Responses to Reviewer1

(Reviewers' comments are in italic font)

Reviewer 1:

General comments:

Black carbon (BC) aerosols have significant impacts on earth system radiative balance due to its strong light-absorbing properties in the visible wavelength. Once BC deposited in snow, it accelerates snow melting, and further impacts the climate. In this study, a physically based snow radiative model was coupled into Polar-WRF to investigate the SDE of BC in the arctic region. The topic is interesting, however, this manuscript cannot be published in the current state, the authors need to resolved several major issues before it can be reconsidered. Please see my comments in detail below.

We thank the reviewer for the valuable comments and suggestions, which were very helpful for improving our manuscript. We revised the manuscript carefully, as described in our point-to-point responses to the comments.

C*omment 1:*

Title of the manuscript underlines the time period is melting season, however I do not see any significance of snow melting in the manuscript. The biggest problem is that the authors did not take BC amplification effects during melting period into modeling. The authors have to solve this issue before it can be reconsidered by ACP. See Flanner et al., JGR, 112, D11202, doi:10.1029/2006JD008003, 2007 and Doherty et al., JGR, 118, 5553–5569, doi:10.1002/jgrd.50235, 2013.

We sincerely appreciate the valuable comments. In this study, our primary aim is to assess the impacts of snowpack properties and land–atmosphere exchange on the reduction in surface snow albedo caused by black carbon (BC) deposition and the corresponding changes in the surface energy balance. Thus, we assumed a uniform distribution of BC in snow and designed a series of sensitivity experiments to evaluate the effects of the snowmelt process and land–atmosphere feedback on the BC-induced snow darkening effect (SDE), with a particular focus on the impacts on snow albedo and the surface energy balance. These experiments are based on an idealized assumption that the BC mixing ratio in snow remains constant and is uniformly distributed within the snowpack. In previous studies (Zhang et al., 2024), we collected observational data on BC in Arctic snow. In the future, we will evaluate BC amplification effects in the Arctic on the basis of observations and another numerical sensitivity study. However, in this study, we focused only on assessing the effects of snowpack changes and land–atmosphere interaction processes on the SDE induced by BC, particularly the impacts on snow albedo and the surface energy balance.

References

Zhang, Z., Zhou, L., & Zhang, M. A progress review of black carbon deposition on Arctic snow and ice and its impact on climate change. Advances in Polar Science, 35(2), 178-191.·doi:10.12429/j.advps.2023.0024,2024

Comment 2:

An assumption of 50 ppb was applied in this study, which largely deviates from the real world. The BC mixing ratios in the arctic can vary from <10 to several hundred ppb. See Doherty et al., ACP, 10, 11647–11680, 2010 and Doherty et al., JGR, 120, 11,391–11,400, doi:10.1002/2015JD024018, 2015. Therefore, I think the SDE values reported by the authors are not trusted.

Thank you for your valuable comment. We sincerely appreciate the valuable comments. In this study, our primary aim is to assess the impacts of snowpack properties and land–atmosphere exchange on the reduction in surface snow albedo caused by black carbon (BC) deposition and the corresponding changes in the surface energy balance. There are significant regional differences in the impacts of BC deposition on snow albedo and the surface energy balance in the Arctic (Dou & Xiao, 2016; Kang et al., 2020). These differences are related not only to the varying amounts of BC deposition across regions but also to the spatial heterogeneity of surface characteristics such as snow distribution in the Arctic. In this study, we assumed an ideal scenario in which BC is uniformly distributed in snow at a fixed concentration. Numerical sensitivity experiments were then used to evaluate the significance of the snowmelt and land–atmosphere exchange processes. In the future, we will assess the changes in snow albedo caused by Arctic BC deposition on the basis of actual observational data (collected by Zhang et al.,2024), but here, we conducted only a numerical sensitivity study.

