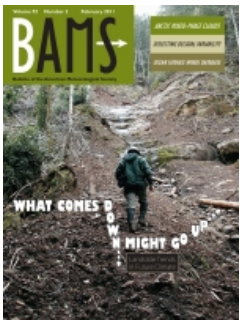

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Dust and Black Carbon in Seasonal Snow Across Northern China

Jianping Huang, Qiang Fu, Wu Zhang, Xin Wang, Rudong Zhang, Hao Ye, and Stephen G. Warren

College of Atmospheric Sciences, Lanzhou University, Lanzhou, Gansu, China

College of Atmospheric Sciences, Lanzhou University, Lanzhou, Gansu, China, and Department of Atmospheric Sciences, University of Washington, Seattle, Washington

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

Abstract

Snow is the most reflective natural surface on Earth. Its albedo (the fraction of sunlight reflected) can be reduced by small amounts of dark impurities such as dust and black carbon (BC) particles. This effect is significant for climate and the hydrological cycle. BC has previously been measured in Arctic snow, but it now appears that the larger effect may be in the midlatitudes because snow at lower latitudes is exposed to more sunlight and is closer to the sources of BC.

A field campaign was conducted across northern China in January and February 2010. Snow samples were collected at 46 sites in six provinces. The absorbing impurities are principally dust and BC particles in northwestern and northeastern China, respectively. The estimated concentration of BC is only 30–50 ppb in the far north of Heilongjiang Province (51°N), which is not much more than that found along the coast of the Arctic Ocean, 2,000 km farther north, but it increases to several hundred parts per billion in heavily industrialized Liaoning Province, Jilin Province, and the southern part of Heilongjiang. The BC content of snow in northeast China is comparable to values found in Europe (20–800 ppb). The steep drop-off in BC content of snow with latitude may indicate that little BC emitted in China in the winter is exported northward to the Arctic.

DUST AND BLACK CARBON IN SEASONAL SNOW ACROSS NORTHERN CHINA

BY JIANPING HUANG, QIANG FU, WU ZHANG, XIN WANG, RUDONG ZHANG, HAO YE, AND STEPHEN G. WARREN

Dust and black carbon have been measured in the seasonal snow across northern China to improve our understanding of the role of absorbing aerosols in the climate system.

Much of northeastern China has a contiguous seasonal snow cover in winter and early spring, and in central and western China large areas are partly covered by thin and patchy seasonal snow. The albedo of snow is therefore a primary determinant of the climate of these regions.

Because snow is the most reflective natural surface on Earth, the presence of small amounts of absorptive impurities, such as black carbon (BC) and dust particles, in snow can reduce the albedo significantly (Warren 1982). The radiative forcing caused by BC in snow has been assessed to be an important anthropogenic forcing for twentieth-century climate (Solomon et al. 2007). Hansen et al. (2005) identified BC in snow and ice as one of the largest sources of uncertainty in their comprehensive assessment of the various radiative forcings for climate change.

Black carbon particles are produced by incomplete combustion in diesel engines, coal burning, forest fires, agricultural fires, and residential wood burning (Bond et al. 2004). When BC particles are injected into the atmosphere, they may travel great distances before being removed by rain or snow precipitation, or by dry deposition. The trends in emission of fossil fuel BC in industrial areas have been investigated by Novakov et al. (2003) and Ito and Penner (2005). For 1950–2000, Novakov et al. (2003) reported a significant decrease in BC emissions in the United Kingdom, Germany, the former Soviet Union, and the United States, but a significant increase in India and China. Ito and Penner (2005) found similar trends in the same period, but with smaller absolute emission amounts.

Jacobson (2004) developed a global model that allows the BC aerosol to enter snow via precipitation and dry deposition, thereby modifying the snow albedo. Flanner et al. (2007) used a general circulation model (GCM) that incorporates snow processes

AFFILIATIONS: HUANG, W. ZHANG, WANG, R. ZHANG, AND YE—College of Atmospheric Sciences, Lanzhou University, Lanzhou, Gansu, China; FU—College of Atmospheric Sciences, Lanzhou University, Lanzhou, Gansu, China, and Department of Atmospheric Sciences, University of Washington, Seattle, Washington; WARREN—Department of Atmospheric Sciences, University of Washington, Seattle, Washington
CORRESPONDING AUTHOR: Prof. Qiang Fu, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195
E-mail: qfuatm@gmail.com

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to simulate the expected concentration of BC in snow of the Northern Hemisphere. They predicted values varying from <10 ng of BC per gram of snow (ng g^{-1}; or ppb by mass) in the Arctic to >1,000 ng g^{-1} in northeastern China. BC has been measured in Arctic snow (Clarke and Noone 1985; Grenfell et al. 2002; Forsström et al. 2009; Perovich et al. 2009; Doherty et al. 2010), but until now there have not been observations of BC in seasonal snow in northeastern China.

