Responses to Editor and Reviewer
(Reviewers' comments are in italic font)

The authors provided reasonable explanations for most of the questions. A few clarifications still needed:

We appreciate that the editor and reviewers recognize our efforts and thank you for your thoughtful suggestions and insights, which have helped improve this manuscript substantially. We have revised the manuscript carefully, as described in our point-to-point responses to the comments.

1. About authors' response "The simulated biases were caused mainly by the model resolution and inaccurate land surface characteristics used in this study," please clarify "inaccurate land surface characteristics" and whether this may influence understanding of surface processes, which is the focus of this study.

Thank you for the comment. In this study, we focused on two surface physical processes: the aging and melting processes of snowpack and the land–atmosphere exchange process. These processes have been integrated into the Polar-WRF/Noah-MP model, which has been extensively validated (e.g., Justino et al., 2019; Li et al., 2022; Smith et al., 2017). The inaccuracy of surface characteristics in this study is mainly due to the land cover and topography inputs, which can introduce biases in the findings. Nevertheless, this does not impact the surface processes and physical mechanisms that were the main focus of the study. As suggested, we clarified it and added explanation in the paper (P10, L339-342 and L348) as follows:

"Surface feedback processes such as land–atmosphere exchange and changes of snowpack have already coupled into the Polar-WRF/Noah-MP and their performances have been widely validated (e.g., Justino et al., 2019; Li et al., 2022; Smith et al., 2017). To better access the impacts of these two surface feedback processes on the reduction in snow albedo caused by BC deposition and the corresponding changes in the surface energy balance, the modeled downward shortwave radiation, sensible heat flux (HS) and latent heat flux (LH) are also compared with the observation data in Alaska (149.3°W, 68.6°N).".

"These biases may result from the inaccurate land surface characteristics (e.g., land cover and topography) used in this study and the coarse model resolution."

References

Li, J., Miao, C., Zhang, G., Fang, Y.-H., Shangguan, W., & Niu, G.-Y. Global Evaluation of the Noah-MP Land Surface Model and Suggestions for Selecting Parameterization Schemes. Journal of Geophysical Research: Atmospheres, 127(5), e2021JD035753.·doi:10.1029/2021JD035753,2022

Justino, F., Wilson, A. B., Bromwich, D. H., Avila, A., Bai, L.-S., & Wang, S.-H. Northern Hemisphere Extratropical Turbulent Heat Fluxes in ASRv2 and Global Reanalyses. Journal of Climate, 32(7), 2145-2166.·doi:10.1175/JCLI-D-18-0535.1,2019

Smith, W. L., Hansen, C., Bucholtz, A., Anderson, B., Beckley, M., Corbett, J. G., Cullather, R. I., et al. Arctic Radiation-IceBridge Sea and Ice Experiment: The Arctic Radiant Energy System during the Critical Seasonal Ice Transition. Bulletin of the American Meteorological Society, 98, 1399-1426.2017

2. *If "the wind speed is not related to the mechanisms of interest in this paper," please clarify the rationale of including this comparison/validation in the paper.*

Similarly, as this paper primarily focused on surface processes, many descriptions related to atmospheric setups (e.g., boundary layer, clouds, etc) may appear redundant. However, I believe these processes are crucial for accurately simulating precipitation and snowfall. Therefore, selecting a better PBL scheme and cloud mechanism is important and should be emphasized in the paper.

Thank you for the comment. In this study, we focused on BC-induced reduction in snow albedo and their associated surface feedback processes (the changes of snowpack properties and land–atmosphere exchange), the role of wind speed was not emphasized. However, the wind speed is still one of the most important meteorological parameters, which is closely related to the surface energy balance and the structure of the atmospheric boundary layer. Thus, the comparison is necessary to validate the basic capabilities of the model and to conduct further investigations.

The Mllor-Yamada-Nakanishi-Niino (MYNN) level 2.5 PBL scheme and the Morrison 2-moment cloud microphysics scheme were selected in this study. Their performances in the Arctic are widely have been widely tested and verified (e.g., Hines & Bromwich, 2017; Hines et al., 2019; Turton et al., 2020; Xue et al., 2021). As suggested, we added more detailed description of these schemes and emphasized their importance in the paper (P7-8, L260-276):

