Science Bulletin xxx (xxxx) xxx

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Enhanced mid-latitude warming due to poleward shift of sea salt aerosols in a warmer future

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A R T I C L E I N F O

Article history:
Received 16 December 2024
Received in revised form 26 March 2025
Accepted 31 March 2025
Available online xxxx

Natural aerosols provide large uncertainties regarding the quantification of the climate effects of aerosols, especially those related to aerosol-cloud interactions [1]. Advancing research on the interaction of natural aerosols and climate can provide a better assessment of the climate impacts of anthropogenic activities. As one of the most dominant natural aerosols, sea salt has the highest proportion of mass in natural aerosols [2]. Sea salt can be regarded as a purely scattering aerosol, causing a negative radiative effect [3] by scattering shortwave solar radiation [4] and acting as cloud condensation nuclei (CCN) through aerosol-cloud interactions [5,6]. Future climate change will influence sea salt distribution, thus modifying the radiative effects of sea salt, which will further affect the climate. However, few previous studies have explored the interactions between sea salt changes under warming scenarios and climate change.

Based on a modified Community Earth System Model version 1 (CESM1) model (Text S1 online) and the Coupled Model Intercomparison Project Phase 6 (CMIP6) emissions, five fully-coupled simulations are conducted to investigate the radiative effect and climate feedback of changing sea salt in a warming climate. Two simulations are performed with sea salt emission prescribed at the 2100 level under the SSP1-2.6 scenario and SSP5-8.5 scenario. Another two coupled simulations are performed with blowing snow sea salt emission added to the original CMIP6 sea salt emissions. One simulation at the 2020 level is conducted for the model evaluation against observations.

Fig. 1a shows the spatial distribution of changes in sea salt emissions at the end of the 21st century under the SSP5-8.5 scenario compared to the SSP1-2.6. In the warmer future under SSP5-8.5, sea salt emissions will increase significantly at high latitudes, especially around 60°S in the Southern Ocean and north of 70°N in the Arctic relative to SSP1-2.6, while the opposite change is observed at mid-latitudes around 40°N and 40°S as predicted by the CMIP6 models. Increases in sea salt emissions are also occurring between 10°–20°S over the South Pacific, South China Sea, parts of Arabian Sea and Central America. The main reason for the changes in sea salt emissions is the differences in the near-surface winds between the two climate change scenarios (Fig. 1b). In the Arctic, the increase in sea salt emissions is due to the melt of sea ice by more than 40% under the high-forcing scenario, providing more open water areas for emitting sea salt (Fig. 1c) [7]. Reduction in sea ice cover can also increase the surface wind speed in the Arctic through weakening the atmospheric stability and reducing the surface roughness [8]. The changes in sea salt emissions in other oceanic regions of the globe are driven by the changes in near-surface winds, which are dominated by the poleward shift of storm tracks in the warmer climate (Fig. 1d). The storm track intensity, which is evaluated by comparing with ERA5 (Text S2, Figs. S1–S2 online), will dramatically increase over the Southern Ocean at the end of the 21st century in a warmer climate under SSP5-8.5 relative to SSP1-2.6 and decrease over the mid-latitude oceans around 40°N and 40°S (Text S3 online), consistent with the changes in sea salt emissions. This poleward shift of

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https://doi.org/10.1016/j.scib.2025.04.023
2095-9273/

Please cite this article as: Y. Yang, Y. Yu, Y. Wang et al., Enhanced mid-latitude warming due to poleward shift of sea salt aerosols in a warmer future, Science Bulletin, https://doi.org/10.1016/j.scib.2025.04.023

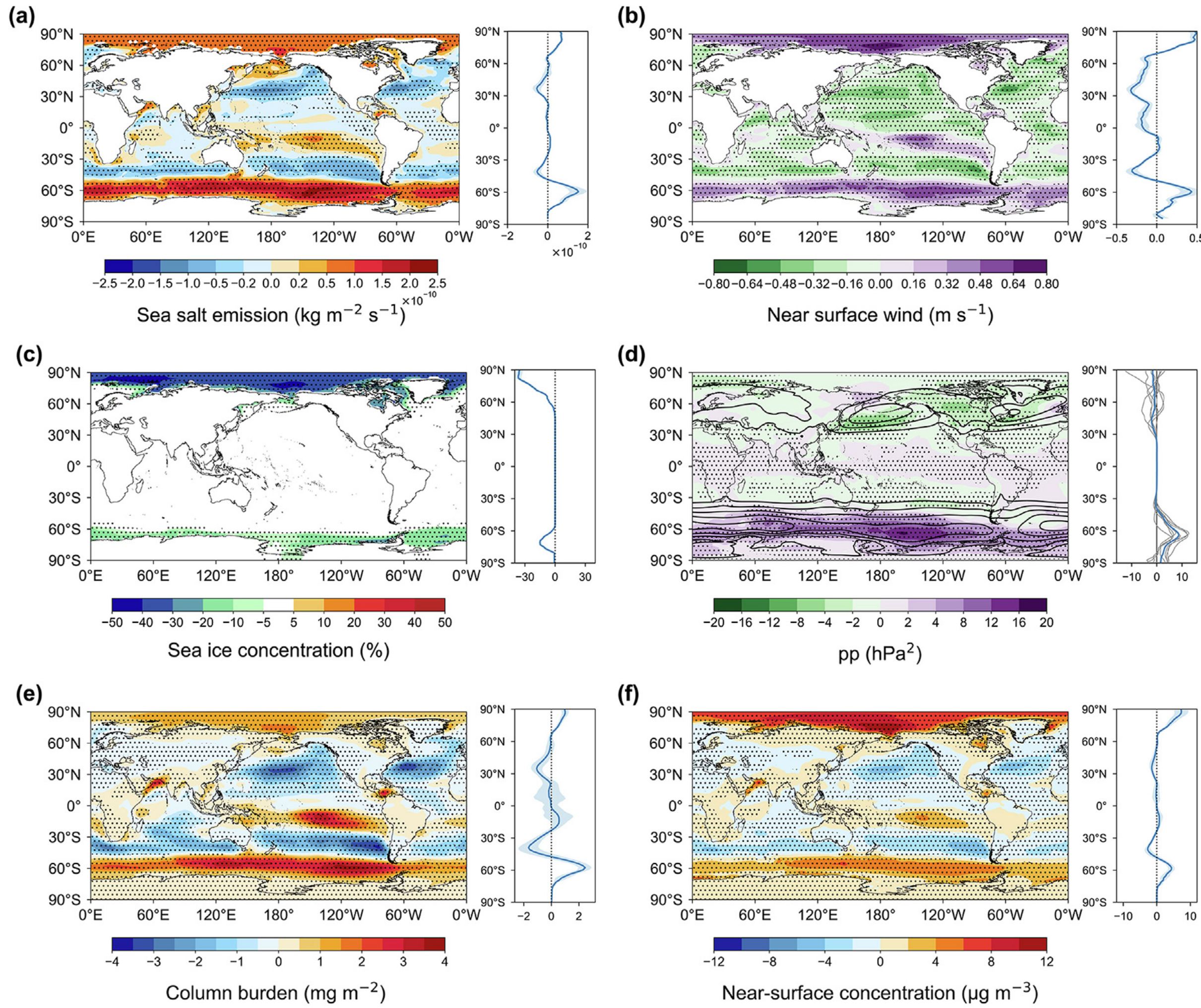

Fig. 1. Future changes in annual mean sea salt emissions and concentrations and the main driving factors. Spatial distribution and zonal mean of (a) sea salt emissions (kg m^{-2} s^{-1}), (b) near-surface wind (m s^{-1}), (c) sea ice concentration (%), and (d) storm track activity (pp, hPa^2) under the SSP5-8.5 scenario compared to SSP1-2.6 in 2100 from CMIP6. CESM1-simulated (e) sea salt column burden (mg m^{-2}) and (f) near-surface sea salt concentrations (μg m^{-3}) under the SSP5-8.5 scenario compared to SSP1-2.6 in 2100. The dotted areas in spatial distribution plots indicate statistical significance at the 95% confidence level from a two-tailed Student's *t*-test. The shaded areas in the zonal mean panels denote $\pm 1\sigma$. The black contour lines in the left panel of (b) indicate pp in the SSP1-2.6 scenario with contour intervals of 20 hPa^2 and the pp changes for individual CMIP6 models are shown in solid gray lines in the right panel of (d).

storm tracks in a warming future was also reported in previous studies [9].

