



A recurrent rapid North Atlantic transport pathway facilitates Saharan dust delivery to the Arctic

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Abstract.

Mineral dust can be transported from lower latitudes to the Arctic across the North Atlantic pathway. It remains unclear whether this rapid Saharan dust transport pathway is isolated or recurrent into the high Arctic. Here, we investigate the rapid pathway using a March 2022 Arctic dust intrusion as a case study, combining GEOS-Chem simulations, satellite observations and long term HYSPLIT trajectories. GEOS-Chem simulation results indicate that, over the Svalbard, emissions from Africa account for more than 95% of the simulated total aerosol optical depth (AOD) for coarse-mode dust. During the event, mean total dust AOD increased to 3.8 times its pre-event background level. Coarse dust AOD increased more strongly, reaching 9.0 times its background level. Satellite observations show enhanced large-mode and nonspherical aerosol signatures near Svalbard. HYSPLIT analysis reveals a recurring North Atlantic transport pathway between 2005 and 2025. