ng $g^{-1}$), and the lower concentrations in the Arctic Ocean, Western Svalbard, and Greenland. BC concentrations in Arctic snow and ice are generally lower than those in Mid-Low latitudes region due to far away from human activity areas (Flanner et al., 2007; Ming et al., 2009). Russia, however, is an exception, where sampling sites are close to human settlements and suffer from more serious local pollution from industrial and biomass emissions (Doherty et al., 2010). The mean and median concentrations north of 65°N are 13.6 ng $g^{-1}$ and 10.7 ng $g^{-1}$ ranging from 1.4 to 164.6 ng $g^{-1}$. Although current data sets cannot completely map the BC concentrations in the Arctic, they provide insight into the range of variability in different Arctic regions.

The measurements also show that the BC concentration significantly decreases with latitude (Fig. 3). The maximum gradient is found in Russian Arctic with large values in the coastal region and much smaller ones in the sea ice region. Except for a small contribution of emissions from shipping (Corbett et al., 2010) and aviation (Whitt et al., 2011) in the Arctic Ocean, most of BC originated from the marginal areas of the Arctic Ocean and long-range transport from Mid-Low latitudes (Law and Stohl, 2007). In the long-range transport to the Arctic, the removal of BC from the atmosphere occurs through a variety of processes, including wet and dry deposition (Spackman et al., 2010), settling of ice crystals, and downward transport in settling wakes (Quinn et al., 2011). Therefore, the BC concentration reduces with increasing distance from source regions, leading to a decrease trend from the marginal region to the center of Arctic Ocean.

In summer time, snow samples were collected on sea ice surface. We compared the BC values obtained in summer and spring Arctic Ocean with the observations carried out in other Arctic regions in spring. Results show that the average BC concentration in snow on summer sea ice is much larger than that in spring, even larger than that obtained in Canada and Alaska in spring. Because of the insolubility in water, BC is able to accumulate in snow surface through melt amplification (Xu et al., 2012; Doherty et al., 2013; He et al., 2014), i.e. BC deposited onto the snow in winter and spring could accumulate in summer snow on sea ice with snow melts, leading to a higher concentration in summer sea ice region.

## 4. Modeled BC deposition over the Arctic

Current observations are insufficient to characterize the detailed spatial distribution and interannual variabilities of BC in snow and ice over each sector of the Arctic. It is necessary to investigate BC deposition (or BC in snow and ice) using atmospheric chemistry and climate models. Jiao et al. (2014) used AeroCom (Aerosol Comparisons between Observations and Models) models to simulate the spatial distribution of BC deposition over the Arctic. Two dozen models were applied (see detailed description about these models in Jiao et al. (2014)), half of which are affiliated with the AeroCom phase I intercomparison project (Kinne et al., 2006; Schulz et al., 2006; Textor et al., 2006, 2007; Koffi et al., 2012) and the others with the more recent phase II project (Myhre et al., 2013; Samset et al., 2013; Stier et al., 2013). Results show that the patterns of BC deposition are similar among the models both for phase I and phase II AeroCom project, with larger concentrations over Northern Europe, North America,