The simulated future changes in column burdens of sea salt (Fig. 1e) show a pattern similar to the sea salt emissions. The increases are located over the Southern Ocean, the Arctic, and oceans around 15°S, with the maximum zonal mean increase in sea salt burden more than 2 mg m^{-2} (more than 20%) around 60°S, while the sea salt burden decreases by less than 2 mg m^{-2} over 30°–45°S and by about 1 mg m^{-2} between 30°–40°N (5%–20%). The maximum increase in near-surface concentrations of sea salt is located in the Arctic, reaching 10 μg m^{-3} (exceeding 100%), most likely related to the increase in local emissions. It should be noted that CESM1 overestimated sea salt concentration compared to the observation (Text S2, Figs. S3–S5 online).

The changes in atmospheric sea salt burden can perturb the radiation balance of the Earth system through changing total aerosol optical properties and cloud microphysics, which further influence climate. The changes of 550 nm AOD in SSP5-8.5 relative to SSP1-2.6 show a significant increase in the Southern Ocean and a decrease in mid-latitude oceans (Fig. S6a online), which are mainly attributed to the AOD changes from sea salt aerosols (Fig. S6b online). The cloud droplet number concentrations and liquid water path also show an obvious poleward shift in SSP5-8.5 compared to SSP1-2.6, which further perturb the Earth's energy balance (Fig. S7 online).

Fig. 2 shows the global distributions of aerosol radiative effect (ARE) as well as the decomposed direct radiative effect (DRE) and cloud radiative effect (CRE) at the top of the atmosphere due to the future changes in sea salt emissions in 2100 in SSP5-8.5 relative to SSP1-2.6. With climate feedback considered, the future changes in sea salt aerosols will lead to a significant negative ARE over the Arctic (−0.35 ± 0.02 W m^{-2}) and the Southern Ocean (−0.35 ± 0.06 W m^{-2} over the 50°–60°S), with the maximum of zonal mean change by about −0.7 W m^{-2} over the Arctic in 2100 under SSP5-8.5 relative to SSP1-2.6 (Fig. 2a). The negative CRE over the Arctic is more significant in summer, when the cloud shading effect overwhelms cloud greenhouse effect, while in winter, with less sunlight, the increase in sea salt produces positive ARE and CRE (Fig. S8 online). The positive ARE is located over oceans in 30–40°N and 30–40°S and coastal areas of the Antarctic. Both DRE and CRE show similar spatial patterns as ARE, with the CRE dominating the ARE at low- and mid-latitudes in all seasons (Fig. S9 online), emphasizing the importance of sea salt radiative effect through aerosol-cloud interactions. Interestingly, the posi-

