Reply to Referee 1#

In the equation for C(h), please state upfront whether h is known at each site or it is estimated, since Figure 1 does not give snowpack depth, only percent of depth. Also, does h vary by site? What is its typical value?

Reply: We agree that it is necessary to clarify 'h' before giving the equation. Snow depth has been observed at most measurement sites in Canadian and Russian Arctic in spring 2007-2009. However, in the measurements of snow depth and BC concentration at each layer, snow density, as an essential factor in the estimation of sBC concentration, was not observed. In view of this, we cannot give an actual and precise concentration of sBC at whole layer snow based merely on current measurements.

In this study, we applied the typical snow densities at surface and subsurface snow layer obtained during SHEBA campaign (Sturm et al, 2002) to represent general vertical profiles of snow density over sea ice and surrounding tundra areas in the Arctic. [Note: Sturm et al. (1995) gave a rough generalization of what kind of snow is expected to be found in different terrain types on land. They suggested the snow found at tundra is the closest substitute for what would be estimated to be found over floating ice (layers of wind slab and possibly new snow and depth hoar in varying order). Accordingly, the measured density values in different layers (Sturm et al, 2002) can be used to give the range in which the snow density (and mass based BC concentrations) vary in the Arctic snow]. Based on the snow density values obtained during SHEBA campaign, we estimated the concentration of sBC in whole snow layer by the equation C(h), in which C(h1) denotes BC concentration at surface layer accounting for 25% of the total depth, C(h2) denotes BC concentration at subsurface layer accounting for the remaining 75% according to the observed BC vertical profile in left panel (based on measurements in Russia) of figure 1. We think the percent of depth is more suitable and clear enough to represent the vertical distribution of sBC in this study.

Reference:

Sturm, M., Holmgren, J. And Liston, G. E.: A seasonal snow cover classification system for local to global applications, J. Geophys. Res., 1261-1283, 1995.

Sturm, M., Holmgren, J. and Perovich, D. K.: Winter snow cover on the sea ice of the Arctic Ocean at the Surface Heat Budget of the Arctic Ocean (SHEBA): Temporal evolution and spatial variability, J. Geophys. Res.,107(C10), 8047, doi:10. 1029/2000JC000400, 2002.

We have revised from (P11250 L10-12):

"The two sets of vertical profiles both involve measurements from dozens of snow pits, thus they are considered to be largely representative of the typical distribution of spring sBC in these regions. "

To:

The two sets of vertical profiles both involve measurements of sBC and snow depth from dozens of snow pits, thus they are considered to be largely representative of the typical distribution of spring sBC in these regions. The typical values of snowpack depth in Russia and Canada were respectively 34±7 cm and 30±14 cm across all measurement sites.

2) We can see that h varied by sites according to the measurements in Russia and Canada. We have given the typical values (characterizing approximate actual snow depths) respectively of

34±7 cm and 30±14 cm in Russia and Canada across all measurement sites in the revised caption in figure 1.

Comment 2: Since the model is run with winds relaxed toward reanalysis fields, it seems to be run as a chemical transport model rather than a climate model, which is defined as a model that predicts, rather than prescribes, meteorology and ocean properties. Please clarify in the text, since the text claims that the model run is a climate model.
Reply: We agree that it is useful to clarify that the model was run in a mode similar to a CTM. The model is a climate model, however, and even when run using observed SSTs/sea-ice and linear relaxation of winds towards reanalysis it differs from a CTM in that other fields evolve based on the internal physics of the model (e.g. water vapor) and though these are influenced by the wind relaxation they are not directly prescribed as they might be in a CTM. Even the nudged winds are not the same as prescribed offline winds as the model relaxes towards them but internal physics maintains an influence. We now say describe the model as being run in a chemical transport model-like mode to facilitate comparison with observations.

We have revised from (P11252L5-8):
" Simulations were performed for 1995–2009 using observed sea surface temperatures (Rayner et al., 2003) and linear relaxation of winds toward either NCEP or MERRA reanalysis (Kalnay et al., 1996; Rienecker et al., 2011), with results analyzed for 2006–2009."
To:
Simulations were performed in a chemical transport model-like mode for 1995–2009 using observed sea surface temperatures (Rayner et al., 2003) and linear relaxation of winds toward either NCEP or MERRA reanalysis (Kalnay et al., 1996; Rienecker et al., 2011) to facilitate comparison with observations. Results are analyzed for 2006–2009.

Comment 3: Please provide a summary of BC emissions by source in a table.
Reply: The BC emissions by source are now given. They are: 3.5 Tg/yr from biomass burning and 5.3 Tg/yr from fossil fuel and biofuel combustion. That's as much detail as we have for these emissions.

Comment 4: Is BC transported vertically in snow and ice in the model? If so, how? If not, how much uncertainty does this bring into the model?
Reply: In this study, the concentration of sBC was calculated from total BC deposition divided by total precipitation in the accumulation period, BC transport in snow and ice has not been taken into account in the model. It is generally thought that the vertical transport of BC play an important role in the redistribution of BC in snow during melting period, especially in late May and early June. However, in the accumulation period, this process contributes much weakly to the redistribution and cannot give a substantial effect on the vertically-integrated sBC in whole snow layer. In this study, we focus on the estimation of concentrations of sBC in whole layer snow and compare them with simulated values to give a

validation to current GISS model. Thus, in the study, we have not taken the BC transport in snow into account though this process may bring some uncertainties too.

Comment 5: How is wet deposition of BC calculated? Is it based on an empirical function precipitation? Similarly, how is BC dry deposition calculated? Is it a function of size?

Reply: Wet deposition depends upon solubility and on transport within convective plumes, scavenging within and below updrafts, rainout within both convective and large-scale clouds, washout below precipitating regions, evaporation of falling precipitation, and both detrainment and evaporation from convective plumes. Dry deposition is calculated using a resistance-in-series model coupled to a global, seasonally varying vegetation dataset. It is not size dependent as the model assumes a fixed size distribution and only carries variations in mass. More details are available in (Koch et al., 1999; Shindell et al., 2001).

We have added this statement in 'model description' part in the revise paper.

Reference:

Koch, D., Jacob, D., Tegen, I., Rind, D., and Chin, M.: Tropospheric sulfur simulation and sulfate direct radiative forcing in the Goddard Institute for Space Studies general circulation model, J. Geophys. Res., 104, 23 799–23 822, 1999.

Shindell, D. T., Grenfell, J. L., Rind, D., Price, C., and Grewe, V.: Chemistry climate interactions in the Goddard Institute for Space Studies general circulation model 1. Tropospheric chemistry model description and evaluation, J. Geophys. Res., 106, 8047–8076, 2001.

Comment 6: It would be useful to see a vertical profile of BC over the Artic and how it would compare with HIPPO data near the Arctic (e.g., Schwarz et al., 2010)?

Reply:

There are two sets of vertical profile measurements of BC known to us, one set was reported in Koch et al. (2009) and the other was reported in Schwarz et al. (2010). In these studies, comparisons of GISS model results with corresponding observations had been done over Arctic Ocean, North American, Canada and Greenland in spring and during a flight line from Anchorage to the north pole (60~80°N) in winter. Results indicate that the simulated vertical profiles were comparable with observations in Greenland, Canada and Arctic Ocean in spring. However, there was significant bias in Alaska and nearby regions whether in spring or winter, with the model underestimating BC concentrations in middle and lower troposphere (see figure 1and 2), which was consistent with the simulation bias at Barrow station. However, the available observations in given areas are from a few aircraft measurements during short time, they can just provide a 'snapshot' of vertical profiles of BC concentrations, which make the comparison with simulated monthly BC distribution quite challenging. One emission event from forest or grass fire over surrounding continent could lead to quite different vertical profile of BC and take great effect to the aircraft measurements at that time. Nevertheless, the large underestimations in Alaska by current GISS model indicate the need for improvement in vertical profile simulations in North American in winter and spring.

