Reviewer 2:

General comments:

This study investigates the effect of black carbon (BC) on snow surfaces over the Arctic using the Snow, Ice, Aerosol, and Radiation (SNICAR) model online and offline with a polar-optimized version of the Weather Research and Forecasting model (Polar-WRF). The research focuses on an important problem as a better understanding of the impacts of snow conditions and land-atmosphere interactions is critical in more accurately assessing the overall impact of BC in the Arctic. However, there are a few major flaws in the manuscript.

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.

Major comments:

Comment 1:

The modeling seems detached from the reality. Only validation of meteorological factors is included. However, other variables, such as BC concentration, snow depth, surface albedo, runoff, etc, also need to be compared with observations to ensure the numbers are in line with those in the real Earth system in order to generate meaningful results. For example, it is unclear how 50 ng/g is selected as BC mixing ratio. For the existing validation, please provide explanations of the simulated biases, especially temperature and wind direction. Also, observations from the two locations cannot sufficiently represent the whole Arctic condition.

Thank you for your valuable comments and advice. 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 explore 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. The snow depth data are employed only as an initial condition input to assess the influence of snow conditions on the SDE. Given that the previous title, "Modeling study of the snow darkening effect by black carbon deposition over the Arctic during the melting

period," did not accurately convey the main purpose of this article, we changed the title to "A numerical sensitivity study on the snow darkening effect by black carbon deposition over the Arctic in spring".

In this study, a fixed mixing ratio of BC was used to eliminate the influence of the BC concentration on the SDE. Previous observations of BC in Arctic snow indicate that the concentration of BC can vary from less than 5 to several hundred ng g^{-1} in the spring. During the melting period, BC can accumulate on the snow surface because of its insolubility (Forsström et al., 2013). Therefore, the BC concentration in Arctic snow may be higher than the reported values from the initial melting period. Considering these factors and our previous study (Zhang et al., 2024), a mixing ratio of 50 ng g^{-1} BC in Arctic snow was selected. This value is reasonable for assessing the potential impacts of snow processes and land–atmosphere interactions on the SDE, and its magnitude is realistic.

The simulated biases were caused mainly by the model resolution and inaccurate land surface characteristics used in this study. We added the relevant content to the introduction of the manuscript. In this study, simulation bias does not affect our main conclusions, as we are focused primarily on the impact of surface feedback mechanisms on BC-induced albedo changes. While the 2-m air temperature can influence surface energy exchange processes, the wind speed is not related to the mechanisms of interest in this paper. These biases do not affect the mechanisms we are focusing on.

The Polar-WRF model is a model specifically designed for polar regions, and its simulation capabilities have been validated in numerous studies (e.g., Hines & Bromwich, 2017; Pilguj et al., 2018; Turton et al., 2020). Comprehensive validation of the model's simulation capabilities is important, but it is not the focus of this paper. In the future, we will conduct more detailed studies on the reduction in snow albedo caused by BC and the corresponding changes in the surface energy balance in the Arctic region.

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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:

The manuscript states that weather models with high temporal and spatial resolution and conducting ensemble simulations are important in accurately assessing the impacts of the snow-darkening effect (SDE). However, these statements are not well justified. Also, this research uses a resolution of 27 km, which is not high.

We sincerely appreciate the valuable comments. We apologize for the misunderstanding and misuse of the term 'ensemble simulation.' We removed the corresponding statements from the manuscript.

The snow albedo reduction caused by BC is directly related to the distribution of snow cover and terrain height. Kang et al. (2020) emphasized the importance of enhancing the spatial resolution of models to more effectively capture the spatial variability in snowpack. Therefore, it is essential to use high-resolution regional simulations that can better capture surface conditions. In this study, we used 0.25°×0.25° ERA5 reanalysis data as the initial and boundary conditions for the model. The 27 km resolution is consistent with the ERA5 reanalysis data to ensure the accuracy of large-scale meteorological conditions. In addition, previous studies have employed global models to evaluate the radiative forcing of BC in Arctic snow, typically with resolutions greater than 1° (e.g., Dong et al., 2018; Jiao et al., 2014; Ren et al., 2020). Thus, a resolution of 27 km has already demonstrated significant improvement. A higher-resolution modeling study will be conducted with the nesting method in the future.

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Comment 3:

The manuscript needs a more comprehensive literature review. There are more studies focusing on BC impacts on snow surfaces using SNICAR over the Arctic areas.

