ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™ Part of the ENVIRONMENTAL RESEARCH SERIES

LETTER • **OPEN ACCESS**

The response of Arctic warming to aerosols

To cite this article: Di Chen and Qizhen Sun 2025 *Environ. Res. Lett.* **20** 064035

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

The response of Arctic warming to aerosols

Di Chen[1,3] and Qizhen Sun[2,*]

[1] Ocean University of China, Qingdao 266003, People's Republic of China
[2] National Marine Environmental Forecasting Center, Beijing 100082, People's Republic of China
[3] School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, People's Republic of China
[*] Author to whom any correspondence should be addressed.

E-mail: qzsun.tj@foxmail.com

Keywords: arctic warming, aerosols, solar radiation

OPEN ACCESS

RECEIVED
22 March 2025

REVISED
30 April 2025

ACCEPTED FOR PUBLICATION
14 May 2025

PUBLISHED
23 May 2025

Abstract

Aerosols are increasingly recognized as critical components in global climate dynamics, yet their complex spatiotemporal variability and observational uncertainties present significant challenges in assessing their climatic impacts, particularly in the context of Arctic warming. This study leverages the latest reanalysis data and single-forcing ensemble models to investigate the origins of Arctic aerosols and their contribution to regional warming over the period from 1980 to 2023. Our findings indicate that aerosols in the Arctic predominantly originate from mid-to-high latitude regions through radial transport. Overall, aerosols mitigate some of the warming effects induced by greenhouse gases, accounting for 19% of Arctic warming, with notable variations among different aerosol types. We demonstrate that aerosols influence cloud formation and alter surface net solar radiation, thereby significantly affecting heat flux and contributing to Arctic warming. Furthermore, we project future Arctic temperature responses to aerosols, offering a theoretical foundation for advancing research on global climate change.

1. Introduction

Atmospheric aerosols, comprising solid and liquid particles suspended in the atmosphere with diameters ranging from 0.001 to 100 μm (Seinfeld *et al* 2016, Carrico 2018), play a pivotal role in global climate dynamics. Major aerosol types include carbonaceous, sulfate, dust, and sea salt aerosols (Liu *et al* 2005). Despite their minimal mass relative to the total atmosphere, aerosols exert significant influence on climate (Carmichael *et al* 2009, Akinyoola *et al* 2024). They directly affect Earth's radiative balance by scattering, absorbing, and reflecting solar radiation, and indirectly influence climate by acting as cloud condensation nuclei, altering cloud properties and lifespan (Seinfeld *et al* 2016, Li *et al* 2022). However, the pronounced spatiotemporal variability and observational uncertainties of aerosols complicate the assessment of their climatic effects (He *et al* 2016, Pan *et al* 2022).

The Arctic, a region highly sensitive to climate change, has experienced warming at a rate exceeding the global average, a phenomenon known as Arctic amplification (Vincent 2020, Rantanen *et al* 2022). The rapid decline in Arctic sea ice, melting of the Greenland ice sheet, and thawing permafrost may reach critical tipping points, with profound global consequences (Swingedouw *et al* 2019, Chen *et al* 2024a). Arctic warming significantly impacts mid-to-high latitude climates, contributing to the increasing frequency of extreme weather events (Coumou *et al* 2018, Chen and Sun 2023).

Research has established a link between Arctic temperature rise and atmospheric aerosols (Wobus *et al* 2016, Schmale *et al* 2021). Aerosols have a prolonged lifespan in the Arctic, exerting substantial influence on regional temperatures (Willis *et al* 2018). Black carbon (BC) aerosols, even in minimal amounts, can significantly enhance warming on ice and snow surfaces (Chen *et al* 2024b). Arctic clouds, predominantly thin, are particularly susceptible to aerosol-induced changes, which can produce warming effects comparable to greenhouse gases (GHGs) (Kay *et al* 2016, Devasthale *et al* 2020). Conversely, sulfate aerosols exert a cooling effect (Feinberg *et al* 2019, Zhao *et al* 2021). Despite extensive research on GHGs' role in Arctic amplification (Serreze and Barry 2011, Screen and Simmonds 2010), the impact of aerosols, particularly the relative contributions of different types, remains underexplored.

This study utilizes the latest reanalysis data to examine the contribution of various aerosols to Arctic warming and explores potential mechanisms. We also employ National Center for Atmospheric Research (NCAR) 's next-generation ensemble models to verify and project Arctic temperature responses to aerosols, aiming to bridge the knowledge gap in this area. The aim of this study is to quantify the contribution of different aerosol types to the Arctic temperature change and to reveal the mechanisms by which they affect the Arctic thermodynamic processes through cloud-radiation interactions.

2. Materials and methods

2.1. Observational and reanalysis datasets

Aerosol optical depth (AOD) is a key parameter reflecting the extinction effect of aerosols throughout the atmospheric column (Zhang *et al* 2020, Ranjan *et al* 2021). High AOD values typically indicate elevated aerosol concentrations (Guo *et al* 2009, Tian *et al* 2017, Sayer *et al* 2020). MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) provides AOD (Gelaro *et al* 2017). This dataset, produced by NASA's Global Modeling and Assimilation Office, includes data on sulfate (SO4), organic carbon (OC), BC, dust, and sea salt aerosols. The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset provides additional variables, including near-surface air temperature (NSAT), sea surface temperature (SST), latent and sensible fluxes, cloud cover, and surface net solar radiation (SNSR) (Hersbach *et al* 2020). Data spans from 1980 to 2023, with anomalies calculated relative to the mean values over this period. MERRA-2 was selected as the core data for this study due to its ability to assimilate AOD at high resolution (Gelaro *et al* 2017) and the validation advantages of ERA5 for Arctic meteorological variables (Hersbach *et al* 2020). Although MERRA-2 and ERA5 provide valuable aerosol and temperature data, both datasets have limitations. MERRA-2's aerosol estimates depend on emission inventories and may underestimate organic aerosol sources (Buchholz *et al* 2022). ERA5 reanalysis, while comprehensive, may not fully capture high-latitude cloud variability due to sparse observational constraints (Devasthale *et al* 2020, Hersbach *et al* 2020). Future studies could integrate ground-based measurements (e.g Polarstern campaigns, ASCOS project) and satellite retrievals (e.g. CALIPSO lidar, MODIS AOD) to validate these biases.