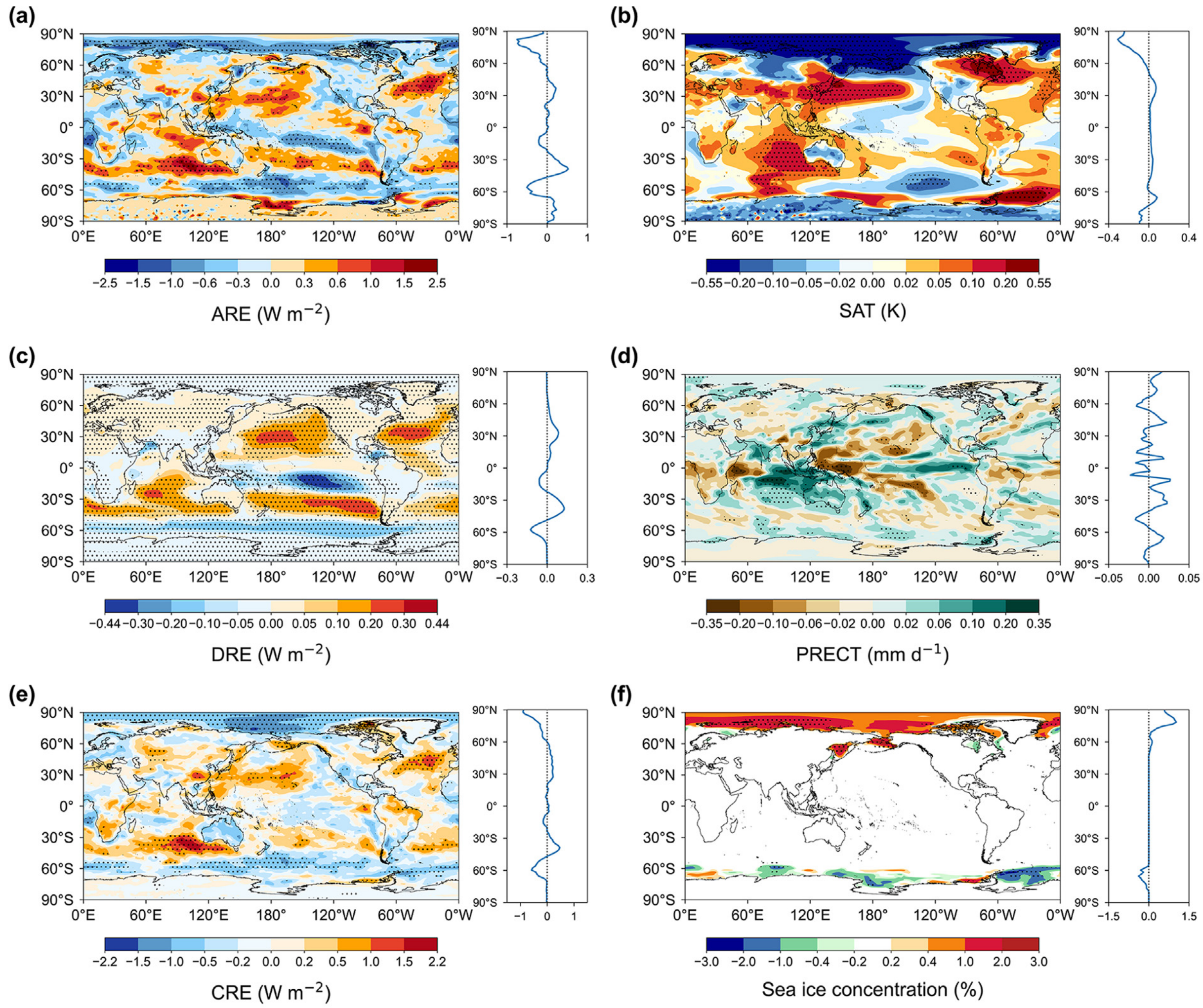

Fig. 2. Climate changes due to sea salt emissions under a warming future. Spatial distribution and zonal mean of CESM1-simulated annual mean changes in (a) aerosol radiative effect (ARE, W m^{-2}), (c) direct radiative effect (DRE, W m^{-2}) and (e) cloud radiative effect (CRE, W m^{-2}) at the top of the atmosphere (TOA), (b) surface air temperature (SAT, K), (d) total precipitation rate (PRECT, mm d^{-1}) and (f) sea ice concentration (%) due to changes in sea salt emissions under the SSP5-8.5 scenario compared to SSP1-2.6 in 2100. The shaded areas indicate statistical significance with 95% confidence from a two-tailed Student's *t*-test.

tive ARE over the coastal areas of the Antarctic cannot be explained by the DRE and CRE, which is related to the transport of warm air and enhanced snow/ice albedo effect (discussed in more detail below). Although sea salt emission changes do not change the global average ARE (close to 0 W m^{-2}), they largely affect the zonal distribution of the energy budget and, therefore, impact regional climate.

At the end of the 21st century, only 0.01 K of the global averaged surface air temperature (SAT) increase is related to the sea salt redistribution. However, changes in sea salt emissions in a warmer climate will lead to significant warming at low and mid-latitudes, especially the North Pacific Ocean, northern North Atlantic Ocean, Indian Ocean, and coastal areas of the Antarctic, and cooling at high latitudes, especially the Arctic (Fig. 2b). Due to the poleward shift of the sea salt emissions, the SAT increases between 50°S–50°N, with maximum warming exceeding 0.2 K, whereas it decreases by 0.17 K (± 0.02 K) over the Arctic (north of 66.5°N). The mechanism for such a strong cooling over the Arctic is likely associated with the Arctic amplification [10], through which the Arctic climate becomes more sensitive to external forcings. Due to the strong negative ARE from aerosol-cloud interactions (Fig. 2e), temperature decreases in the Arctic (Fig. 2b), resulting in an increase in the sea ice fraction by 1%–2% in many regions of the Arctic (Fig. 2f). The temperature increase in the tropical central-eastern Pacific is linked to the Arctic-tropical teleconnection [11]. The tropospheric cooling in boreal winter, resulted in the cyclonic wind change at 850 hPa over north Pacific and anomaly westerly wind over the tropical Pacific (Fig. S10 online), affecting SAT over the Pacific.