We have added detailed discussion on this comparison in the revised paper (P11257L13-23).

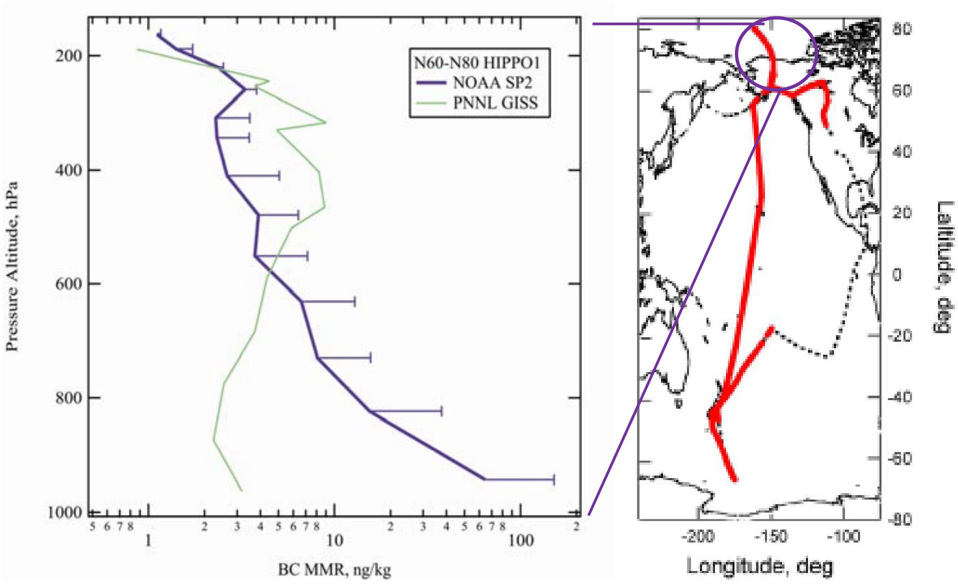
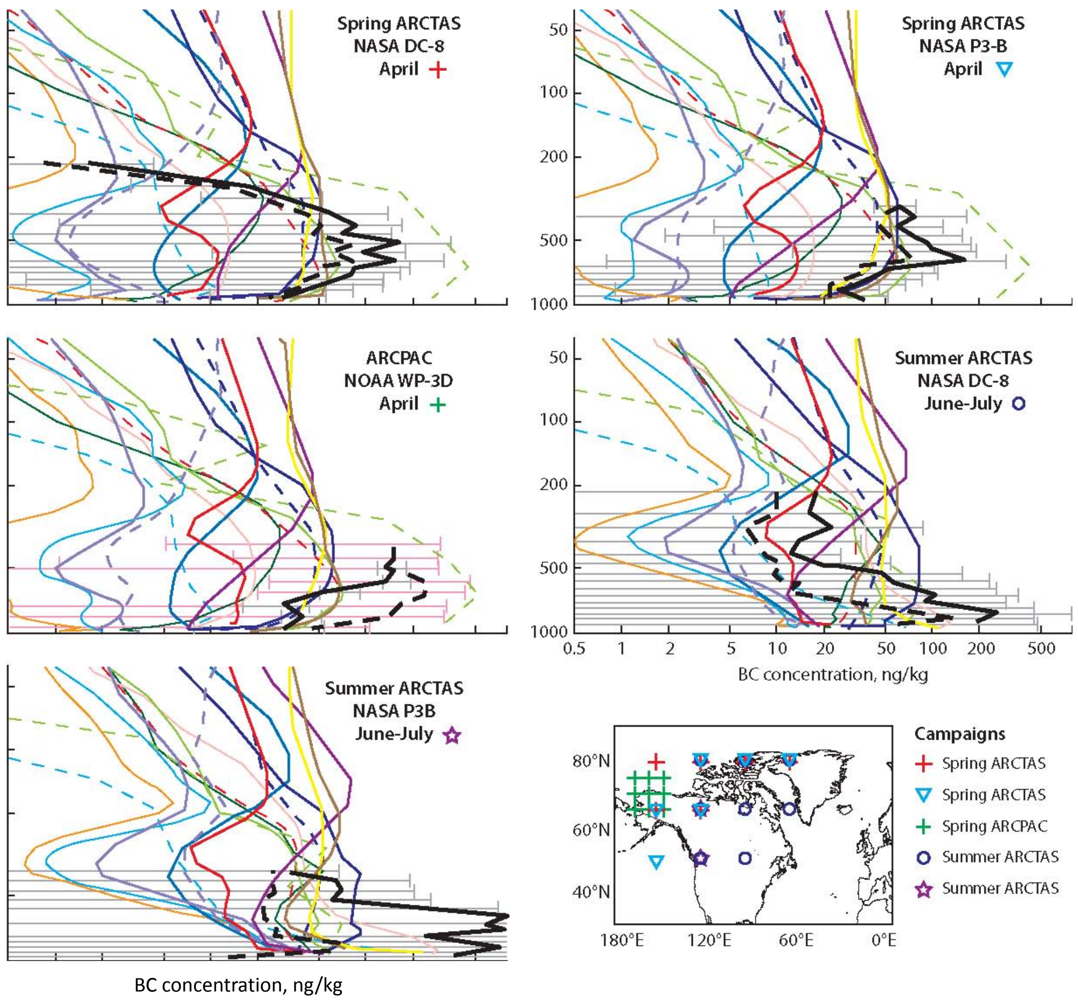


Figure 1: Comparison of vertical profile of BC from GISS model with aircraft measurements obtained during HIPPO campaign carried out by one flight from Anchorage to the north pole (60~80N) in January 2009. BC observations are supplied by Joshua Schwarz (NOAA).



ARQM SPRINTARS MOZART UIO GCM (dash) GOCART TM5 (dash) CAM LOA MPI ULAQ (dash)

MATCH **GISS** LSCE MIRAGE UMI (dash) UIO CTM DLR (dash)

Figure 2. Comparison with measurements obtained winthin the framework of the IPY POLARCAT projects ARCPAC and ARCTAS over high-latitude in spring and summer 2008. Mean (solid) and median (dashed) observations are shown in black. [Source: Koch et al. (2009)]

Comment 7: The authors should provide the ratios of wet deposition to wet plus dry deposition worldwide and over the Arctic and compare with other studies.

Reply：

Table 1. Ratio of wet deposition to total deposition over the Arctic north of 66N

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
2007	0.96344	0.94662	0.92799	0.91143	0.89891	0.89153	0.91904	0.93311	0.91329
2008	0.93996	0.9311	0.90514	0.89069	0.90389	0.9159	0.91119	0.91892	0.9007
2009	0.94687	0.94869	0.92871	0.92951	0.88451	0.88881	0.92808	0.92877	0.93672

Wet/Total deposition: range 88% ~96%. Winter: 90% , Spring: 92%

Table 2. Ratio of wet deposition to total deposition in Northern Hemisphere

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
2007	0.78268	0.78803	0.77537	0.75049	0.73923	0.75426	0.7573	0.76854	0.75677
2008	0.77669	0.76897	0.76032	0.7499	0.75107	0.75044	0.75764	0.75704	0.74661
2009	0.79229	0.79165	0.77187	0.76539	0.74268	0.74913	0.77317	0.77387	0.7769

Table 3. Ratio of wet deposition to total deposition worldwide

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
2007	0.8062	0.81939	0.81939	0.80837	0.80207	0.81105	0.81668	0.8208	0.80841
2008	0.80558	0.80191	0.80429	0.80988	0.8134	0.81728	0.81922	0.81412	0.80303
2009	0.82192	0.81522	0.81666	0.8126	0.80337	0.81877	0.82846	0.82008	0.82302

Table 4. Ratios of wet deposition to wet plus dry deposition in the model from September to May, 2007-2009

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
North of 66°N	0.95	0.94	0.92	0.91	0.90	0.90	0.92	0.93	0.92
Northern Hemisphere	0.78	0.78	0.77	0.76	0.74	0.75	0.76	0.77	0.76
Worldwide	0.81	0.81	0.81	0.81	0.81	0.82	0.82	0.82	0.81

From above tables, we can see wet deposition is the dominant removal process in the model. We have added wet fraction of total deposition in a table, it can be seen that the ratios of wet deposition to total deposition worldwide and over the Arctic are comparable with those in other models of 78% to >95% (Textor et al., 2006; Huneeus et al., 2011).