This paper describes a field campaign, the first large-area survey of absorbing impurities in seasonal snow over northern China, and reports the preliminary results.

FIELD CAMPAIGN. Seasonal snow was collected in January/February 2010 on a road trip at 40 sites in the provinces of Inner Mongolia, Heilongjiang, Jilin, and Liaoning. A shorter trip in mid-February 2010 obtained snow samples at six sites in Qinghai and Gansu Provinces. The sampling locations are shown in Fig. 1. A few pictures taken when collecting snow samples are shown in Fig. 2. At each site, samples were gathered from individual snow pits at several depths to examine snow deposited at different times during the winter (Fig. 3). The sampling sites were chosen to be far from local sources of pollution, so that the data could represent large areas. An exception is site 4, which is only 30 km from the large city of Baotou and is to investigate the influence of the city. In the semiarid regions, the snow was thin and patchy, so that sampling was sometimes possible only in drifts that were much deeper than the average snow depth. Snow density was also measured as a function of depth, so that the total water content of the snowpack can be determined.

The precipitation in Qinghai, Gansu, and Inner Mongolia comes mostly in summer, but the northeastern provinces experience significant snowfall in winter. In this particular year, we were able to sample freshly fallen snow at only two sites. The snow that falls in winter is subject to sublimation (Liston and Sturm 2004), which can enhance the concentrations of impurities in the top layer of snow. Dry deposition of aerosol also occurs during intervals between snowfall events. These are probably the explanations for why we often find lower concentrations in the deeper snow layers. However, sometimes we observed a thin surface layer of recently fallen snow that had a lower impurity concentration than the layer below it, which, by contrast, may have been exposed at the surface for a long time prior to being covered by the new snow.

About 300 snow samples were collected. Processing and initial analyses were carried out at Lanzhou University and at three temporary laboratories en route (Fig. 4), using the filtering techniques pioneered by Clarke and Noone (1985) and also used for Arctic snow by Doherty et al. (2010). Each sample was melted rapidly in a microwave oven and then immediately drawn through a 0.4-μm Nuclepore filter to extract the particulates. Small samples of meltwater, both before and after filtration, were taken and refrozen for later chemical analysis to be used in source–attribution studies, as was done for Arctic snow by Hegg et al. (2009, 2010). Each filter was compared visually against a set of standard samples provided by A. D. Clarke, to allow an initial estimate of the equivalent BC loading of the samples. The filters will be measured in an integrating-sandwich spectrophotometer (Clarke 1982; Grenfell et al. 2011), and the slope of absorption versus wavelength will be used to distinguish BC from other absorbers (dust and organic carbon). Here we report only an "equivalent BC" value, that is, the concentration of BC that would be needed to obtain the same absorption as the actual absorbers in the snowpack. The values reported here have been multi-

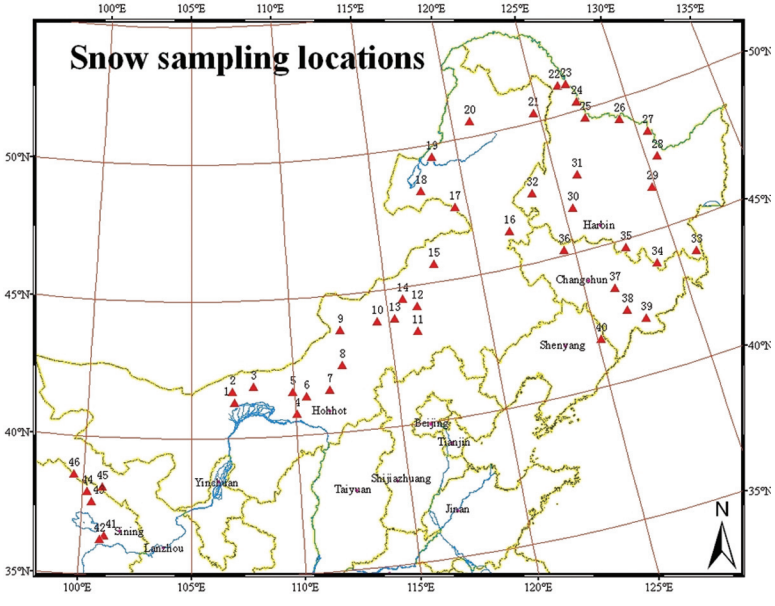

Fig. 1. Locations of the 46 sampling sites (red triangle with the site number), ranging in latitude from 36° to 51°N and in longitude from 99° to 131°E.