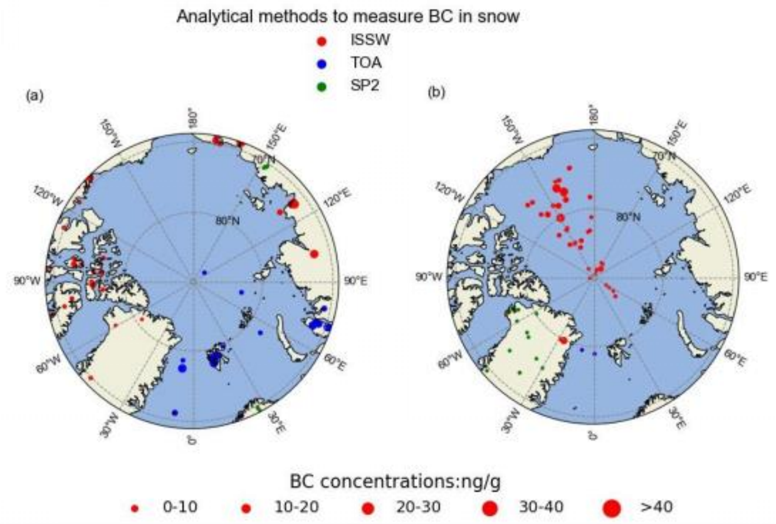

Figure 1. Locations and concentrations of BC snow observations collected from Arctic campaigns between 2005 and 2018 in spring (a) and summer (b). The figure is from Zhang et al. (2024).

References

Dou, T.-F., & Xiao, C.-D. An overview of black carbon deposition and its radiative forcing over the Arctic. Advances in Climate Change Research, 7(3), 115-122. • doi:10.1016/j.accre.2016.10.003,2016

Kang, S., Zhang, Y., Qian, Y., & Wang, H. A review of black carbon in snow and ice and its impact on the cryosphere. Earth-Science Reviews, 210. • doi:10.1016/j.earscirev.2020.103346,2020

Zhang, Z., Zhou, L., & Zhang, M. A progress review of black carbon deposition on Arctic snow and ice and its impact on climate change. Advances in Polar Science, 35(2), 178-191. • doi:10.12429/j.advps.2023.0024,2024

Specific comments

Comment 1:

Abstract: Title of the manuscript is "Modeling study of the snow darkening effect by black carbon deposition over the Arctic during the melting period." However, I did not see any discussion related to the effects of melting on SDE due to BC in the abstract.

Thank you for the valuable comments. In this study, our primary aim is to assess the impacts of snowpack properties and land–atmosphere exchange on the reduction in surface snow albedo caused by black carbon (BC) deposition and the corresponding changes in the surface energy balance. Other processes and impacts related to the SDE due to BC will be discussed in future studies. In addition, to better reflect the purpose of the paper, the title was changed to "A numerical sensitivity study on the snow darkening effect by black carbon deposition over the Arctic in spring".

Comment 2:

The abstract is unnecessarily long, needs to be shortened substantially.

Thank you for the valuable comments. We reorganized our abstract as follows:

"The rapid warming of the Arctic, driven by glacial and sea ice melt, poses significant challenges to Earth's climate, ecosystems, and economy. Recent evidence indicates that the snow-darkening effect (SDE), caused by black carbon (BC) deposition, plays a crucial role in accelerated warming. However, high-resolution simulations assessing the impacts from the properties of snowpack and land–atmosphere interactions on the changes in the surface energy balance of the Arctic caused by BC remain scarce. This study integrates the Snow, Ice, Aerosol, and Radiation (SNICAR) model with a polar-optimized version of the Weather Research and Forecasting model (Polar-WRF) to evaluate the impacts of snow melting and land–atmosphere interaction processes on the SDE due to BC deposition. The simulation results indicate that BC deposition can directly affect the surface energy balance by decreasing snow albedo and its corresponding radiative forcing (RF). On average, BC deposition at 50 ng g^{-1} causes a daily average RF of 1.6 W m^{-2} in offline simulations (without surface feedbacks) and 1.4 W m^{-2} in online simulations (with surface feedbacks). The reduction in snow albedo induced by BC is strongly dependent on snow depth, with a significant linear relationship observed when snow depth is shallow. In regions with deep snowpack, such as Greenland, BC deposition leads to a 25–41% greater SDE impact and a 19–40% increase in snowmelt than in areas with shallow snow. Snowmelt and land–atmosphere interactions play significant roles in assessing changes in the surface energy balance caused by BC deposition based on a comparison of results from offline and online coupled simulations via Polar-WRF/Noah-MP and SNICAR. Offline simulations tend to overestimate SDE impacts by more than 50% because crucial surface feedback processes are excluded. This study underscores the importance of incorporating detailed physical processes in high-resolution models to improve our understanding of the role of the SDE in Arctic climate change."