2.2. Single forcing large ensemble model simulations

The simulations consist of a 100-member ensemble conducted with CESM2 using the Community Atmosphere Model version 6 (CAM6) (Danabasoglu *et al* 2020). The 'Single Forcing' Large Ensemble Project explores the impacts of individual forcings on historical and future climate change. Simulations, initiated in 1850, extend to 2050, following CMIP6 historical forcings until 2015 and transitioning to SSP3-7.0 forcings thereafter. Four single-forcing ensembles are included: GHG, anthropogenic aerosols (AAERs), biomass burning aerosols (BMBs), and other factors (EE). AAER and BMB are combined to investigate total aerosols (TAER). The CESM2 model was selected due to its single-forcing experimental design that can effectively separate the independent climate effects of aerosols and GHGs (Danabasoglu *et al* 2020). CESM2 simulations may underestimate the contribution of organic aerosols, especially from biogenic and wildfire sources, which have become increasingly important under intensified wildfire activity in recent years (Moschos *et al* 2022).

2.3. Singular value decomposition (SVD) analysis

SVD, a mathematical technique for matrix factorization, is used to study interactions between two fields, revealing spatial and temporal variations in multivariate datasets (Akritas and Malaschonok 2004). SVD was chosen over methods like EOF and CCA because it maximizes spatial-temporal covariance between two fields (AOD and cloud cover), offering an optimal way to uncover their coupled variations. Robustness tests show that the first two SVD modes together explain over 80% of the covariance, confirming the stability of results.

2.4. Trend analysis

Linear temperature trends were estimated using ordinary least squares (OLSs) regression (Draper and Smith 1998). Bootstrap resampling (1000 iterations, Efron and Tibshirani 1994) was employed to construct confidence intervals, with effective sample sizes adjusted to account for autocorrelation in the time series.

2.5. Granger causality analysis

Granger causality analysis (Granger 1969) is a statistical method for causal inference, which was applied to rigorously assess the causal relationship between AOD and Arctic NSAT variations. We implemented a bivariate vector autoregression (VAR) model with the optimal lag length of 4, as determined by the akaike information criterion (AIC) (Barnett and Seth 2014). Prior to analysis, both time series were detrended and normalized to eliminate long-term trends and scale disparities. The null hypothesis of no Granger causality (i.e. AOD does not predict NSAT) was rejected when the F-test yielded p-values < 0.05 (Mosedale *et al* 2006). To ensure robustness, we performed 1000 bootstrap iterations to assess the stability of our results (Efron and Tibshirani 1994).

2.6. Total least-squares optimal fingerprinting

For attribution, we employed a total least-squares optimal fingerprinting approach using a generalized linear regression model to represent Arctic temperature changes as a linear combination of changes induced by various forcing agents (Allen and Stott 2003).

The regression model expresses observations as:

$$T = \beta_1 T_{SO_4} + \beta_2 T_{BC} + \beta_3 T_{OC} + \beta_4 T_{DU} + \beta_5 T_{SS} + \beta_6 T_{CO_2} + \varepsilon$$

where T represents Arctic near-surface temperature anomalies, T_{SO_4} T_{BC} T_{OC} T_{DU} T_{SS} T_{CO_2} are estimates of the responses to SO_4, BC, OC, DU, SS aerosols and CO_2 concentration forcing, respectively. The β terms are the corresponding scaling factors, and ε represents residual variability generated internally within the climate system.

3. Results

3.1. Variation of NSAT in global and Arctic regions

The study reveals that global average temperatures have significantly increased due to GHGs, particularly carbon dioxide (CO_2) (Solomon *et al* 2009). However, the Arctic has experienced a more pronounced warming trend, with temperatures rising at a rate 2–3 times the global average, and in some cases, even 4 times faster (Jansen *et al* 2020, Shu *et al* 2024). This phenomenon, known as Arctic amplification, has been widely documented, though the exact magnitude of warming varies depending on the indicators, regional settings, data sources, and time spans analyzed (Chen and Sun 2024, Liang *et al* 2022). To better understand these differences, we analyzed NSAT data from the ECMWF ERA5 reanalysis dataset, focusing on the period from 1980 to 2023.

The spatial distribution of Arctic temperatures shows significant variability (figure 1(a)). The Atlantic sector of the Arctic Ocean exhibits higher temperatures, while the Asian-Eurasian sector is characterized by lower temperatures. Greenland remains the coldest region, with temperatures significantly below the Arctic average. The variance in temperature changes also shows distinct spatial patterns, with the highest variability observed in the Asian-Eurasian sector near Svalbard and Novaya Zemlya, and the lowest variability in the Atlantic sector near Iceland, the Greenland Sea, and the Barents Sea (figure 1(b)).

Multi-year seasonal variations in global and Arctic temperatures reveal a consistent trend, though the amplitude of changes in the Arctic is much greater than the global average (figure 1(c)). From the 1990s onward, both global and Arctic temperatures exhibit clear interannual and interdecadal variability, with Arctic temperatures consistently higher than global temperatures. However, there are periods where temperature changes are not synchronized, suggesting different underlying mechanisms driving these variations.

The mean temperatures for the global and Arctic regions from 1980 to 2023 were 5.21 °C and −12.20 °C, respectively, with standard deviations of 1.41 °C and 2.62 °C. The standard deviation of Arctic temperatures is nearly twice that of the global average, indicating significant temperature anomalies in the Arctic. Trend analysis shows that the average temperature trends for the global and Arctic regions were 0.23 °C/decade and 0.63 °C/decade, respectively. The Arctic warming rate is approximately 2.74 times the global rate, consistent with previous findings (Rantanen *et al* 2022). However, from 2021 to 2023, there appears to be a slowdown in the warming trends for both the global and Arctic regions, with the Arctic experiencing a more pronounced deceleration. This phenomenon may be linked to recent global high-temperature events and significant wildfires in North America, which have increased emissions of OC aerosols (Buchholz *et al* 2022, Liang *et al* 2022).

3.2. Carbon dioxide and aerosols in relation to Arctic temperature changes

To determine the influence of CO_2 and aerosols on Arctic temperatures, we conducted a correlation analysis. The results indicate that CO_2 and aerosols have opposing relationships with Arctic temperatures. CO_2 is positively correlated with temperature increases, while aerosols are negatively correlated (figure 2). The strongest correlation between AOD and NSAT occurs at a 10 month lag, with a correlation coefficient of −0.45 ($p < 0.001$). This suggests that aerosols have a delayed influence on Arctic temperatures, likely due to their indirect effects on cloud formation and surface radiation. Granger causality analysis (see Materials and Methods) demonstrates that AOD anomalies exert a statistically significant causal influence on subsequent Arctic temperature variations ($p = 0.014$, 4 lags). This robust temporal precedence (AOD→temperature) provides empirical evidence for aerosol-driven regional warming. The identified causality is mechanistically consistent with our proposed framework of aerosol-cloud-radiation interactions.

3.3. Composition and sources of Arctic aerosols

The composition of Arctic aerosols is dominated by sulfate (65.3%), followed by OC (24.4%), BC (5.4%), dust (2.9%), and sea salt (2.1%). Sulfate aerosols, formed through the oxidation of sulfur dioxide (SO_2) in the atmosphere, exert a cooling effect by scattering solar radiation and increasing cloud albedo (Feinberg *et al* 2019, Zhao *et al* 2021). This cooling effect partially offsets the warming induced by GHGs, playing a crucial role in maintaining the global energy balance.

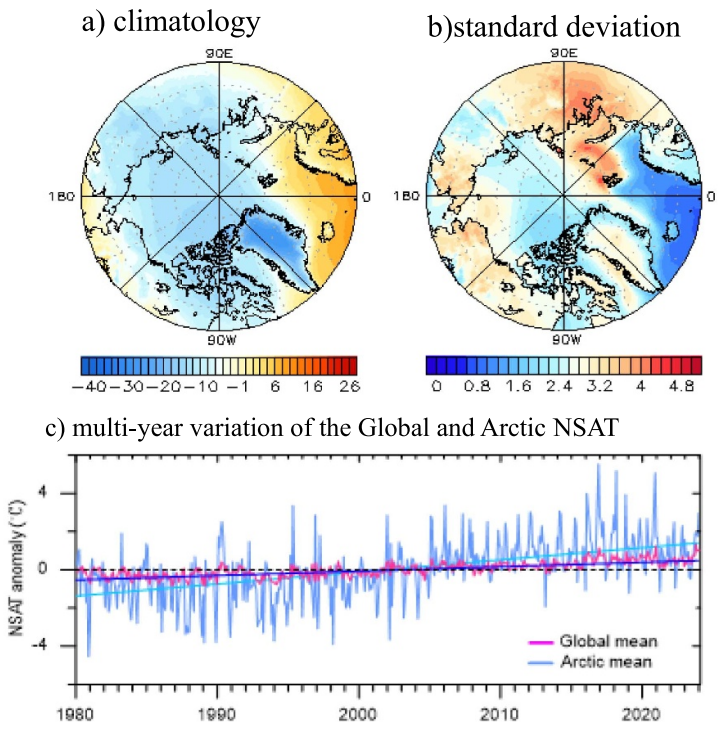

Figure 1. Spatial distribution of the Arctic climatology (a) and standard deviation (b) of the near-surface temperature (NSAT) for 1980–2023. (c) Multi-year curves of the global and Arctic (66.5°–90° N) mean near-surface temperatures. The units are C°.