plied by 1.15 as an "undercatch" correction, because approximately 15% of the BC passes through the 0.4-μm filter (Clarke and Noone 1985; Doherty et al. 2010). The values are preliminary because they are based on visual inspection of the filters. Comparison with photometric analysis (Fig. 11 of Grenfell et al. 2011) shows that the visual estimate of an individual filter may be in error by as much as a factor of 2.

DUST OR SOOT? Figure 5 compares filters from the grasslands to filters from the northeast. In the grasslands of Inner Mongolia, Qinghai, and Gansu, dust (and sand) was by far the dominant absorber, as indicated by the yellow–brown color of the filters. These areas are used for grazing, and the density of grazing animals is high, reducing the vegetation cover and eroding the soil (Zhao et al. 2005). Much of the dust in the snow is coarse grained and sourced in the immediate vicinity, sometimes from only a few centimeters away where a sheep's hoof broke through the thin snow and kicked up sand. [The importance of dust in lowering snow albedo has also been documented in Colorado (Painter et al. 2007).]

As we moved east from the arid/semiarid region to the moist region (i.e., from grassland into forested and agricultural regions), dust was no longer noticeable on the filters, which were just gray (Fig. 5). Estimated concentrations of BC were high in heavily industrialized Liaoning Province, Jilin Province, and the southern part of Heilongjiang Province. The far north of Heilongjiang Province (51°N) had the cleanest snow, with BC values of 30–50 ng g^{-1}, which are not much higher than those of the Siberian Arctic, 2,000 km farther north (Grenfell et al. 2009; Doherty et al. 2010). In Liaoning our site (number 40) was not far from the Horchin Desert, and the influence of dust is seen together with soot in the filters from that site, which are intermediate in color between brown and gray.

The natural vegetation of Heilongjiang is forest. It is now partly forest and partly farmland, growing mostly corn (whose burning after harvest is also a source of soot). In this region the major anthropogenic effect on climate is to *raise* the albedo by replacing dark forest (which hides the snow) with farmland [which has high albedo when snow covered (see Kung et al. 1964; Kukla and Brown 1982; Robock and Kaiser 1985; Bonan et al. 1992)]. This cooling effect on climate would outweigh the soot warming effect in the regions where the dark forest was replaced with farmland; both impacts should be quantified.

The far north of Inner Mongolia is grassland, yet the filters are not brown; they are intermediate between brown and gray. Sites 15–17 may be influenced by industrial cities to the east, and the northernmost grassland sites (sites 18 and 19) are directly east of some major Siberian cities.

In Qinghai and Gansu, there was very little snow cover in mid-February. The snow was mostly