Comment 3:

L21: instantaneous RF or daily-averaged RF here? Please clarify.

Thank you for the comments. The RF in this study is calculated as the daily average over the simulation period on the basis of the model results. We also indicated this in the manuscript for better understanding.

Comment 4:

L31: What is Noah-MP?

Thank you for your comments. Land surface models (LSMs) are useful modeling tools for resolving terrestrial responses to and interactions with the atmosphere, ocean, glaciers, and sea ice in the Earth system. Traditionally, LSMs are thought to provide lower boundary conditions to coupled atmospheric models. The Noah-MP is a widely used land surface model and has been used in many studies and operational weather/climate models (HRLDAS, WRF, WRF-Hydro/NWM, NOAA/UFS, NASA/LIS, etc.). In this study, Noah-MP was coupled with Polar-WRF to investigate the impact of BC deposition on snow albedo and the surface energy balance.

Comment 5:

I think the authors need to clarify in the introduction that why did they want to investigate the SDE during melting season instead of snow accumulation season or stable season? And proper citations are required.

Thank you for your comments. In this study, we selected the spring snowmelt period as our simulation period for two main reasons. First, during the spring melt period, the relatively strong solar radiation combined with the near-maximum snowpack depth makes the impact of BC on the SDE particularly significant for the terrestrial Arctic surface (Doherty et al., 2010; Zhang et al., 2024). Additionally, during this period, the aging and melting processes of snow affect the reduction in snow albedo induced by BC (Dang et al., 2015; He & Ming, 2022), and the influence of snow processes on BC-induced changes in snow albedo has not been well evaluated. We also included the relevant content in the introduction of the manuscript (L80-85).

References

Dang, C., Brandt, R. E., & Warren, S. G. Parameterizations for narrowband and broadband albedo of pure snow and snow containing mineral dust and black carbon. Journal of Geophysical Research: Atmospheres, 120(11), 5446-5468. • doi:10.1002/2014JD022646,2015

Doherty, S. J., Warren, S. G., Grenfell, T. C., Clarke, A. D., & Brandt, R. E. Light-absorbing impurities in Arctic snow. Atmospheric Chemistry and Physics, 10(23), 11647-11680. • doi:10.5194/acp-10-11647-2010,2010

He, C., & Ming, J. Modelling light-absorbing particle – snow – radiation interactions and impacts on snow albedo: fundamentals, recent advances and future directions. Environmental Chemistry, 19(5), 296-311. • doi:10.1071/en22013,2022

Zhang, Z., Zhou, L., & Zhang, M. A progress review of black carbon deposition on Arctic snow and ice and its impact on climate change. Advances in Polar Science, 35(2), 178-191. • doi:10.12429/j.advps.2023.0024,2024

Comment 6:

L98: SSNICAR->SNICAR

We apologize for our carelessness, and we replaced it with “SNICAR”.

Comment 7:

L99: Please briefly describe surface feedbacks in the modeling experiments.