We have included Table 4 in 'model description' part in the revised paper.

Reference:

Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Feichter, H., Fillmore, D., Ghan, S., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I., Iversen, I., Kloster, S., Koch, D., Kirkev°ag, A., Kristjansson, J. E., Krol, M., Lauer, A., Lamarque, J. F., Liu, X., Montanaro, V., Myhre, G., Penner, J., Pitari, G., Reddy, S., Seland, Ø., Stier, P., Takemura, T., and Tie, X.: Analysis and quantification of the diversities of aerosol life cycles within AeroCom, Atmos. Chem. Phys., 6, 1777–1813, 2006.

Huneeus, N., M. Schulz, Y. Balkanski, J. Griesfeller, J. Prospero, S. Kinne, S. Bauer, O. Boucher*, M. Chin, F. Dentener, T. Diehl, R. Easter, D. Fillmore, S. Ghan, P. Ginoux, A. Grini, L. Horowitz, D. Koch, M. C. Krol,W. Landing, X. Liu, N. Mahowald, R. Miller, J.-J. Morcrette, G. Myhre, J. Penner, J. Perlwitz, P. Stier, T. Takemura, and C. S. Zender: Global dust model intercomparison in AeroCom phase Ⅰ, Atmos. Chem. Phys., 11, 7781-7816, 2011.

P. 11253. “Model results have been interpolated: : :” What interpolation method was used?

Reply:

Bilinear interpolation has been used in the calculation.

Figure 1. The figure shows percent of total snow depth. It would be helpful to put approximate actual snow depths in the caption.

Reply:

Done, we have added “The snowpack depths in Russia and Canada were respectively 34±7 cm and 30±14 cm across all measurement sites” in the caption.

Figures 3 and 5. The results for each 2007-2009 look similar. I would suggest to consolidate into one average plot for the three-year period.

Reply:

We agree with your view that the three figures look generally similar. However, little difference in the concentration of sBC and albedo reduction can lead to great difference in the resulting radiative forcing in the Arctic regions because widely distributed snow and long time solar radiation in polar days. Indeed, values in Eastern Russia are substantially higher in the model in 2008 than in 2007. Analyses also indicate that there are significant annual variations in radiative forcings due to BC deposition in our study time 2007-2009, they are respectively 0.7, 1.1, 1.0 w/m^2 in these years, and most of the annual variations resulted from the annual difference in the Arctic Ocean and surrounding areas. Therefore, we think the three figures are useful to reflect the annual variations. Considering our focus on the Arctic, we think all of these figures would be necessary in this study.

Figure 6. A scatterplot of modeled versus measured values from this figure would appear not to give nearly the same accuracy of the scatterplot in Figure 4. Please explain why the error in Figure 6 is so much larger than that in Figure 4.

Reply:

Evaluation of the model's ability to capture regional sBC variations is really a test of the emissions and the lifetime of BC in the model. Hence the generally successful reproduction of observed sBC implies the overall BC lifetime is reasonable. However, the model-observation comparisons of aBC also suggested that there was large discrepancy in near surface BC simulations, especially during winter period, although the seasonality has been greatly improved. That said, current model still has some problems in predicting the vertical profiles of BC in the Arctic. This could also be verified by comparison with aircraft measurements, which showed that the model significantly underestimated BC in middle and lower troposphere in measurement areas but overestimated it in the upper troposphere and lower stratosphere (Koch et al., 2009; Schwarz et al., 2010).

We have given detailed discussion on the possible reason leading to the poor performance in simulating the vertical profiles of BC and observed near surface BC at several stations in the revised paper (P11257L23-27).

Reply to Referee 2#

Comment 1: a) It is not very clear, how the snow black carbon is measured, it may be standard procedure but it will be really important to include in the paper for the benefit to the readers. b) The density of snow is very much dependent on the meteorological conditions; it will be interesting to include meteorological parameters for the period in which measurements are presented, i.e. July 2010, August 2005 and 2010.

Reply to a): The measurement technology applied in our study was the same as that applied in *Forsstrom et al.* (2009) and all of the observations reported in this paper are measured by merely two methods (Table 1). We have included the description of sBC measurements in the text (P11251L13-15).

Table 1. BC observations applied in this study and their measurement technologies

Reference	This study	*Doherty et al.* [2010]	*Doherty et al.* [2010]	*Forsstrom et al.* [2009]
Site	Arctic Ocean	Central Arctic basing	Arctic Ocean, Canada, Russia and Greenland	Svalbard
Time	summer 2010	summer 2005 and 2008	spring 2007, 2008 and 2009	spring 2007
Sample	Snow /sea ice	Snow/sea ice	Snow	Snow
Filter	Quartz microfiber	Nuclepore (0.4 µm)	Nuclepore (0.4 µm)	Quartz microfiber
Method	Thermal-optical NIOSH 5040	Spectro-photometry	Spectro-photometry	Thermal-optical NIOSH 5040

Reply to b): Yes, the density of snow is greatly influenced by the meteorological conditions. We measured the air and snow temperature over sea ice during the 3rd Arctic expedition (July 21th~Aug 25th), from below figure 1 we can see that snow temperature increased gradually by depth (from -2.0 to -0.5℃). We have also given figures to illustrate the spatial distribution of meteorological parameters for the period in which measurements are presented (see details in figure 2). It can be seen that there was not significant annual variations in the Arctic Ocean during measurement periods in summer (Jul. ~ Sep.).

We have not included the analyses on meteorological parameters in the text, because the model was driven by observed meteorology (via relaxation towards reanalysis), so includes variability of meteorological parameters for the period in which measurements are presented. Additionally, it is generally thought that the given snow densities have also included the influences of meteorological field.

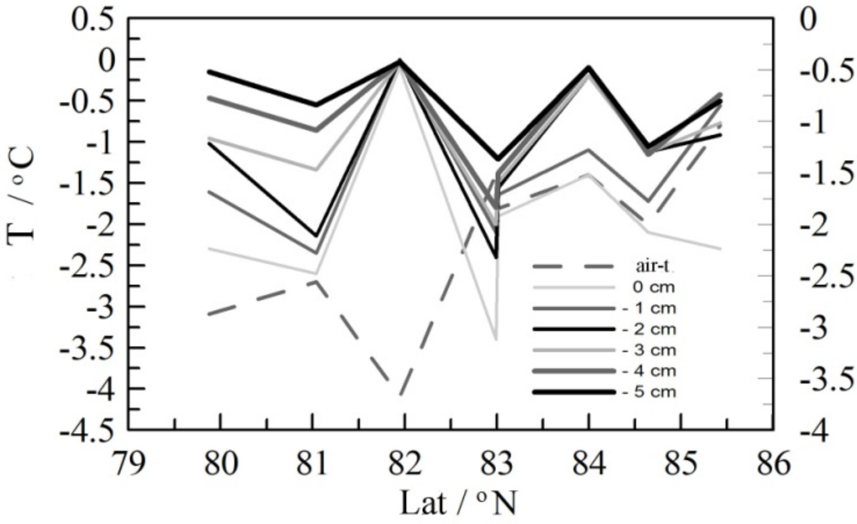


Figure1. Observed temperature varies by snow depth in the Arctic from 79~86N. Air temperature is also included.

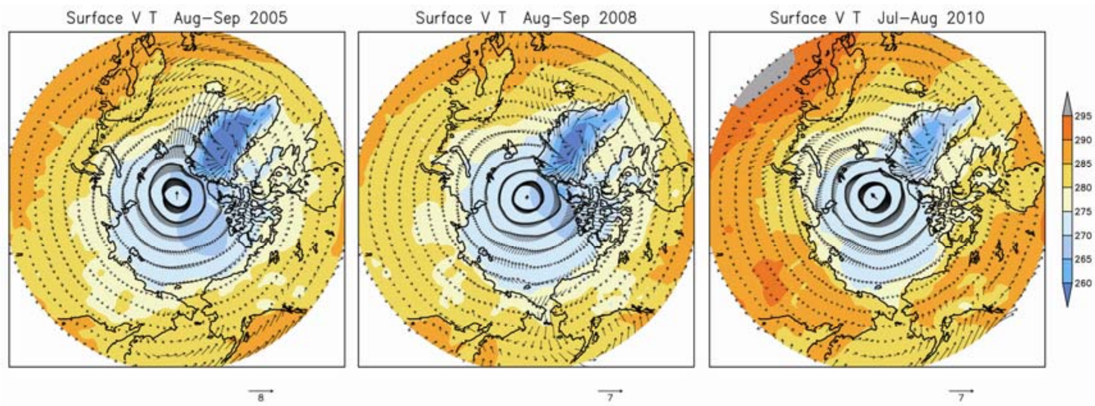


Figure2. Spatial distribution of surface wind and temperature in the Arctic during measurement period. Source: NCEP reanalysis data.

Comment2: 1) Snow density is a very important parameter. Authors have taken a mean value of surface and subsurface snow observed in different types of snow layers from the SHEBA campaign. In the absence of real snow density data a large uncertainty in model simulations may occur. 2) How the radiative forcing was estimated?

Reply: 1) We agree that a large uncertainty may occur due to absence of real snow density. However, in current situation of limited observations, the values of snow density obtained during SHEBA campaign would be a better choice to estimate the whole layer concentrations of sBC in the Arctic. We have added discussions to illustrate the availability of estimated values of snow density applied in this study and given corresponding uncertainties in table 1 and table 3 in the revised paper.

We have added one sentence on P11250L22-25 to illustrate availability of estimated values of snow density applied in this study:

"Sturm et al (1995) gave a rough generalization of snow kinds in different terrain types and suggested that the snow found at tundra is the closest substitute for what would be estimated to be found over floating ice. Accordingly, ……"

Reply to 2): The radiative forcing was estimated by convolving the albedo reduction derived from Fig. 2 in Warren et al. (1985) with the NCEP incoming solar radiation at the surface. In the calculation of decrease in albedo due to BC deposition, we assume snow grain radius was a constant and the albedo reduction was not impacted by snow density. More details are available in (Warren et al, 1985; Wang et al., 2011).

Reference:

Warren, S. G. and Wiscombe, W. J.: Dirty snow after nuclear war, Nature, 313, 467–470, 1985.

Wang, Q., Jacob, D. J., Fisher, J. 5 A., Mao, J., Leibensperger, E. M., Carouge, C. C., Le Sager, P., Kondo, Y., Jimenez, J. L., Cubison, M. J., and Doherty, S. J.: Sources of carbonaceous aerosols and deposited black carbon in the Arctic in winter-spring: implications for radiative forcing, Atmos. Chem. Phys., 11, 12453–12473, doi:10.5194/acp-11-12453-2011, 2011.

Comment3: The authors have used two data sets, discussion related to two data sets may be mentioned. Biomass burning emissions can disperse up to short and long ranges depending upon meteorology, these emissions are only restricted to the Russian Arctic and beyond! Abstract may be rewritten, authors may include some quantitative values of decrease of snow albedo and radiative forcing.

Reply:

We have added relevant discussion on two model runs on P11254L29, after "the observed concentrations."

Further study indicates that the simulations from two model runs present small differences over each Arctic region, NCEP run performs slightly better in the Arctic Ocean, Svalbard and Greenland, MERRA run performs slightly better in Russia and Canadian and Alaskan Arctic, although they both have significant underestimation in Russian Arctic, and overestimation in Svalbard and Greenland (Table 2). However, the difference between two model runs is far less than current simulation bias, therefore, we suggest that the discrepancy between model results and observations comes from some other sources, but not different meteorology field applied.

Table 2. Observation-to-model ratios between observations and model results from NCEP and MERRA runs over each Arctic sector

	Arctic Ocean	Canada and Alaska	Russia	Svalbard	Greenland
NCEP	**0.92**	1.09	1.81	**0.84**	**0.81**
MERRA	0.89	**1.05**	**1.77**	0.73	0.78

We also have rewritten the abstract and included some quantitative values of decrease of snow albedo and radiative forcing.

Comment4: Introduction, line 20 It is still controversial – it is not controversial, it depends on uncertainty in ground measurements and physical parameters, mostly lack of data.

Reply:

We have revised it in the text.

Comment5: Observations The earliest observations of sBC mainly started : : :: : :: : :: : :. Include only references associated with measurements.

Reply:

We have deleted irrelevant references here.

Comment6: Page 11250, line 21 Do not use short form It's The authors have mentioned that it is impossible to measure actual density which is one of the important parameters and this can cause a large uncertainty in the results discussed in the paper.

Reply:

We have revised from:

"Because there are not observations of snow density that correspond to sBC measurements in various depths, it's impossible to calculate the actual and precise C_h of each site at present."

To:

Note that it's difficult to calculate the precise C_h based on present limited observations, because we have not obtained the snow density values that correspond to BC measurements in various snow depths. In this study, we……

4. Initial field in the Arctic Ocean??? – The authors mentioned about SWE, not very clear of the purpose of its inclusion.

Reply:

Model deposition in our study began from Sep., it is generally thought there is still snow left on sea ice surface in this period. In order to estimate the spatial distribution of sBC in the Arctic more reasonably and accurately, we gave an initial field which represented the distribution of snow cover and BC content within it that survived melt season. Snow water equivalent (SWE) here denotes the snow mass on per unit area, which was calculated by: [SWE] = [Snow density] * [Snow Depth], (Density here is in decimal form), the precipitation and BC deposition from model would accumulate on the initial field month by month and finally get a spatial map of sBC.

5. Inter-comparison between model results and observations As stated in the paper, "Present observations of sBC show sketchy but identifiable variations", when it is sketchy, authors may provide firm observations, of course sBC may show contrast depending upon the meteorological conditions and close to the source of emissions and long range transport of emissions. In the present paper, all these parameters are not clear in the paper. The wind

pattern may be shown if there is any event during 2007-2010 when black carbon could have been transported from continent.

Reply: The model was driven by observed meteorology (via relaxation towards reanalysis), so includes variability in transport during 2007-2009. Thus evaluation of the model's ability to capture regional sBC variations is really a test of the emissions and the lifetime of BC in the model. Hence the generally successful reproduction of observed sBC implies the overall BC lifetime is reasonable, and we infer that the large regional biases in Russia shown in the analysis are likely attributable to emissions biases in that region.