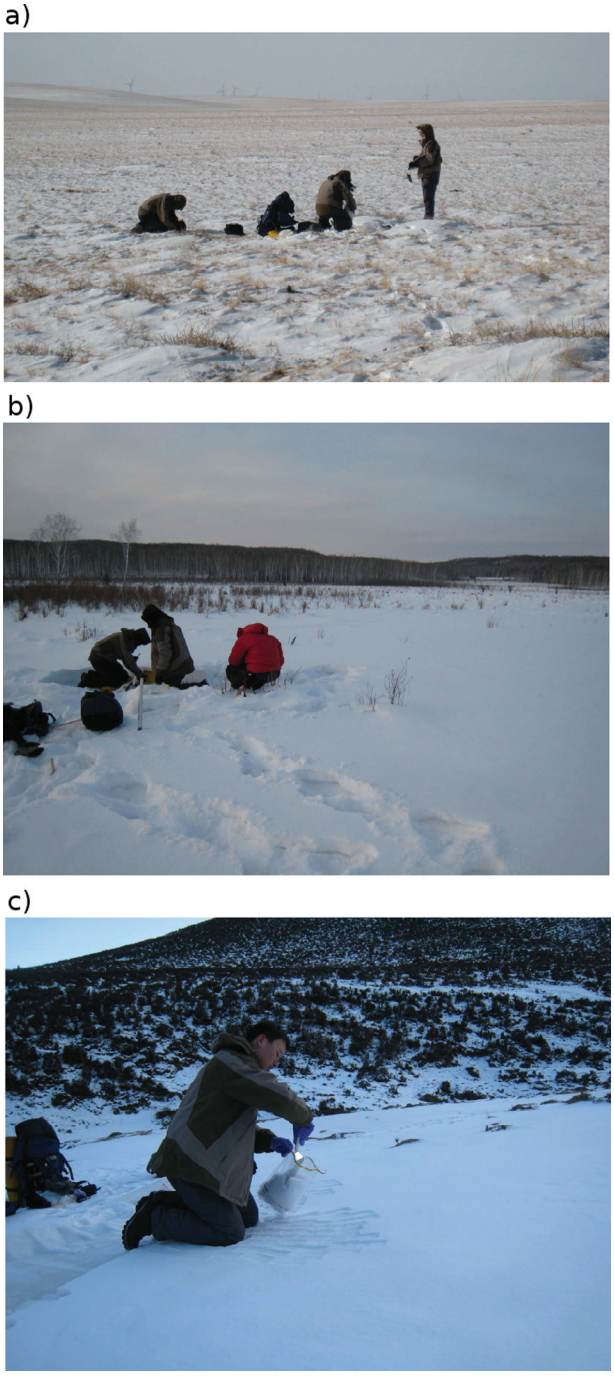

Fig. 2. Snow collection in (a) a grassland in Inner Mongolia (site 5), (b) a frozen swamp in Heilongjiang (site 26), and (c) on a frozen river in the Qilian Mountains near the Gansu–Qinghai border (site 45).

Fig. 3. Examples of snow pits at a site in (left) Inner Mongolia and (right) Heilongjiang.

Fig. 4. Filtering meltwater in a hotel room in Shilinhot.

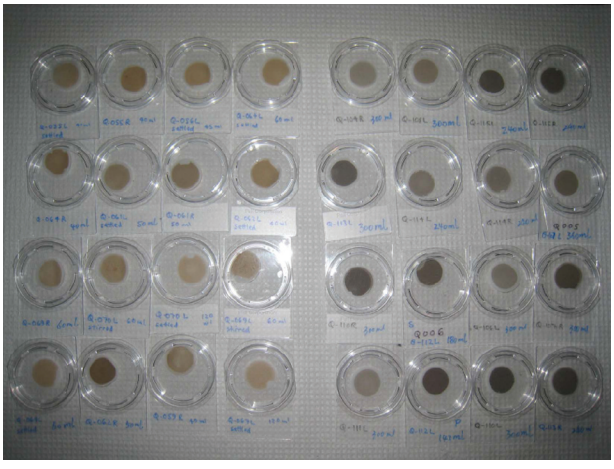

Fig. 5. Examples of filters from snow of (left) Inner Mongolia and (right) the northeastern provinces.

restricted to elevations above 3,500 m, and even there it was patchy. Our snow samples in these provinces were taken near mountain passes, where the immediate surroundings had estimated snow-covered fractions of 1%–70%, with a median of 30%. Because the fractional area of snow cover overall in the region we traveled on the second trip (northeastern Qinghai) is small (perhaps 1%–2%), there is negligible radiative forcing of climate from impurities in snow there, even though the impurity content (mostly dust) is high.

SUMMARY OF PRELIMINARY RESULTS.

In the dust-dominated region of Inner Mongolia (sites 1–15), the estimated surface concentrations range from 100 to 4,300 ng g^{-1} BC equivalent, with a median of 400 ng g^{-1}. In the northeast region dominated by soot, the estimated surface concentration of BC ranged from 40 to 1,600 ng g^{-1}, with a median of 500 ng g^{-1}.