Thank you for the comments. Two surface feedback processes are considered in this paper: the aging and melting processes of snow, in which changes in snow density and snow depth directly affect the reduction in snow albedo caused by BC, and the interaction between the land and atmosphere. The feedback processes between land and atmosphere can influence the impact of BC on the surface energy balance. In this study, the effects of these two key processes on snow albedo reduction caused by BC are assessed by comparing the differences in results between offline and online experiments. We also included the relevant content in the introduction of the manuscript (L304-309).

Comment 8:

L105: Please delete “and” after “processes through”.

We apologize for our carelessness, and we deleted it.

Comment 9:

L109: What is Noah-LSM? Same for CLASS and BATS in L113-114. I highly suggested the authors generate a list of Abbreviations in the appendix for the readers, too many model names in the manuscript.

Thank you for the comments. Land surface models (LSMs) are useful modeling tools for resolving terrestrial responses to and interactions with the atmosphere, ocean, glaciers, and sea ice in the Earth system. Traditionally, LSMs are thought to provide lower boundary conditions to coupled atmospheric models. The Noah-LSM is a widely used land surface model and has been used in many studies and operational weather/climate models, such as WRF and the Polar-WRF.

CLASS is the Canadian Land Surface Scheme snow albedo parameterization in Noah-MP, and BATS is the Biosphere–Atmosphere Transfer Scheme snow albedo parameterization in Noah-MP. Both of them are snow albedo schemes originally used in Noah-MP, but none of them account for the impact of BC on snow albedo. Therefore, in this study, we coupled the SNICAR model as the snow albedo scheme with the Polar-WRF/Noah-MP to assess the effect of BC on snow albedo.

We apologize for our carelessness, and we generated a list of abbreviations in Appendix A4 as follows:

Abbreviation	Definition
BC	Black Carbon
SDE	Snow darkening effect
Polar-WRF	Polar-optimized version of the Weather Research and Forecasting model
SNICAR	Snow, Ice, Aerosol, and Radiation (SNICAR) model, in this study, the SNICAR was coupled in Polar-WRF/Noah-MP as a snow albedo parameterization to investigate the SDE by BC.
RF	Radiative Forcing
LSM	Land surfacing model
Noah LSM	A land surface model that simulates the interactions between the land and atmosphere. It has already been coupled with WRF as a land

	surface scheme. In Polar-WRF, the Noah has been optimized for polar regions.
Noah-MP	The community Noah land surface model with multiple parameterization options. It is based on the Noah LSM developed by Niu et al. (3011). It has already been coupled with WRF as a land surface scheme. In Polar-WRF, the Noah-MP has been optimized for polar regions.
CLASS	The Canadian Land Surface Scheme snow albedo parameterization in Noah-MP
BATS	The Biosphere–Atmosphere Transfer Scheme snow albedo parameterization in Noah-MP

References

Niu, G.-Y., Yang, Z.-L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., Kumar, A., et al. The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. Journal of Geophysical Research: Atmospheres, 116(D12).·doi:10.1029/2010JD015139,2011

Comment 10:

Please think about remove Sec. 3.2. Similar results have been reported in other studies such as He, C. 2022, https://doi.org/10.1071/EN22013, and nothing interesting of the results.

Thank you for the valuable comment. Although the content of this section has been previously reported, it is still necessary for the discussions in the following two sections. Therefore, we condensed this section and moved Figure 4 to the supplementary materials.

Comment 11:

3.3: I do not agree with the authors that they used a fixed BC mixing ratios in Arctic snow, and the values about BC RF they reported are with very low confidence.

Thank you for the valuable comment. In this numeric sensitivity study, our primary aim is to assess the impact of snowpack properties and land–atmosphere exchange on the reduction in surface snow albedo caused by BC deposition and the corresponding changes in the surface energy balance. The assessment of the RF induced by BC is not the primary objective of this study, and it will be evaluated in future studies.

Comment 12:

3.4: Where is the BC deposition time series data from? I did not see the data source.

Thank you for the comments. In this numeric sensitivity study, we assumed an ideal scenario in which BC is uniformly distributed in snow at a fixed concentration. The BC deposition time series data were not used in this study.