"In addition to surface processes, atmospheric conditions like the boundary layer and clouds play a key role in effectively simulating precipitation and snowfall, which can influence the reliability of the simulation outcomes. As a result, choosing the appropriate boundary layer and cloud microphysics schemes is essential. In this study, the Mllor-Yamada-Nakanishi-Niino (MYNN) level 2.5 PBL scheme and the Morrison 2-moment cloud microphysics scheme were selected. Their performances in the Arctic are widely have been widely tested and verified (e.g., Hines & Bromwich, 2017; Hines et al., 2019; Turton et al., 2020; Xue et al., 2021).The MYNN model is a kind of second-order closure model that was proposed by Nakanishi and Niino (Nakanishi and Niino 2004, 2006, 2009) and is formulated as a modification of the Mellor-Yamada closure model (Mellor and Yamada 1982). In comparison to the MYNN level-3 scheme, the MYNN 2.5-level scheme retains the significant performance on the stable boundary layer simulations and reduces the computational cost (Kitamura, 2010; Nakanishi & Niino, 2009). 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), which is a key factor in assessing the reduction in snow albedo caused by BC deposition and the corresponding changes in the surface energy balance.

The Morrison 2-moment cloud microphysics scheme is a double-moment microphysics scheme that parameterizes the mixing ratio and number concentration of hydrometeors, covering cloud droplets, rain, ice crystals, snow, and graupel (Morrison & Gettelman, 2008). In the Polar-WRF, its droplet concentration is reduced from 250 cm^{-3} to 50 cm^{-3}, which is more applicable to polar regions (Hines & Bromwich, 2017). It has been extensively tested and has shown a great simulation capabilities, especially in the representation of mixed-phase clouds in the Arctic (Arteaga et al., 2024; Cho et al., 2020)."

References

Arteaga, D., Planche, C., Tridon, F., Dupuy, R., Baudoux, A., Banson, S., Baray, J.-L., et al. Arctic mixed-phase clouds simulated by the WRF model: Comparisons with ACLOUD radar and in situ airborne observations and sensitivity of microphysics properties. Atmospheric Research, 307, 107471.·doi:10.1016/j.atmosres.2024.107471,2024

Cho, H., Jun, S.-Y., Ho, C.-H., & McFarquhar, G. Simulations of Winter Arctic Clouds and Associated Radiation Fluxes Using Different Cloud Microphysics Schemes in the Polar WRF: Comparisons With CloudSat, CALIPSO, and CERES. Journal of Geophysical Research: Atmospheres, 125(2), e2019JD031413.·doi:10.1029/2019JD031413,2020

Hines, K. M., & Bromwich, D. H. Simulation of Late Summer Arctic Clouds during ASCOS with Polar WRF. Monthly Weather Review, 145(2), 521-541.·doi:10.1175/MWR-D-16-0079.1,2017

Kitamura, Y. Modifications to the Mellor-Yamada-Nakanishi-Niino (MYNN) Model for the Stable Stratification Case. Journal of the Meteorological Society of Japan. Ser. II, 88(5), 857-864.·doi:10.2151/jmsj.2010-506,2010

Mellor, G. L., & Yamada, T. Development of a turbulence closure model for geophysical fluid problems. Reviews of Geophysics, 20(4), 851-875.·doi:10.1029/RG020i004p00851,1982

Morrison, H., & Gettelman, A. A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests. Journal of Climate, 21(15), 3642-3659.·doi:10.1175/2008JCLI2105.1,2008

Nakanishi, M., & Niino, H. Development of an Improved Turbulence Closure Model for the Atmospheric Boundary Layer. Journal of the Meteorological Society of Japan. Ser. II, 87(5), 895-912.·doi:10.2151/jmsj.87.895,2009

Olson, J. B., Kenyon, J. S., Angevine, W. A., Brown, J. M., Pagowski, M., & Sušelj, K. A Description of the MYNN-EDMF Scheme and the Coupling to Other Components in WRF–ARW [Technical Memorandum].·doi:10.25923/n9wm-be49,2019

3. 27 km is higher than typical resolutions used in global simulations. 27 km cannot be considered a high resolution by itself. Please make this clear in the paper.

Thank you for the comment. As suggested, we included relevant sentences to clarify this as follows (P7, L242-245):

"The 27 km resolution is consistent with the ERA5 reanalysis data to ensure the accuracy of large-scale meteorological conditions, and it is significantly higher than the usual resolution employed in global climate models (which is typically over 1°) in earlier research (e.g., Dou et al., 2012; Jiao et al., 2014; Ren et al., 2020)."