Comparison with model predictions. Figure 6 compares our visual estimates with the model predictions of Flanner et al. (2009) for the soot-dominated

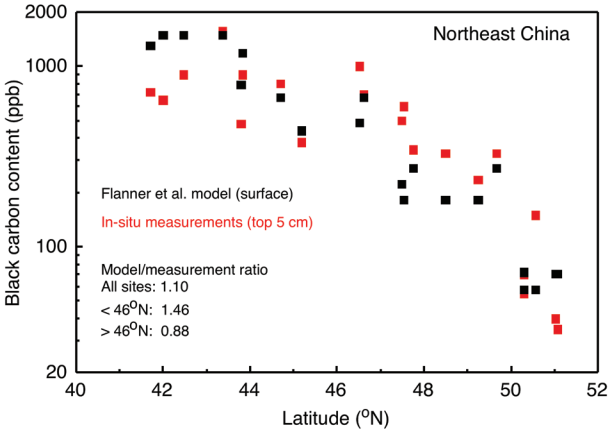

FIG. 6. BC content in snow of northeastern China as a function of latitude, averaged over the top 5 cm of the snowpack, for each of the sites 20–40 (red points). Also plotted (black) are average values for surface snow at these locations from the model of Flanner et al. (2009). Monthly values for Jan and Feb were provided by Mark Flanner; they have been averaged for this plot, because all of the snow samples were obtained in late Jan or early Feb.

northeastern sites (sites 20–40). For this comparison we used the average at each site of the model's monthly values in the top 2 cm of snow in January and February, because our samples at these sites were all collected in late January or early February. The observed values are averages at each site of the top 5 cm. The model and measurement agree in showing a steep drop-off in BC content with latitude, from ~800 ppb at 46°N, to 30–50 ppb at 51°N. The steep drop-off in BC content of snow with latitude suggests that most of the BC emitted in China is removed from the atmosphere by precipitation within China, so that little is exported northward to the Arctic. This result is consistent with the finding that a dominant source for the measured Arctic snow-deposited BC is biomass burning (Hegg et al. 2009). It is noted that the measured BC in Arctic snow does not show an increasing trend in last 25 years (Clarke and Noone 1985; Doherty et al. 2010).

The ratio of model/measurement has an average value of 1.10 for these 21 sites. This ratio is 1.46 for the 8 sites below 46°N, while it is 0.88 for the 13 sites above 46°N. As noted above, the measurements are for "effective BC," including the radiative effect of dust on the filters, so our estimate of the actual BC content may be lower after the filters are analyzed spectrophotometrically. On the other hand, we have determined that some of the BC in the snow was lost prior to filtration, but this has not yet been quantified. Measurements with larger spatiotemporal coverage in China are also required for a comprehensive comparison between model results and observations.

Comparison with other measurements. Measurements of BC have previously been carried out on glaciers in Tibet and Xinjiang Province using a controlled-combustion method rather than our filter method (Ming et al. 2008, 2009; Xu et al. 2006, 2009); they show concentrations of 4–120 ng g^{-1}, encompassing the lowest values we find in the northeast. The controlled-combustion method obtains the mass of BC only, not dust.

The BC content of snow in northeast China is higher than that found at a few midlatitude sites in North America (10–60 ng g^{-1}), but comparable to values found in Europe [20–800 ng g^{-1} (see Flanner et al. 2007, their Table 2; Chylek et al. 1999)]. To make a more definitive comparison, a comprehensive field campaign similar to what we carried out in China should be undertaken across the midlatitudes of North America.

DISCUSSION AND CONCLUSIONS. Our main observational findings are the following. First, the absorbing impurities in snow are dominated by dust and BC particles in northwestern and northeastern China, respectively. Second, the estimated concentration of BC is low in the far north of Heilongjiang Province (51°N), which is not much higher than that found along the coast of the Arctic Ocean, 2,000 km to the north. The BC content becomes high, several hundred parts per billion, in heavily industrialized Liaoning Province, Jilin Province, and the southern part of Heilongjiang Province. (Some impact of dust can also be seen in the lower latitudes of the northeastern provinces, which may lead to an overestimation of the BC contents there.) Third, as one moves northeastward away from the major industrial regions, the BC content of snow drops off rapidly, as is also predicted by a GCM.

The data from this field campaign should be useful for testing transport and climate models in terms of simulated BC in snow and its effect on albedo. Our observations also suggest that the impact of dust in snow on albedo, which is significant in large arid and semiarid regions, should also be considered in climate models. Furthermore, the conversion from forest to farmland in the midlatitudes, which greatly enhances the albedo in winter and spring, should also be quantified as part of the anthropogenic impact on climate. A similar comprehensive field campaign should be conducted across the midlatitudes of North America.

Finally, the climatic importance of BC pollution is also well recognized for its radiative forcing in the atmosphere (Ramanathan et al. 2007). The filtering technique that we used is relatively inexpensive and easy to operate. Thus, the field measurement can be easily conducted over a large area, and the measured BC content may also provide a useful proxy of the BC in the atmosphere in the winter season.

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