Thank you for the comment. The physically based Snow, Ice, Aerosol, and Radiation (SNICAR) model (Flanner et al., 2012; Flanner & Zender, 2005) is widely used to estimate the contributions of BC to the reduction in snow albedo and its corresponding radiative forcing (RF) in the Arctic. Flanner et al. (2007) incorporated SNICAR into the National Center for Atmospheric Research Community Atmosphere Model (NACR CAM3, Version 3) global climate model (GCM) to improve the quantification of climate forcing from BC in snow. Using the NCAR CAM5 coupled with SNICAR, Zhou et al. (2012) reported that in the spring season, the Arctic forcing increases from +0.29 W m^{-2} to +0.37 W m^{-2} due to BC deposition. On the basis of field observations conducted by Doherty et al. (2010), Dang et al. (2017) used SNICAR to calculate the reduction in snow albedo caused by BC in the Arctic and highlighted the impact of snowpack properties on the assessment of the SDE. In addition, SNICAR was also applied to quantify the reduction in snow and ice albedo caused by long-range-transported Asian dust (Zhao et al., 2022). All of the aforementioned studies were reviewed and added to the introduction. (L89-100)

References

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Comment 4:

The Mellor-Yamada-Nakanishi-Niino (MYNN) scheme is used to represent the boundary layer. However, modeling the Arctic boundary layer is very challenging. Please explain why the MYNN is selected and how it behaves over the Arctic. Also, do clouds play a role in the simulations?

We sincerely appreciate the valuable comments. In this study, all the physical parameterization options applied in this study are based on a wide range of studies of PWRF over the Arctic (e.g, Hines & Bromwich, 2017; Wilson et al., 2011; Zou et al., 2021). Two PBL schemes are preferred when the PWRF model is used. The Mellor–Yamada–Janjić (MYJ) turbulent kinetic energy scheme (Janji, 1994) was first tested by the Polar Meteorology Group and has demonstrated superior performance on Arctic land and ocean surfaces (Bromwich et al., 2009; Wilson et al., 2011). However, the MYNN PBL scheme became more widely used after the WRFV4 release. The new version of the MYNN 2.5-level scheme implemented in WRF/PWRF Version 4.1.1 can improve downward shortwave radiation at the surface (Olson et al., 2019), and its performance was also validated by Zou et al. (2021) and Xue et al. (2021). In our study, downward shortwave radiation at the surface was a key factor in assessing the SDE caused by BC. Therefore, the MYNN scheme was chosen to represent the Arctic boundary layer. We also added the relevant description in L268-270.

In our study, the Morrison 2-moment scheme for cloud microphysics was used, which has also been widely tested in the Arctic (Hines & Bromwich, 2017; Hines et al., 2019; Turton et al., 2020; Xue et al., 2021). The effects of clouds, such as their impact on radiation and snowfall, have already been considered in the model. However, exploring the role of clouds is not the focus of this paper, and further research is needed in the future.

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Comment 5:

Please explain the difference between CLM and Noah-MP, and highlight why Noah-MP is selected.

We are grateful to the reviewer for these comments. In this study, the greatest difference between CLM and Niah-MP is their parameterizations for snow. The snowpack in the CLM can reach twelve layers (Lawrence et al., 2019), whereas that in the Noan-MP can reach three layers (Niu et al., 2011). Both models are commonly used land-surface schemes, and numerous studies have compared the differences between them (e.g., Chen et al., 2014; Constantinidou et al., 2020; Van Den Broeke et al., 2018). However, in this study, we evaluate the impact of BC on the Arctic surface energy balance via Polar-WRF, which is specifically optimized for simulating polar regions. In Polar-WRF, only the Noah and Noah-MP land surface models (LSMs) have been modified and optimized for polar regions, and Noah-MP performs better than Noah in simulating snow processes. Consequently, the Noah-MP model was selected for this study, and SNICAR was employed as the snow albedo scheme within the Polar-WRF/Noah-MP framework.

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Comment 6:

A five-day spin up is used. However, it is unclear whether this is sufficient. For example, less variabilities are simulated during the first few days, as shown in the temporal evolution plots. Should these first few days also be considered spin-up?

Thank you for your valuable comment. In this study, we employed the ERA5 reanalysis data for the initial and boundary conditions and enabled upper-air nudging to maintain consistency between the continuously updated boundary conditions and the initial conditions. Thus, the 5-day spin-up time is sufficient for atmospheric conditions (Gómez-Navarro et al., 2015; Jerez et al., 2020), but the surface requires more time to respond (Chen et al., 1997; Cosgrove et al., 2003).

In this study, the low variability observed in the temporal evolution plots can be attributed to changes in snowpack properties. As the temporal evolution plots indicate, the snow is fresh and has a low density during the initial days, which can diminish the changes in snow albedo caused by BC. In contrast, as snow ages and begins to melt, the effects of the snow darkening effect (SDE) induced

7

by BC increase. This evolution of snow properties and its impact on snow albedo reduction is one of the mechanisms that this study aims to highlight; therefore, we included it in this study.