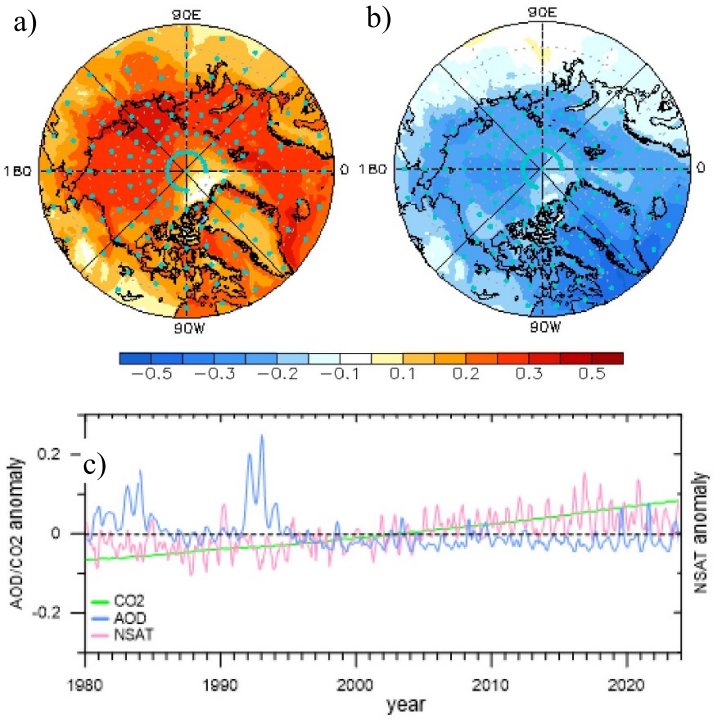

Figure 2. Correlation distributions of the near-surface temperature with CO_2 (a) and AOD (b). The dotted areas indicate regions where the correlations are statistically significant above a 99.9% confidence level. (c) Monthly mean anomaly variations of AOD and CO2 in global mean, as well as near-surface temperature (NSAT) in the Arctic (66.5°–90° N) for 1980–2023. The best correlation of −0.45 ($p < 0.001$) occurs when NSAT lags AOD by 10 months. The thick solid lines (blue, purple, green) represent orthogonal polynomial fittings for CO2, AOD, and near-surface temperature.

To understand the sources and transport of aerosols to the Arctic, we analyzed the seasonal variation of sulfate column v-wind mass flux (figure 3). The results show that aerosol transport to the Arctic is highest in winter, followed by spring, autumn, and summer. Variance analysis indicates that the

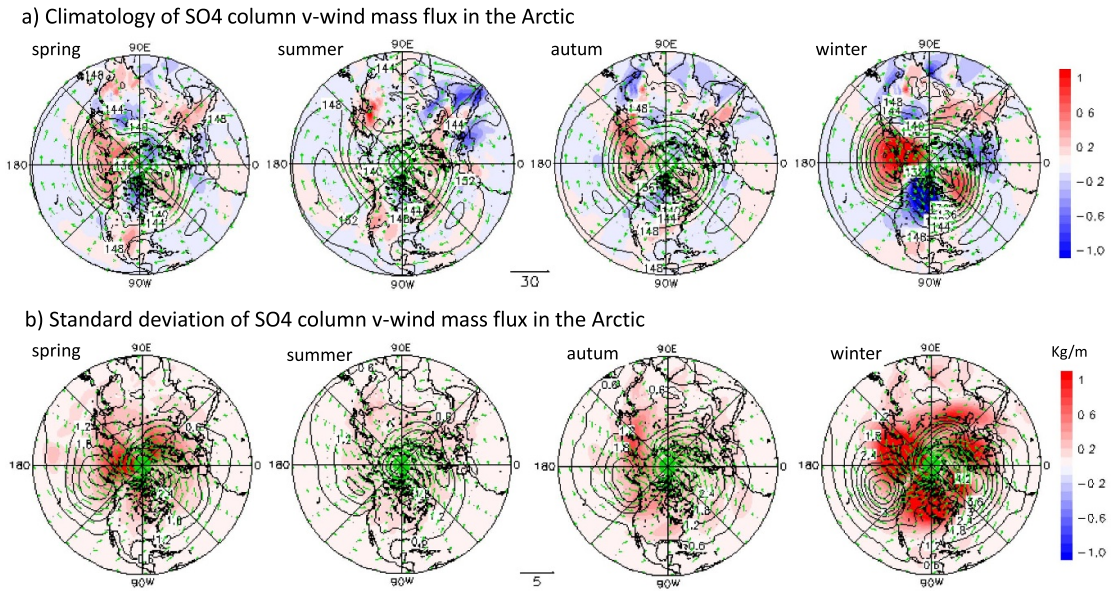

Figure 3. Climatology (a) and variance (b) of SO4 column v-wind mass flux for different seasons from 1980–2022 based on MERRA2 reanalysis. Units is g m.s^{-1}; the vector represents wind speed at 500 hPa. Units is m s^{-1}.

aerosol transport variance is largest in winter and smallest in summer. Regardless of the season, the Arctic acts as an accumulation zone for aerosols transported from mid- to low-latitude regions. This meridional transport of aerosols, particularly sulfate, significantly influences Arctic temperature changes. Recent observational studies (Willis *et al* 2018, Schmale *et al* 2021, Moschos *et al* 2022) suggest that sea salt often dominates Arctic aerosol composition during summer and near-surface layers. Our MERRA-2-based results emphasize sulfate due to wintertime high-altitude poleward transport. Differences highlight the seasonal and vertical complexity of Arctic aerosol sources.

3.4. Impact of aerosols on Arctic temperature

Aerosols influence Arctic temperatures through their effects on cloud formation and SNSR. Using SVD analysis, we examined the relationship between AOD and cloud cover in the Arctic (figure 4). The first mode of the coupled SVD results for AOD and cloud cover indicates a coherent in-phase variation across the region, with a coupled variance contribution of 83.9% and a correlation coefficient of 0.46 ($p < 0.001$). This suggests a strong correlation between aerosol concentrations and cloud cover. When AOD increases (decreases) in the Arctic, local cloud cover tends to increase (decrease) accordingly. Long-term time series further validate this finding, with notable aerosol anomalies in 2019 and 2021 linked to large wildfires in western California and British Columbia, Canada. According to the Copernicus Atmosphere Monitoring Service, carbon emissions from wildfires in Canada reached approximately 290 million tons by the end of July 2023, doubling the total emissions from the previous record year of 2014 (Copernicus Atmosphere Monitoring Service, 2023).