Figure 6 shows a large difference in model and observed results in contrast. Why there is large difference in the observed and modeled values. Sometime difference is higher in winter, sometime during summer? The results must be discussed in detail.

Reply: Done.

The model-observation comparisons suggested that there was still large simulation bias in current model, especially during winter and spring period although the seasonality has been greatly improved (Figure 3). The biases could also be found in the comparison with vertical profiles of BC, with significant underestimation in middle and lower troposphere in measurement areas but overestimation in the upper troposphere and lower stratosphere (Koch et al., 2009; Schwarz et al., 2010). Liu et al. (2011) pointed out that winter concentrations of BC in the Arctic could increase largely throughout much of the tropospheric column by improving BC aging and deposition parameterization in the model. The dry deposition process has little effect on the seasonal pattern of BC in the Arctic lower troposphere, the observed seasonality of BC in the Arctic troposphere is mainly due to the seasonal changes in aerosol removal by wet scavenging and seasonal injections of BC from Europe and the former USSR (Huang et al., 2011). Koch et al., (2009) also suggested that current simulation bias may be due to lack of sufficient removal by precipitating clouds and low-level pole-ward transport. Quinn et al. (2011) indicated that biomass burning emissions contributed largely to the BC concentrations in the Arctic middle and upper troposphere. Therefore, current model could perhaps be enhanced by improving the representations of wet deposition processes and biomass burning emissions in Northern Eurasia. Of course, this still needs to be verified by a series of sensitivity test with the model. However, present BC observations also have large uncertainties from various measurement technologies (Koch et al., 2009) and every aircraft measurement was actually carried out in a short time during flight campaign, which could just provide a ‘snapshot’ of vertical profiles of BC concentrations, making the comparison with simulated monthly BC distribution quite challenging. Thus, more long-term and spatial wide observations are needed to validate current model especially over Eurasia, the oceans and the biomass burning regions.

Above discussions on current simulated bias at several Arctic stations have been included in the “discussion and conclusion section” in the revised paper.

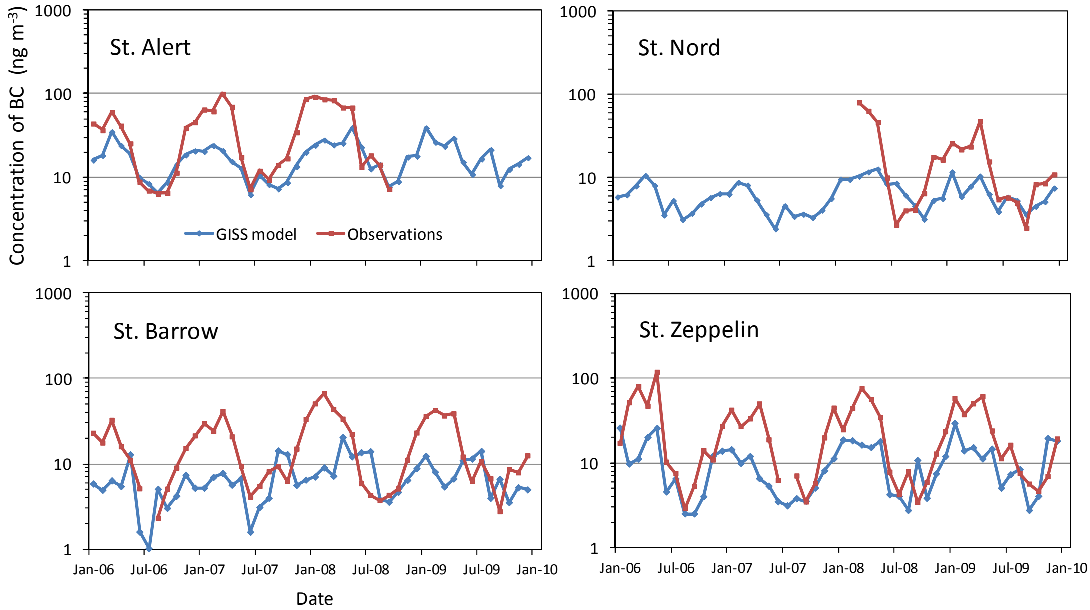


Figure3. Comparison of modeled BC from GISS model with the observations obtained at Alert, Barrow, Nord and Zeppelin station in the Arctic from Jan 2006 to Dec 2009.

References:

Huang, L., Gong, S. L., Jia, C. Q. and Lavoue, D.: Importance of deposition process in simulating the seasonality of the Arctic black carbon aerosol, J. Geophys. Res., 115, D17207, doi:10.1029/2009JD013478, 2010.

Koch D, Schulz, M., Kinne, S., McNaughton, C., Spackman, J. R., Balkanski, Y., Bauer, S., Berntsen, T., Bond, T. C., Boucher, O., Chin, M., Clarke, A., De Luca, N., Dentener, F., Diehl, T., Dubovik, O., Easter, R., Fahey, D. W. et al.: Evaluation of black carbon estimations in global aerosol models, Atmos. Chem. Phys.,9,9001-9026, doi:10.5194/acp-9-9001-2009, 2009.

Schwarz, J. P., J. R. Spackman, R. S. Gao, L. A. Watts, P. Stier, M. Schulz, S. M. Davis, S. C. Wofsy, and D. W. Fahey: Global-scale black carbon profiles observed in the remote atmosphere and compared to models, Geophys. Res. Lett., 37, L18812, doi:10.1029/2010GL044372, 2010.

Liu, J, Fan, S., Horowitz, L. W. and Levy, H. II, February: Evaluation of factors controlling long-range transport of black carbon to the Arctic, J. Geophys. Res., 116, D04307, doi:10.1029/2010JD015145, 2011.

Quinn, P. K., Stohl, A., Arneth, A., Berntsen, T., Burkhart, J. F., Christensen, J., Flanner, M., Kupiainen, K., Lihavainen, H., Shepherd, M., Shevchenko, V., Skov, H., and Vestreng, V.: The impact of black carbon on Arctic climate, Arctic Monitoring and Assessment Programme (AMAP), Oslo, 72 pp., 2011.

The albedo of snow is highly wavelength dependence, decrease of albedo is qualitatively mentioned but wavelength is not mentioned.

Reply:

Spectrally averaged albedo change due to BC deposition has been applied in this study. We add this in revised paper.

Since there is a large difference in observed and model results, the authors may try to improve model to get a realistic simulation.
Reply:
We agree that this model still needs to be improved. However, this study mainly focuses on the comparison between model and observations, and gives some suggestions for further targeted improvement. This improvement requires new observations, more comprehensive input of data set and improved parameterization. Therefore, we would give further improvements in future studies.

At several instances in the manuscript, structure of sentences is not clear, authors may improve language and focus their discussion.
Reply:
We have improved this in the revised paper by English origined co-authors, and wish meet requirements.

Reply to Referee 3#
Major issues:
P11250 L 4-5 (Concentrations ... data analysis)
A reference or explanation for the bias is needed before changing other people's results.
Reply: Done, after publication of [Doherty, S. J.,Warren, S. G., Grenfell, T. C., Clarke, A. D., and Brandt, R. E.: Light-absorbing impurities in Arctic snow, Atmos. Chem. Phys., 10, 11647–11680, doi:10.5194/acp-10-11647- 30 2010, 2010], Doherty et al. found an error in the data analysis which resulted in a low bias in the concentration-dependent parameters ($C_{BC}^{\max}$,C_{BC}^{est} and C_{BC}^{equiv} ; see below) of 11%. They corrected for this error in the data file sent to us.