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Comment 7:

Please provide more detailed description about experimental design. For example, which experiments are offline and which ones are online. Also, what's the meaning of "except for snow depth" etc.

Thank you for your comments. In this study, the SNICAR-OFF and SEN experiments are offline simulations. SNICAR-OFF is an offline coupled simulation that is used to calculate the baseline of the SDE induced by BC deposition without snow cover changes or land–atmosphere exchange processes. The online coupled simulation (SNICAR-ON) is fully coupled with Polar-WRF, and the impacts of the SDE at every model timestep are computed by contrasting the dirty and clean snow albedos under the current surface and atmospheric conditions. Discrepancies between SNICAR-OFF and SNICAR-ON outcomes demonstrate the importance of atmospheric and surface feedback processes in comprehensively assessing the impacts of snow darkening effects (SDEs).

The SEN experiments are offline sensitivity experiments for the SNICAR model. SEN1-3 were designed to test the effects of snow density, snow depth, and snow grain size on the reduction in snow albedo caused by BC, respectively. SEN4 was designed to test the impact of the distribution

of BC within snow on BC-induced changes in snow albedo. The purpose of the SEN experiments is to test the sensitivity of SNICAR to snow properties and to preliminarily assess the impact of snow characteristics on the reduction in snow albedo caused by BC. 'Except for snow depth' means testing the impact of snow depth on the reduction in snow albedo caused by BC while keeping all other conditions the same. To improve understanding, we added the corresponding content to the manuscript (L294-315) and reorganized Table 1 as follows:

Table 1. Summary of model simulations

Name	Mixing ratio of BC (ng g^{-1})	Snow density (kg m^{-3})	Snow depth (m)	Snow grain radius (μm)	BC distribution with snow	Surface feedback processes
CTL	0	Provided by NCEP GDAS final analysis data	Provided by NCEP GDAS final analysis data	100 μm (new snow) or 1000 μm (old snow)	Vertically uniform distribution	Included
SNICAR-OFF	50	Same as CTL	Same as CTL	Same as CTL	Same as CTL	Not included
SNICAR-ON	50	Same as CTL	Same as CTL	Same as CTL	Same as CTL	Included
SEN1	50	Same as CTL	Same as CTL	Set as 50, 150, 250,500,100	Same as CTL	Not included
SEN2	50	Set as 100, 200,500	Same as CTL	Same as CTL	Same as CTL	Not included
SEN3	50	Same as CTL	Set as 0.05, 0.1,0.25,0.5,1.0	Same as CTL	Same as CTL	Not included

SEN4	50	Same as CTL	Same as CTL	Same as CTL	BC at top 5 cm layer	Not included

Comment 8:

Please clarify how the model accounts for snow-ice transition. For example, after melting and refreezing, can we still treat the surface as snow? As the study does not account for ice, clarification like this is necessary.

Thank you for the valuable comment. In this work, we retained the treatment of snow hydrological processes and snow–ice transitions from the original Noah-MP model without making any modifications. In the Noah-MP model, snow consists of liquid water and ice particles. Initially, the liquid water content within the snowpack is zero. When the simulation begins, the snow ice content and liquid water content in each snow layer are updated whenever melting or refreezing occurs, provided that the snowpack has explicit snow layers (snow depth >= 2.5 cm). If snow is present but its thickness is insufficient to form an explicit snow layer, the snow ice content and liquid water content will no longer be calculated, and all liquid water in the snow is assumed to be ponded on the soil surface (He et al., 2023). The liquid water content and ice content in each snow layer affect the total column snow mass and snow optical thickness, which consequently influence the reduction in snow albedo caused by BC. More detailed descriptions are provided in He et al. (2023).

References

He, C., P. V., M. Barlage, F., Chen, D., Gochis, R., Cabell, T., Schneider, R. R., et al. The Community Noah-MP Land Surface Modeling System Technical Description Version 5.0, (No. NCAR/TN-575+STR).·doi:10.5065/ew8g-yr95,2023

Comment 9:

Section 3.4 is hard to follow. The time series plots show dense information, but the explanations are brief. It is unclear how shallow, moderate, and deep snow depths are defined. There are brief explanations on Line 444, yet information like this should be placed in the beginning of the section and also be expanded on to give a clear background to facilitate a better understanding of the temporal evolutions.

Thank you for the valuable comment. In this study, the three snow conditions are determined on the basis of the total snow depth (h_{sno}): shallow ($0.025m < h_{sno} < 0.25m$), moderate

($0.25m \leq h_{sno} < 0.45m$) and deep ($h_{sno} \geq 0.45m$). The detailed information is shown in Appendix A3.