Aerosols also impact SNSR, which plays a crucial role in Arctic heat flux. SVD analysis of cloud cover and SNSR reveals an anti-phase relationship, with a variance contribution rate of 53.8% (figure 5). When cloud cover decreases (increases) in the Arctic center, SNSR increases (decreases) in the Arctic center, and vice versa in the Arctic periphery. This coupling relationship demonstrates that changes in Arctic cloud cover directly affect the intensity of SNSR variations, with a coupling correlation coefficient of -0.37 ($p < 0.001$). From 1980 to 2023, there was a trend of increasing cloud cover and decreasing SNSR before the 2000s, followed by a decrease in cloud cover and an increase in SNSR after the 2010s. However, SNSR decreased after 2021, likely due to increased cloud cover associated with wildfire emissions.

3.5. Contribution of aerosols to Arctic warming and underlying mechanisms

Quantitative analysis using total least-squares optimal fingerprinting shows that CO_2 and AOD contribute 65% and 19%, respectively, to Arctic temperature changes. Among the aerosol components, sulfate (SO_2) contributes the most (38%), followed by OC (14%), BC (14%), dust (14%), and sea salt aerosols (10%). The results of this study are consistent with the range of aerosol contributions (15% – 25%) proposed by Schmale *et al* (2021), but further differentiate between the differences in different aerosol types. Although aerosols contribute less than CO_2, their impact on Arctic warming is significant. Aerosols influence Arctic temperatures by altering cloud properties and SNSR, which in turn affect heat flux and the

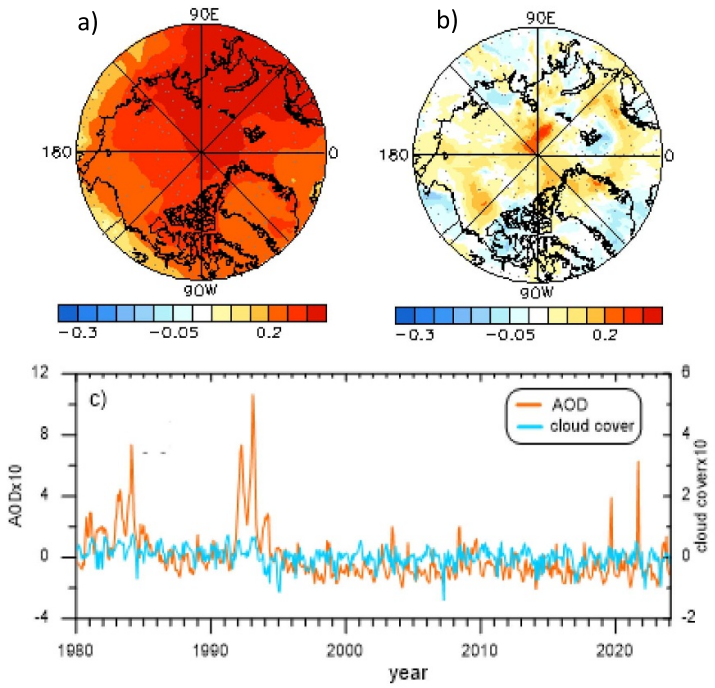

Figure 4. The leading SVD spatial patterns and time series of Arctic AOD and cloud cover for 1980–2023. (a) Shows the spatial pattern of the first SVD mode for Arctic AOD. (b) Presents the spatial pattern of the first SVD mode for Arctic cloud cover. (c) Displays the time coefficients corresponding to the first mode of Arctic AOD and total cloud cover. The correlation between the time coefficients of these two fields is 0.33 ($P < 0.001$). The variance contribution of the first mode is 91.6%.

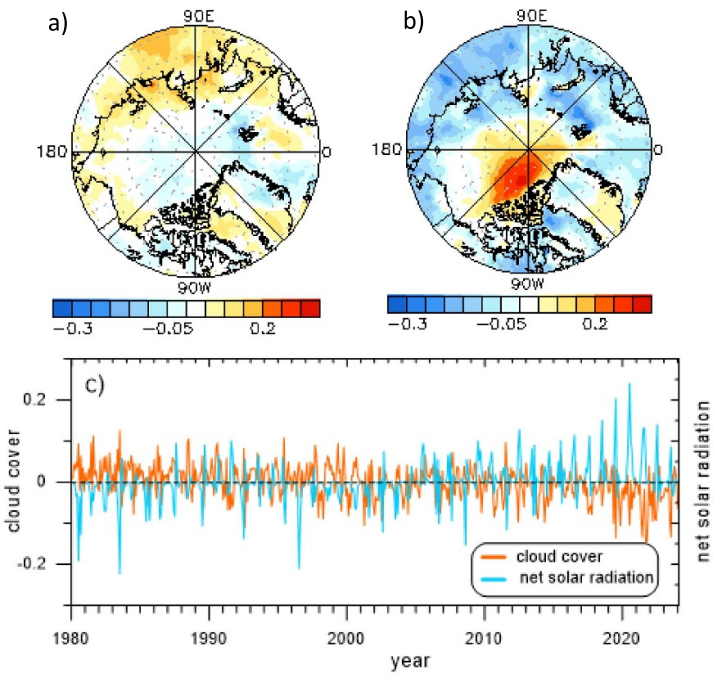

Figure 5. The leading SVD spatial patterns and the time series of the Arctic cloud cover and surface net solar radiation. (a) Represents the Arctic cloud cover of the first model. (b) Displays the Arctic net solar radiation of the first model. (c) Illustrates the time coefficient corresponding to the first mode of them. The correlation between the time coefficients of the two fields is −0.37 ($P < 0.001$).

Arctic's energy balance. These findings align with previous studies, which have shown that aerosols play a key role in Arctic climate dynamics (Willis *et al* 2018, Schmale *et al* 2021).