We would explain this revision of 11% by changing:
"Concentrations reported by Doherty et al. (2010) were increased by 11% to correct for a low bias in the previous data analysis"
To:
"Concentrations supplied by S. J. Doherty have been increased by 11% relative to those reported in Doherty et al., (2010), in order to correct for a low bias in the concentration-dependent parameters ($C_{BC}^{\max}$,C_{BC}^{est} and C_{BC}^{equiv}) which resulted from an error in the earlier data analysis".

P 11250 L 22 – P 11251 L 1 (In this study ... bottom by turns.)
The reference (Sturm et al, 2002) gives the snow pack structure averaged over all sampling locations within 16.4 km radius from the station floating with the ice at the peak of accumulation period 1998. In the perspective of the large scale modeling this should be seen as one measurement point at one spring 14 years ago. The generalization of the snow layer structure over the whole Arctic and densities with 3 meaningful numbers based on this data simply cannot be done. For estimating the density of the snow pack I suggest the following approach: Sturm et al, 1995 give a rough generalization of what kind of snow is expected to be found in diffferent terrain types on land. The snow found at tundra is the closest substitute for what would be estimated to be found over floating ice (layers of wind slab and possibly new snow and depth hoar in varying order). The measured density values in different layers (Sturm et al, 2002) can then be used to give the range in which the snow density (and mass based BC concentrations) vary. (Sturm, M., Holmgren, J. And Liston, G. E.: A seasonal snow cover classification system for local to global applications, J. Geophys. Res., 1261-1283, 1995.)
Reply: Done.
We have added one sentence on P11250L22-25 to illustrate availability of estimated values of snow density applied in this study:
"Sturm et al (1995) gave a rough generalization of snow kinds in different terrain types and suggested that the snow found at tundra is the closest substitute for what would be estimated to be found over floating ice. Accordingly, ……"

P 11253 L 24 – P 11254 L 1 (The correlation ... in the Arctic.)
Correlation is not very good estimate for the performance of a model. Two sets of values can correlate perfectly even if all values in one set are larger than maximum value in the other set. Also the number of observation points is statistically low, the correlation coefficients between the models and observations are very close to each other with both models, and in both cases the fitted (least mean square) line is heavily affected by the six points in the Russian Arctic (Fig.4.). I wouldn't make the conclusion that one meteorological reanalysis is better than the other, but rather that they are roughly equal and the discrepancy between model results and observations comes from some other source.
Reply: We have revised the statement on this point and give more detailed explanation.

We delete:
"The correlation coefficient between them can be up to 0.64 (for NCEP run in Fig. 4b and 0.6 for MERRA run). That said, the model result from NCEP run is closer to the measured sBC than that from the MERRA run. Hence we recommend the NCEP reanalyses are a better choice for current GISS simulation of BC in the Arctic. "

And add the following paragraph and table 4 on P11254L29, after "…… the observed concentrations."

Further study indicates that the simulated concentrations of sBC from two model runs present small differences over each Arctic region, with the NCEP run performing slightly better in the Arctic Ocean, Svalbard and Greenland and the MERRA run performing better in

Russia and Canadian and Alaskan Arctic, although they both underestimated concentrations of sBC in Russian Arctic, and overestimated concentrations in Svalbard and Greenland (Table 1). However, the differences between two model runs were far less than current simulation biases. Therefore, we suggest that the discrepancy between current model results and observations comes from some other sources, but not the meteorology fields applied.

Table 1. Observation-to-model ratios between observations and model results from NCEP and MERRA runs over each Arctic sector

	Arctic Ocean	Canada and Alaska	Russia	Svalbard	Greenland
NCEP	**0.92**	1.09	1.81	**0.84**	**0.81**
MERRA	0.89	**1.05**	**1.77**	0.73	0.78

P 11257 L 27 – P11258 L 2 (we suggest that ... and sea ice.)

If there is significant underestimation of aBC in this model (similarly to other current models), how does this model get the sBC right when other models do not. Please explain.

Reply:

Evaluation of the model's ability to capture regional sBC variations is really a test of the emissions and the lifetime of BC in the model. Hence the generally successful reproduction of observed sBC implies the overall BC lifetime is reasonable, and we infer that the large regional biases in Russia shown in the analysis are likely attributable to emissions biases in that region. Significant underestimation of aBC in this model indicated that current model still has some problems in predicting the vertical profiles of BC in the Arctic. This could also be verified by comparison with aircraft measurements (Koch et al., 2009; Schwarz et al., 2010). We have given detailed discussion on the possible reason leading to the poor performance in simulating the vertical profiles of BC and observed near surface BC at several stations in the revised paper (P11257L23-27).

P 11257 L 11-12 (The overall ratio of observed to modeled sBC is 1.1.)

If this ratio was produced by simply taking the average of the ratios at each grid point where there were measurements, the ratio is heavily biased towards the Canadian Arctic where the number of measurements points is largest (and measured values increased by 11%). In this case the ratio does not represent the Arctic as a whole, and should not be given this way. I suggest giving these values separately for each area with both model runs (See comments to figuer 4.)

Reply: Yes, the ratio of observations to model results varied by regions. We agree that the overall ratio 1.1 in current paper cannot reflect the actual model performance very well. It is more suitable and clear to give the ratios separately for each Arctic sector with both model runs (Table 1). We can find from this table that model performs differently in various regions both for two runs, with significant underestimation in Russian Arctic, and overestimation in Svalbard and Greenland. It performs well in Canadian and Alaskan Arctic and the Arctic Ocean.

Also, please see details in the reply to the comment on figure 4.

Minor issues

P 11248 L 4 (The average radiative forcing...)

I assume this refers to the global average. If so, please include the word global.

Reply:

Done, we have included word "global" in the sentence " The global averaged radiative forcing from BC by altering surface albedo was estimated as +0.1Wm^{-2} (IPCC, 2007), with estimates varying from 0.01 to 0.16Wm^{-2} (Flanner et al., 2007; Hansen et al., 2004, 2007; Koch et al., 2009a)".

P 11248 L 13-17 (The comparison ... winter and spring.)

This sentence remains unclear to me. What is the meaning with "some points of sBC" in the middle?

Reply:

Done, we have deleted these words and relative reference, which would not influence on the whole sentence and what we want to say …

Change:

The comparisons between model simulations and aerosol BC (aBC) observed in Barrow, Alert and Zeppelin stations and some points of sBC have shown that most previous models underpredict BC in the Arctic, especially in winter and spring (Flanner et al., 2007; Shindell et al., 2008; Koch et al., 2009b; Huang et al., 2010a; Liu et al., 2011).

To:

The comparisons between modeled and observed aerosol BC (aBC) at Barrow, Alert and Zeppelin stations have shown that most previous models underestimated concentrations of BC throughout much of the troposphere in the Arctic, especially in winter and spring (Shindell et al., 2008; Koch et al., 2009b; Huang et al., 2010a; Liu et al., 2011).

P11249 L 17-19 (references)

Do all the given references refer to the earlier observations in mid-1980s? If not, please rephrase the sentence or remove unnecessary references.

Reply:

Done, we delete the reference not related to this statement.

P11249 L 19-21 (Camp Century ... Arctic Ocean sites.)

Camp Century and Dye 3 are clarified be located in Greenland, whereas no clarification is given for Alert or Barrow. Please be consistent.

Reply:

Done.