For clarity, we adjusted the order and added more detailed explanations at the beginning of Section 3.4 as follows: (L460-467).

"As discussed above, the impacts of the SDE can be affected by changes in snowpack properties through two primary mechanisms. First, this study assumed that the distribution of BC was uniform throughout the snowpack, indicating that deeper layers of snow contained higher concentrations of BC particles. The overall mass of BC present in snow can influence the modeling effects of the SDE. In addition, as snow ages and begins to melt, the effects of the SDE induced by BC increase due to the reduced snow albedo (He & Ming, 2022). To analyze the impact of the evolution of snow on the SDE, this study categorized snow into three types on the basis of snow depth and investigated the related changes on the SDE as snow ages and melts. The three snow conditions are determined on the basis of the total snow depth (h_{sno}): shallow ($0.025m < h_{sno} < 0.25m$), moderate ($0.25m \leq h_{sno} < 0.45m$) and deep ($h_{sno} \geq 0.45m$). The detailed information is shown in Appendix A3."

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Minor comments:

Comment 1:

Inconsistent titles in the manuscript and the supplementary materials.

We apologize for our carelessness and mistakes. We revised the title of the supplementary material and made it more consistent with the manuscript.

Comment 2:

In the result section, please clarify which results are coming from which experiments.

Thank you for the comment. In this study, the RFs caused by BC were calculated via both SNICAR-ON and SNICAR-OFF. The relationship between snow depth and snow albedo reduction by BC was observed in SNICAR-OFF. The temporal evolution of the changes in the surface energy balance was investigated via SNICAR-ON. The importance of snow melting and the land –

atmosphere exchange process was evaluated by comparing the results from online (SNICAR-ON) and offline (SNICAR-OFF) coupled simulations. The relevant content was included in the Results section.

Comment 3:

Many typos, such as Line 105 "through and", Line 318 "f-j", Line 342 "each maximum levels"; Line 481 "shows the how," etc.

We apologize for our carelessness and mistakes. We checked and revised all the typos that we could find.

Comment 4:

Please add more descriptions regarding the advantage of Polar-WRF. Simply refereeing to other documents is not good enough to provide a background for this study.

Thank you for the comments. The main advantages of the Polar-WRF model include (a) optimizing the treatment of heat transfer for ice sheets and revised surface energy balance calculations in the Noah and Noah-MP LSMs; (b) comprehensively describing sea ice in Noah and Noah-MP; and (c) improving cloud microphysics for polar regions. Detailed descriptions of Polar-WRF were added to the manuscript (L146-160).

Comment 5:

Please provide brief description of the data downloaded from the Arctic Data Center.

Thank you for the comment. The Arctic Data Center is the primary data and software repository for the Arctic section of the National Science Foundation's Office of Polar Programs. In this study, we downloaded the energy exchange data measured by an eddy covariance system in terrestrial systems across Alaska. We also added a brief description of the data in the manuscript as follows (L280-283).

"The observed downward shortwave radiation, sensible heat flux and latent heat flux in Alaska (149.3°W, 68.6°N) were downloaded from the Arctic Data Center (https://arcticdata.io/). These measurements were conducted by the University of Alaska Fairbanks (UAF) and are part of the Arctic Observing Network (AON) project. For these measurements, an eddy covariance system was employed to measure the fluxes of CO_2, water, and energy, and it was positioned on a 3-meter-high tripod in the center of the site. The data were averaged over 30-minute intervals and span the entire

year, with quality control measures implemented.".

Comment 6:

Line 325, how is the "absolute mass of BC represented by the snow depth"?

Thank you for the comment. In this study, we assume that the distribution of BC is uniform throughout the snowpack, indicating that deeper layers of snow contain a greater mass of BC particles. To make this easier to understand, we revised it to "the mass of BC in snow is directly related to snow depth."

Comment 7:

For Section 2.3, please clarify whether the calculations are included in WRF as one of the diagnostics, or are these offline calculations based on modeled results.

Thank you for the comment. In this study, the calculations of the surface energy balance were coupled into the Polar-WRF. We clarified this in the manuscript (L229).

Comment 8:

Please clarify "The high RF caused by BC deposition reached 1-4 W m^-2"

Thank you for the comment. In this study, the most pronounced RF caused by BC occurred mainly in regions with deep snow depths and high snow densities. The RF caused by BC deposition can reach greater than 4 W m^{-2} in Greenland, Baffin Island, and East Siberia. We modified this sentence in the manuscript for clarity (L620-622).