We also found the strong relationship between NSAT and heat fluxes, including latent heat flux (LHF) and sensible heat flux (SHF), underscores the critical role of sea-air heat exchange in the Arctic

heat balance (Figure omitted). The variance contribution of the first mode for NSAT and LHF is 45.7%, while for NSAT and SHF, it is 43.4%. These findings align with previous research, which has demonstrated that Arctic temperature changes are closely tied to variations in latent and SHFs, particularly under the influence of aerosol-induced changes in cloud cover and SNSR (Shupe and Intrieri 2004, Kay *et al* 2016).

3.6. Arctic temperature feedback under aerosols and projections

Historical trends from 1980 to 2023 show significant Arctic warming, with CO_2 playing a dominant

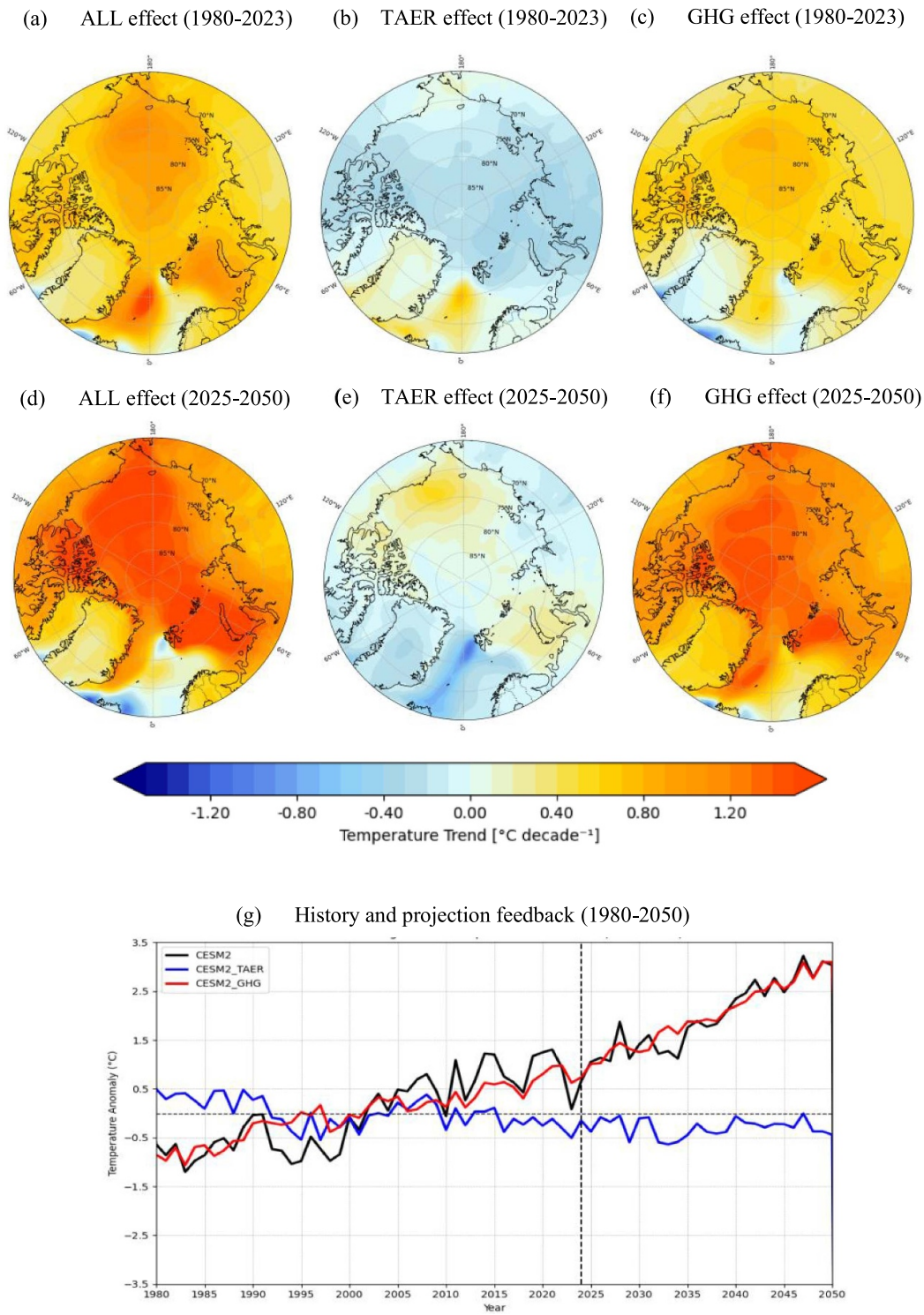

Figure 6. (a)–(d): CESM2-LE NSAT Trend 1980–2023 ((a). ALL, (b). TAER, (c). GHG); (e)–(f): CESM2-LE NSAT Trend 2025–2050 ((d). ALL, (e). TAER, (f). GHG) (g): CESM2-LE NSAT historical and future trends of Arctic temperature under ALL, TAER and GHG.

role (figure 6(a)). Aerosols, however, exhibit a cooling effect in most regions, except for Greenland and northern Europe, where they contribute to warming (figure 6(b)). Future projections indicate that Arctic warming will intensify between 2025 and 2050, with previously notable warming areas expanding to cover northern Canada and the entire central Arctic ice cap (figure 6(e)). GHGs, particularly CO_2, will continue to drive significant warming (figure 6(f)), while aerosols will play a complex role, with some regions experiencing cooling and others warming (figure 6(g)).