P11250 L 13-14 (... derive an empirical formula ...)
How was this formula derived?
Reply:
We have known that snow depth ‘h’ varied by sites according to present measurements in Doherty et al. (2010), and higher values of sBC mainly concentrated on upper 25% layer and lower values concentrated on the bottom 75%. Therefore, in the paper, we gave an equation to calculate the concentration of sBC per unit area in whole layer snow based on present BC and snow density observations. Numerator in the equation $(25\%*h*\rho(h_1)*C(h_1) + 75\%*h*\rho(h_2)*C(h_2))$ denotes the total mass of sBC (ng) per unit area in whole layer snow, and denominator $(25\%*h*\rho(h_1)+75\%*h*\rho(h_2))$ denotes total mass of whole layer snow in per unit area.

We have revised from P11250L13-16:
“We calculate the surface and subsurface concentrations of sBC from the observations at different depths, and then derive an empirical formula for estimating the integrated-layer concentration (C_h, $h = h1+h2$) of sBC. In the case of surface sBC > subsurface sBC:”

To：

We calculate the surface and subsurface concentrations of sBC from the observations at different depths, and then give an equation for estimating the integrated-layer concentration (Ch, h=h1+h2) of sBC. In the case of surface sBC > subsurface sBC (for most measurement sites in Russian Arctic):

P 11250 L 19-20 (...and h1 and h2 are as given in Fig.1.)
This would be better if written here. Eg: ...and h1 is the top 25% of the snow pack depth and h2 the bottom 75%.
Reply:
Done, this has been revised.

P 11251 L 10-13 (The vertically ... great uncertainties.)
Leaving out values simply because they are too large is not a good practice. Please include those values in the analysis or find a real reason to exclude them. (Possible local contamination?).
Reply:
In most cases we believe the data included in this study are free of the influence of local sources. However, we would like to highlight one sub-set of the data where this was not the case: entries 604-609 from ~67.718°N, 64.379°E were taken ~30km from the Russian city of Vorkuta. The BC concentrations here were much higher than anywhere else in the Arctic due to local contamination and we believe therefore that they are not more broadly representative of northwest Russia, though they do highlight the fact that a sufficiently large source of BC can influence a relatively large region.

We revised from:
“The vertically-integrated …….”

To:
The vertically-integrated values larger than 70ng g -1 were also not applied because too large difference between surface and subsurface concentrations occurred in these sites due to local contamination, which may bring great uncertainties.

P 11252 L 8 (Repeating year 2000 monthly-varying...)
Are the year 2000 emissions representative for the modeled period 2007-2009? How much uncertainty does this bring?
Reply: Year 2000 were the latest emissions available in Lamarque et al (2010). Later emissions for the IPCC scenarios come from Integrated Assessment Models, so bring their own uncertainties. The year 2000 emissions were meant to be representative of conditions around that time rather than the year 2000 in particular. We expect differences are small going out only a few years in the future for most parts of the world, though it is difficult to quantify these impacts. We now note that uncertainties in emissions (with time) may play a role.

We add this on p 11258, L 7: after "play a role" add "and could have changed over the 2000s decade".

P 11253 L 3-5 (The entire ... located with it.)
Why was the Arctic divided to latitude bands? Why was no longitudal separation appleid?
Reply: There is spatial variation of sBC in measurement areas as latitude, but not as longitude (below figure). We can just give a rough description of sBC distribution in summer Arctic Ocean based on current observations, though this would bring uncertainty. In this study, the entire Arctic Ocean is divided into three latitudinal bands: south of 80°N, 80–85°N and the Arctic Ocean center, with mean values：17.7ng g^{-1} , 9.5ng g^{-1} , 7.5ng g^{-1} respectively.

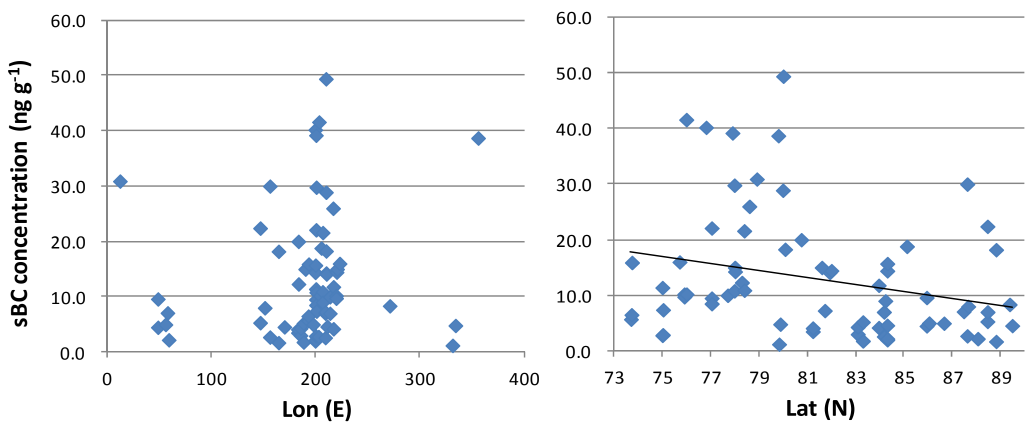


Figure. Spatial variation of sBC as longitude (left) and latitude (right).

P 11254 L 12-13 (Most observations ... Arctic Ocean.)

If the sBC values observed in the center of Arctic Ocean were assumed to be too low because only surface snow was measured, that would require the subsurface sBC to be significantly higher. This is not the case in the Canadian or Russian Arctic where sBC profiles were measured. Please explain or give a reference why the sBC would be concentrated in subsurface snow on the Arctic Ocean.

Reply:

Done. Actually, there were very few BC observations applied for comparison between model results and observations in the Arctic Ocean, and the overestimation only occured over the regions north of 88°N (near North pole) for 4~5 point measurements, which would make the whole concentrations of BC look overestimated. In the revised paper, we included more observations over Arctic Ocean from S. J. Doherty for the comparison. Results showed that rough agreement between the model and observations is found in the Arctic Ocean with mean values of 8.2±0.9 ng g^{-1} in the model and 7.4±2.3ng g^{-1} in the observations, the ratio of observations to modeled values is 0.92 (also can be seen in figure 3 and table 4).

We have deleted the previous statements on P11254L9-13 and added "Rough agreement between the model and observations is found in the Arctic Ocean and Canadian and Alaskan Arctic sector, respectively with mean values of 8.2±0.9 ng g^{-1} and 7.2±1.3ng g^{-1} in the model and 7.4±2.3ng g^{-1} and 7.8±2.4ng g^{-1} in the observations." in the revised paper.

P 11255 L 11-13 (Result shows ... and 2009.)

Besides temporal variation, it would be nice to give some numbers for the spatial variation (Fig.5.) in the text.

Reply:

Done.

Russia: 1.25%

Canada and Alaska: 0.43%

Arctic Ocean: 0.58%

Greenland: 0.64%

Svalbard: 0.39%

We have included this discussion on P11255-L7. "The resulting albedo reduction presents significant space-time variations, with highest mean value of 1.25% in the Russian Arctic, which was much larger than those in other Arctic regions ranging 0.39% to 0.64%."

P 11255 L 19-21 (Rahn et al ... pollution products.)

The structure of this sentence is unclear.

Reply:

Done,

Change:

Rahn et al. (1980) first indicates that the Arctic atmosphere is hazy in winter and spring, that resulting from fossil fuel burning, industrial, and agricultural processes, by long-range transport of mid-latitude pollution products.

To:

Rahn et al. (1980) reported that the Arctic atmosphere is hazy in winter and spring, and indicated this phenomenon may be caused by fossil fuel burning, industrial and agricultural processes, by long-range transport of mid-latitude pollution products.

P 11258 L 26-29 (It also needs ... Arctic regions.)

I don't see this line being enough for adressing the snow density issue.

Reply:

Done, we delete the sentence which would not influence on this study.