References

Dou, T., Xiao, C., Shindell, D. T., Liu, J., Eleftheriadis, K., Ming, J., & Qin, D. The distribution of snow black carbon observed in the Arctic and compared to the GISS-PUCCINI model. Atmospheric Chemistry and Physics, 12(17), 7995-8007.·doi:10.5194/acp-12-7995-2012,2012

Jiao, C., Flanner, M. G., Balkanski, Y., Bauer, S. E., Bellouin, N., Berntsen, T. K., Bian, H., et al. An AeroCom assessment of black carbon in Arctic snow and sea ice. Atmospheric Chemistry and Physics, 14(5), 2399-2417.·doi:10.5194/acp-14-2399-2014,2014

Ren, L., Yang, Y., Wang, H., Zhang, R., Wang, P., & Liao, H. Source attribution of Arctic black carbon and sulfate aerosols and associated Arctic surface warming during 1980–2018. Atmospheric Chemistry and Physics, 20(14), 9067-9085.·doi:10.5194/acp-20-9067-2020,2020

4. The discussion of how the model accounts for snow-ice transitions needs to be added to the paper, besides referring to He et al. (2023). This information is crucial to support readers' understanding about the processes.

Thank you for the comment. As suggested, we added more relevant description about the snow process in the paper as follows (P6-7, L216-239):

"In the Noah-MP, the evolution of snowpack properties, including snow ice and liquid water content, snow thickness, and water flux out of snowpack bottom. If the snow layer temperature is higher than freezing point (273.15 K), then the snow layer ice is melting; if snow layer liquid water content is greater than 0, and snow layer temperature is lower than freezing point, then ice is refreezing. Once melting or freezing active, the snow ice amount will be updated. The amount of phase-change water is computed as:

$$\Delta W_{phase}(i) = \frac{H_{M,phase}(i) \times \Delta t}{C_{LH,fus}} \tag{7}$$

where ΔW_{phase} (kg m^{-2}) is amount of phase-change water, i is the snow layer, $H_{M,phase}$ (W m^{-2}) is the energy residual (surplus or loss), and it is computed as:

$$H_{M,phase}(i) = \frac{T_{snso}(i) - T_{frz}}{\Delta t} \times C_{h,snow} \times \Delta z \tag{8}$$

where T_{sno} (K) is the snow temperature, $T_{frz} = 273.15$ (K) is the freezing point, Δz (m) is the thickness of snow layer, $C_{h,snow}$ (J m^{-3} K^{-1}) is the volumetric specific heat capacity of snow and it is calculated as:

$$C_{h,snow} = C_{h,ice} \times \theta_{ice,sno} + C_{h,wat} \times \theta_{liq,sno} \tag{9}$$

where $C_{h,ice}$ (J m^{-3} K^{-1}) and $C_{h,wat}$ (J m^{-3} K^{-1}) are the volumetric specific heat capacity of ice and water, respectively, $\theta_{ice,sno}$ and $\theta_{liq,sno}$ are partial volume of ice and liquid water in snow layer, respectively.

For each snow layer, if the freezing is active, then the snow ice content ($W_{ice,sno}$, [kg m^{-2}]) is updated as:

$$W_{ice,sno,new}(i) = \min\left(W_{snow,old}(i), W_{ice,sno,old}(i) - \Delta W_{phase}(i)\right) \tag{10}$$

If the melting is active, then the snow ice content ($W_{ice,sno}$, [kg m^{-2}]) is updated as:

$$W_{ice,sno,new}(i) = \max\left(0, W_{ice,sno,old}(i) - \Delta W_{phase}(i)\right) \tag{11}$$

Then, the snow liquid water content ($W_{liq,sno}$, [kg m^{-2}] is updated as:

$$W_{liq,sno,new}(i) = \max\left(0, W_{snow,old}(i) - W_{ice,sno,new}\right) \tag{12}$$

As the snow melts, the amount of liquid water content in the snowpack will rise, leading to an increase in snow density. Once the liquid water content surpasses the snowpack's maximum capacity to hold water, the snowpack will start to flow out, resulting in a reduction in snow depth. These changes in snow properties will influence the snow albedo reduction caused by BC."

5. My original comment "In the result section, please clarify which results are coming from *which experiments" was not fully addressed. There was a list of simulations performed, as shown in Table 1. Besides stating "SNICAR-ON" vs. "SNICAR-OFF" the authors also need to clarify each result section corresponds to which simulation setups.*

Thank you for the comment. We apologize for our carelessness. As recommended, we have revised and clarified the simulation setups in each results section. For example, in the Section 3.4, we clarified that the changes in the surface energy balance was investigated via the SNICAR-ON and the snow processes are included in this experiment (P15, L469-470):

"Based on SNICAR-ON simulation results (include the snow processes), the temporal evolution of the SDE caused by a fixed 50 ng g^{-1} BC has been studied."