From 1980 to 2023, aerosols are projected to decrease Arctic temperatures by approximately 0.25 °C, and by around 0.5 °C by 2050. This cooling effect, though relatively small compared to the warming induced by GHGs, highlights the importance of aerosols in modulating Arctic climate dynamics. The regional differences in aerosol impacts, with some areas experiencing warming and others cooling, warrant further investigation to better understand the underlying mechanisms and improve future climate projections.

4. Conclusion

Using ECMWF reanalysis data (1980–2023), we analyzed Arctic (66.5° N–90° N) and global near-surface temperatures. The Arctic showed twice the temperature variability and warmed 2.7 times faster (0.63 vs 0.23 °C/decade) than global averages, highlighting its exceptional climate sensitivity. This sensitivity is predominantly regulated by GHGs and aerosols. While CO_2 drives 65% of Arctic warming, aerosols contribute 19% through AOD changes. Though smaller in overall impact, aerosol effects are disproportionately strong in the Arctic compared to global averages. These amplified effects are closely tied to aerosol origins and composition. Arctic aerosols mainly originate from mid-latitude transport, with sulfate (SO_2) particularly important for their cooling effect. By modifying cloud properties and surface radiation, these aerosols significantly influence Arctic warming patterns. To assess how these mechanisms may evolve, CESM2 projections indicate continued Arctic warming, primarily driven by GHGs. Future sulfate and BC aerosol impacts may diverge from historical patterns, showing distinct regional effects. These findings underscore that understanding aerosol impacts is crucial for designing Arctic mitigation strategies, particularly focusing on the reduction of short-lived climate pollutants such as BC. Enhanced policy measures targeting aerosol emissions could contribute significantly to slowing Arctic warming.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

We acknowledge support from the National Key R&D Program of China (Grant No. 2022YFFF0802000). This study utilized data from the ERA5 and MERRA-2 reanalysis datasets provided by ECMWF and NASA GMAO, as well as CESM2 ensemble simulations from NCAR. We sincerely thank the two anonymous reviewers for their constructive comments and thoughtful suggestions, which have greatly improved the quality and clarity of this manuscript.

Data and code availability

The ERA5 and MERRA-2 reanalysis datasets used in this study are publicly available from ECMWF and NASA GMAO, respectively. CESM2 Single Forcing Large Ensemble outputs are accessible through the NCAR Earth System Grid. The analysis scripts are available from the corresponding author upon reasonable request.

ORCID iD

Qizhen Sun https://orcid.org/0000-0002-9567-3034

References

Akinyoola J A, Oluleye A and Gbode I E 2024 A review of atmospheric aerosol impacts on regional extreme weather and climate events *Aerosol Sci. Eng.* **8** 249–74

Akritas A G and Malaschonok G I 2004 Applications of singular-value decomposition (SVD) *Math. Comput. Simul.* **67** 15–31

Allen M R and Stott P A 2003 Estimating signal amplitudes in optimal fingerprinting, part I: theory *Clim. Dyn.* **21** 477–91

Barnett L and Seth A K 2014 The MVGC multivariate Granger causality toolbox: a new approach to Granger-causal inference *J. Neurosci. Methods* **223** 50–68

Buchholz R R *et al* 2022 New seasonal pattern of pollution emerges from changing North American wildfires *Nat. Commun.* **13** 2043

Carmichael G R *et al* 2009 Asian aerosols: current and year 2030 distributions and implications to human health and regional climate change *Environ. Sci. Technol.* **43** 5811–7

Carrico C M 2018 Atmospheric aerosols and their measurement *Handbook of Environmental Engineering* (Wiley) pp 493–517

Chen D, Fu M, Liu X and Sun Q 2024a Assessment of Arctic sea ice simulations in cGENIE model and projections under RCP scenarios *Sci. Rep.* **14**

Chen D and Sun Q 2023 Northern Pacific extratropical cyclone variability and its linkage with Arctic sea ice changes *Clim. Dyn.* **61** 5875–85