Tables

The two large tables fill a major fraction of this manuscript. They give information on the spring and late summer sBC concentrations at sites around the Arctic. The respective sBC values from the GISS-PUCCINI model are not included in the tables. In both tables the columns labeled "surface", "subsurface" and "whole layer" need better labels so that the reader can understand what they are and what are the units. Also column "uncertainty of estimation" needs units. Many references in the tables are given as field campaign names or other acronyms (NPEO, APLIS/SEDNA, U.Vic, HOTRAX). Has this data been published elsewhere? If yes, please give appropriate reference. If the data is first published in this study, please mark it so. The tables (especially table 2) do not bring out much of the results, but mostly values reported elsewhere. Therefore I suggest the authors to consider whether they would be better given as Appendix or supplementary material (if the journal format allows this).

Reply:

Done, we have revised the tables and give them as Appendix.

Figures

Figure 1

What are the vertical lines in the figures and what is the horizontal line at right panel at 90% snow depth? Those are not in the original figure (Doherty et al., 2010). Since the 25% / 75% division is made to all sites, it would be good to have the h1 and h2 in both figures. Also, please correct the unit format on the vertical axis of the left panel.

Reply:

Done. Two cases were considered in the calculation of vertically-integrated concentration in this study, they are: 1) when surface values are much higher than those in subsurface (for most measurement sites in Russian Arctic and few sites in Canadian Arctic), we estimated the whole layer values based on the left panel in figure 1 in which higher values mainly concentrated on the upper 25% layer. 2) when the value of surface sBC was close to or less than that of subsurface sBC, we calculated the whole layer concentrations based on right panel in figure 1, and took the depth-weighted average of the concentration values in each layer as the estimated vertically-integrated concentration. Additionally, we cannot give a horizontal line in right panel according to present observations and Doherty et al. (2010). We delete the vertical lines in the figures in revised paper. We think this new figure could give enough information for current study.

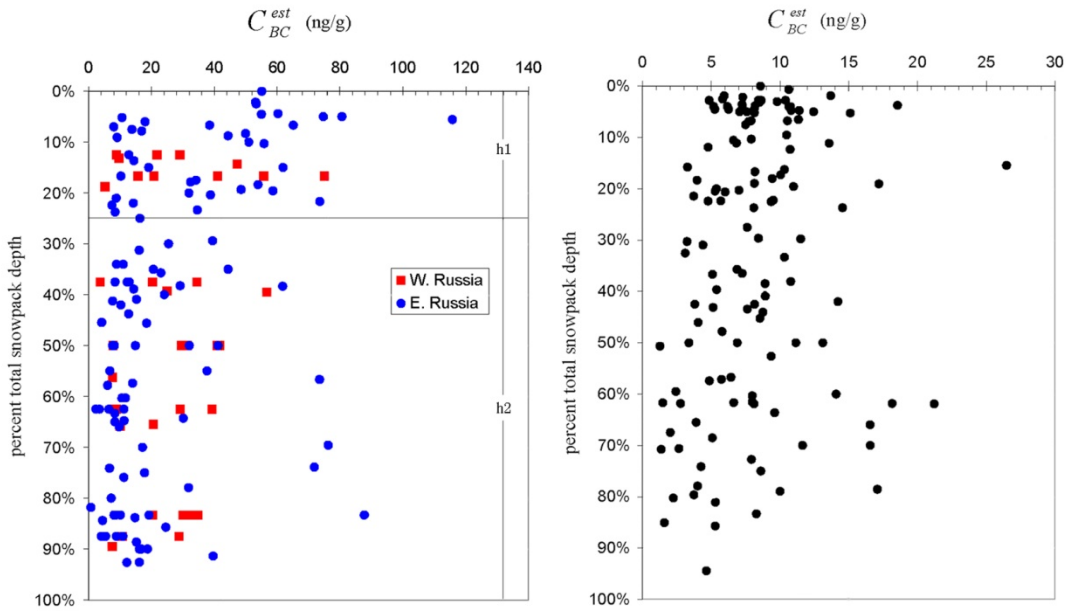


Figure 2

The observation site numbers in the X-axis do not match the ones in table 1. (I assume the values are spring-time sBC concentrations.) Therefore the only real information on X-axis is the separation between the Canadian and Russian Arctic, which can easily be seen also in figure 1. I recommend removing this figure, because it does not give any new information.

Reply:

Done. This figure has been removed in revised paper.

Figure 3

This is a good and informative figure. It could, however, be further improved by putting the measurement locations from each year in the same panel with the modeled sBC values and by removing the top left panel (obs). The three panels would be good to present as in figure 5.

Reply:

Done.

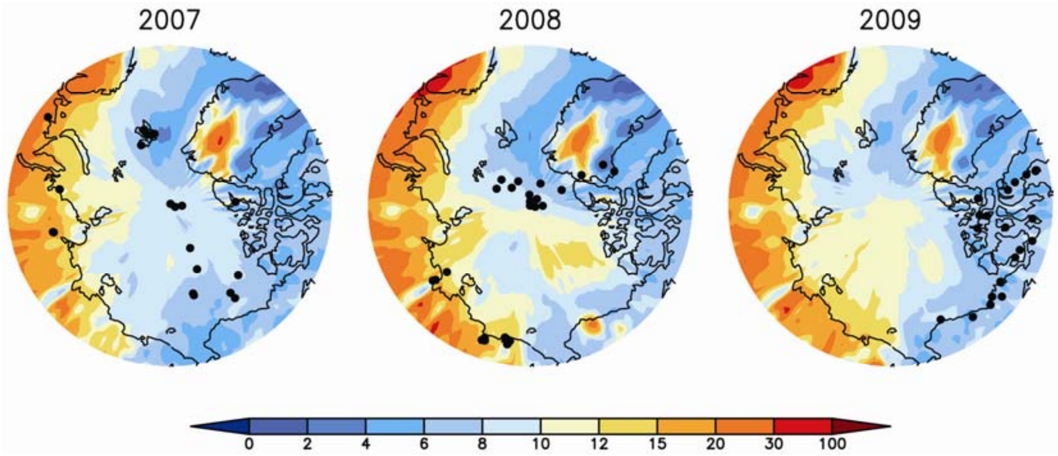


Figure 4
This figure consits of two separate figures. Both of them have some significant issues. In the top figure the X-axis is a major problem. The bars cannot be connected to individual grid boxes and thereafter to individual measurement points since only the region is given in the axis, and even that to only every second group of bars. Averaging the values over each region would produce a more clear figure and would tell the model's ability to produce the measured values in each region. In the bottom figure the fitted line is governed by the six (Russian) grid boxes with high sBC concentrations. Also units are missing. Since the discrepancy between modeled and observed high sBC concentrations is not caused by the fact that the sBC values are high (discussed in the text), the lower figure does not give much useful information. I recomment removing the lower figure.
Reply:
Yes, the bars of X-axis have some problems as you said. We have deleted the lower figure and revised the bars in upper figure to make them clear enough to be connected to individual grid boxes point to point. We still retain the histogram because there are very few measurement points in some regions, such as Greenland and Svalbard where the averaged values may be greatly influenced by one or two high value. Averaging values over these regions may mask the actual ability of model and cannot reflect the spatial variations over each region. For example, model performs well in Western Greenland, although there is large discrepancy between model and observations averaged in whole Greenland (ratio of observation to model was 0.8). The discrepancy was caused by simulation bias in North Greenland but not in the Western Greenland. Similar situation occurred in Svalbard, Model performs well in eastern Svalbard, but with significant overestimation in western Svalbard.

Figure 5
A good figure, where I only suggest to change the word "decrease" to "change" in the caption.
Done.

Figure 6

The time axis would be much more clear if only the years (or January 1st for each year) were given.

Done.