Changes in precipitation show a strong zonal fluctuation but the spatial distribution follows the temperature changes. With a strong increase in temperature in the tropical central-eastern Pacific, weakening of the Walker circulation results in increased precipitation in the tropical central-eastern Pacific and decreased precipitation in the tropical western Pacific. Compared to SSP1-2.6, precipitation in SSP5-8.5 increases in the Indian Ocean and oceans over the 45°N and 70°S latitudinal bands and decreases in the tropical western Pacific and oceans over the 60°N and 50°S latitudinal bands (Fig. 2d). The small but significant increases of precipitation in the Indian Ocean and along 70°S are related to the surface warming and near-surface wind anomalies (Figs. S2b, S11 online).

The energy imbalance induced by changes in sea salt in the warmer future also influences winds (Fig. S11 online). The sea surface warming due to the decreases in sea salt over the Northern Pacific Ocean and Indian Ocean produces anomalous anticyclones and cyclones, respectively, over these two regions (Fig. S11b online).

The near-surface wind speed shows a significant increase over 60°S of the Southern Ocean (Fig. S11a online) related to the equator-to-polar temperature difference and atmospheric circulation change due to sea salt emission change. The poleward shift of sea salt cools the polar atmosphere and warms the upper mid-latitude troposphere (Fig. S12a online), increasing the upper-level temperature gradient and the zonal wind shear, pushing the eddy kinetic energy poleward [12] and resulting in the near-surface wind change in the Southern Hemisphere. The sea ice melts over 60°S results from the southward transport of warm air in the lower atmosphere from mid-latitude regions (Fig. S12b online), which is associated with the cooling along 50°S due to the poleward shift of sea salt. The southward transport of warm air also induces a temperature increase in coastal areas of the Antarctic, which is further intensified by the snow/ice albedo effect.

In the polar regions, blowing snow is also one important source of sea salt [13], yet most climate models in CMIP6 did not consider this process [14], which could potentially affect the results shown above. The fine mode (Aitken and accumulation modes) of sea salt mass emission from blowing snow calculated with the CMIP6 data over the Arctic is 0.36 Tg a^{-1} in 2100 under the SSP1-2.6 scenario, in the same order with 1.0 Tg a^{-1} presented in Huang et al. [15] in 2005 calculated using the GEOS-Chem model. The CMIP6 multi-model results yield an Arctic open ocean sea salt emission in fine mode of 2.83 Tg a^{-1}, much higher than the blowing snow sources calculated in this study and Ref. [15]. However, in the warmer future under SSP5-8.5, fine mode sea salt emission over the Arctic open ocean increases by 0.24 Tg a^{-1} relative to SSP1-2.6, and this increase is almost dampened by the less blowing snow source (−0.22 Tg a^{-1}) (Fig. S13 online).

Taking the decreasing sea salt from blowing snow into account, the cooling in the Arctic is weakened and the mid-latitude warming in the Northern Hemisphere is more pronounced (Fig. S14a online) compared to that without the blowing snow mechanism. It is attributed to the reduction in sea salt around 60°N due to less blowing snow in a warmer future (Fig. S13b online). Note that, the cooling in the Southern Ocean is more significant, mainly due to the less significant southward transport of warm air with the consideration of blowing snow (Fig. S14b online). The cooling in the Southern Ocean is more consistent with the substantial increases in sea salt in this region due to the poleward shift of storm tracks, indicating that the sea salt from blowing snow should be considered when investigating sea salt-climate interactions.

This study concluded that CMIP6-predicted sea salt emissions will increase notably in the Arctic and the Southern Ocean and decrease over oceans around 40°S and 40°N due to the poleward shift of storm tracks and a stronger sea ice melt in a warmer climate. It contributes to mid-latitude warming through aerosol radiative effects, with regional maxima exceeding 0.2 K, based on aerosol-climate model simulations. The mid-latitude warming is further enhanced by the decline in sea salt from blowing snow in the Arctic. Although the warming due to the sea salt feedback is much weaker than that induced by other anthropogenic forcings (Fig. S15 online), it should be considered in future climate projections. However, we note that the results of sea salt feedback are based on CESM1 simulations, which could be model- dependent and require further validation using more aerosol-climate models in future studies. This study underscores the potential for enhanced mid-latitude warming attributable to the sea salt feedback processes if the greenhouse gas concentrations continue rising, providing a novel perspective on the intricate interplay between natural aerosols and climate change.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2024YFF0811400), the National Natural Science Foundation of China (42475032), Jiangsu Science Fund for Carbon Neutrality (BK20220031), and Jiangsu Innovation Research Group (JSSCTD202346). The Pacific Northwest National Laboratory (PNNL) is operated for DOE by the Battelle Memorial Institute under contract DE-AC05-76RLO1830.

Author contributions

Yang Yang and Yang Yu contributed to the conception and design of the work and drafted the manuscript. Yang Yang directed the analysis. Yang Yu performed the analysis. All authors contributed to the review and revision of the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.04.023.

References

[1] Carslaw KS, Lee LA, Reddington CL, et al. Large contribution of natural aerosols to uncertainty in indirect forcing. Nature 2013;503:67–71.
[2] O'Dowd CD, Smith MH, Consterdine IE, et al. Marine aerosol, sea-salt, and the marine sulphur cycle: a short review. Atmos Environ 1997;31:73–80.
[3] Zakey AS, Giorgi F, Bi X. Modeling of sea salt in a regional climate model: fluxes and radiative forcing. J Geophys Res 2008;113:D14221.
[4] Li J, Carlson BE, Yung YL, et al. Scattering and absorbing aerosols in the climate system. Nat Rev Earth Environ 2022;3:363–79.
[5] Quinn PK, Coffman DJ, Johnson JE, et al. Small fraction of marine cloud condensation nuclei made up of sea spray aerosol. Nat Geosci 2017;10:674–9.
[6] Xu W, Ovadnevaite J, Fossum KN, et al. Sea spray as an obscured source for marine cloud nuclei. Nat Geosci 2022;15:282–6.
[7] Yan J, Jung J, Lin Q, et al. Effect of sea ice retreat on marine aerosol emissions in the Southern Ocean. Antarctica Sci Total Environ 2020;745:140773.
[8] Vavrus SJ, Alkama R. Future trends of arctic surface wind speeds and their relationship with sea ice in CMIP5 climate model simulations. Clim Dyn 2022;59:1833–48.
[9] Priestley MDK, Catto JL. Future changes in the extratropical storm tracks and cyclone intensity, wind speed, and structure. Weather Clim Dyn 2022;3:337–60.
[10] Zhang R, Wang H, Fu Q, et al. Local radiative feedbacks over the Arctic based on observed short-term climate variations. Geophys Res Lett 2018;45:5761–70.
[11] Chen S, Chen W, Zhou W, et al. Interdecadal variation in the impact of Arctic Sea Ice on the El Niño-Southern Oscillation: the role of atmospheric mean flow. J Clim 2024;37:5483–506.
[12] Chemke R. The future poleward shift of Southern Hemisphere summer mid-latitude storm tracks stems from ocean coupling. Nat Commun 2022;13:1730.
[13] Gong X, Zhang J, Croft B, et al. Arctic warming by abundant fine sea salt aerosols from blowing snow. Nat Geosci 2023;16:768–74.
[14] Lapere R, Thomas JL, Marelle L, et al. The representation of sea salt aerosols and their role in polar climate within CMIP6. J Geophys Res Atmos 2023;128: e2022JD038235.
[15] Huang J, Jaeglé L. Wintertime enhancements of sea salt aerosol in polar regions consistent with a sea ice source from blowing snow. Atmos Chem Phys 2017;17:3699–712.