Chen D and Sun Q 2024 Impact of rapid Arctic sea ice decline on China's crop yield under global warming *Environ. Dev. Sustain.* **26** 1263–80
Chen D, Sun Q and Fu M 2024b Aerosol in the subarctic region impacts on Atlantic meridional overturning circulation under global warming *Clim. Dyn.* **62** 9539–48
Copernicus Atmosphere Monitoring Service (CAMS) 2023 Canadian wildfires in 2023: carbon emissions reach record levels (European Centre for Medium-Range Weather Forecasts (ECMWF)) (available at: https://atmosphere.copernicus.eu/canadian-wildfires-2023-carbon-emissions-reach-record-levels)
Coumou D, Di Capua G, Vavrus S, Wang L and Wang S 2018 The influence of Arctic amplification on mid-latitude summer circulation *Nat. Commun.* **9** 2959
Danabasoglu G *et al* 2020 The community Earth system model version 2 (CESM2) *J. Adv. Model. Earth Syst.* **12** e2019MS001916
Devasthale A, Sedlar J, Tjernström M and Kokhanovsky A 2020 A climatological overview of Arctic clouds *Physics and Chemistry of the Arctic Atmosphere* ed A Kokhanovsky and C Tomasi (Springer) pp 331–60
Draper N R and Smith H 1998 *Applied Regression Analysis* 3rd edn (Wiley)
Efron B and Tibshirani R J 1994 *An Introduction to the Bootstrap* (CRC Press)
Feinberg A, Sukhodolov T, Luo B-P, Rozanov E, Winkel L H E, Peter T and Stenke A 2019 Improved tropospheric and stratospheric sulfur cycle in the aerosol–chemistry–climate model SOCOL-AERv2 *Geosci. Model Dev.* **12** 3863–87
Gelaro R *et al* 2017 The modern-era retrospective analysis for research and applications, version 2 (MERRA-2) *J. Clim.* **30** 5419–54
Granger C W J 1969 Investigating causal relations by econometric models and cross-spectral methods *Econometrica* **37** 424–38
Guo J-P *et al* 2009 Correlation between PM concentrations and aerosol optical depth in eastern China *Atmos. Environ.* **43** 5876–86
He Q, Zhang M and Huang B 2016 Spatio-temporal variation and impact factors analysis of satellite-based aerosol optical depth over China from 2002 to 2015 *Atmos. Environ.* **129** 79–90
Hersbach H *et al* 2020 The ERA5 global reanalysis *Q. J. R. Meteorol. Soc.* **146** 1999–2049
Jansen E *et al* 2020 Past perspectives on the present era of abrupt Arctic climate change *Nat. Clim. Change* **10** 714–21
Kay J E, L'Ecuyer T, Chepfer H, Loeb N, Morrison A and Cesana G 2016 Recent advances in Arctic cloud and climate research *Curr. Clim. Change Rep.* **2** 159–69
Li J *et al* 2022 Scattering and absorbing aerosols in the climate system *Nat. Rev. Earth Environ.* **3** 363–79
Liang Y, Polvani L M and Mitevski I 2022 Arctic amplification, and its seasonal migration, over a wide range of abrupt CO2 forcing *npj Clim. Atmos. Sci.* **5**
Liu X, Penner J E and Herzog M 2005 Global modeling of aerosol dynamics: model description, evaluation, and interactions between sulfate and nonsulfate aerosols *J. Geophys. Res.* **110**
Moschos V, Dzepina K, Bhattu D, Lamkaddam H, Casotto R, Daellenbach K R and Baltensperger U 2022 Equal abundance of summertime natural and wintertime anthropogenic Arctic organic aerosols *Nat. Geosci.* **15** 196–202
Mosedale T J, Stephenson D B, Collins M and Mills T C 2006 Granger causality of coupled climate processes: ocean feedback on the North Atlantic Oscillation *J. Clim.* **19** 1182–94
Pan H, Huang J, Kumar K R, An L and Zhang J 2022 The CALIPSO retrieved spatiotemporal and vertical distributions of AOD and extinction coefficient for different aerosol types during 2007–2019: a recent perspective over global and regional scales *Atmos. Environ.* **274** 118986
Ranjan A K, Patra A K and Gorai A K 2021 A review on estimation of particulate matter from satellite-based aerosol optical depth: data, methods, and challenges *Asia-Pac. J. Atmos. Sci.* **57** 679–99
Rantanen M, Karpechko A Y, Lipponen A, Nordling K, Hyvärinen O, Ruosteenoja K, Vihma T and Laaksonen A 2022 The Arctic has warmed nearly four times faster than the globe since 1979 *Commun. Earth Environ.* **3** 168
Sayer A M *et al* 2020 A review and framework for the evaluation of pixel-level uncertainty estimates in satellite aerosol remote sensing *Atmos. Meas. Tech.* **13** 373–404
Schmale J, Zieger P and Ekman A M L 2021 Aerosols in current and future Arctic climate *Nat. Clim. Change* **11** 95–105
Screen J A and Simmonds I 2010 The central role of diminishing sea ice in recent Arctic temperature amplification *Nature* **464** 1334–7
Seinfeld J H *et al* 2016 Improving our fundamental understanding of the role of aerosol-cloud interactions in the climate system *Proc. Natl Acad. Sci.* **113** 5781–90
Serreze M C and Barry R G 2011 Processes and impacts of Arctic amplification: a research synthesis *Glob. Planet. Change* **77** 85–96
Shu Q, Wang Q, Årthun M, Wang S, Song Z, Zhang M and Qiao F 2024 Arctic Ocean amplification in a warming climate in CMIP6 models *Sci. Adv.* **8** eabn9755
Shupe M D and Intrieri J M 2004 Cloud radiative forcing of the Arctic surface: the influence of cloud properties, surface albedo, and solar zenith angle *J. Clim.* **17** 616–28
Solomon S, Plattner G-K, Knutti R and Friedlingstein P 2009 Irreversible climate change due to carbon dioxide emissions *Proc. Natl Acad. Sci.* **106** 1704–9
Swingedouw D, Colin C, Eynaud F, Ayache M and Zaragosi S 2019 Impact of freshwater release in the Mediterranean Sea on the North Atlantic climate *Clim. Dyn.* **53** 3893–15
Tian P *et al* 2017 Aerosol vertical distribution and optical properties over China from long-term satellite and ground-based remote sensing *Atmos. Chem. Phys.* **17** 2509–23
Vincent W F 2020 Arctic climate change: local impacts, global consequences, and policy implications *The Palgrave Handbook of Arctic Policy and Politics* ed K S Coates and C Holroyd (Springer) pp 507–26
Willis M D, Leaitch W R and Abbatt J P D 2018 Processes controlling the composition and abundance of Arctic aerosol *Rev. Geophys.* **56** 621–71
Wobus C, Flanner M, Sarofim M C, Moura M C P and Smith S J 2016 Future Arctic temperature change resulting from a range of aerosol emissions scenarios *Earth's Future* **4** 270–81
Zhang S, Wu J, Fan W, Yang Q and Zhao D 2020 Review of aerosol optical depth retrieval using visibility data *Earth Sci. Rev.* **200** 102986
Zhao M, Cao L, Bala G and Duan L 2021 Climate response to latitudinal and altitudinal distribution of stratospheric sulfate aerosols *J. Geophys. Res.* **126** e2021JD035379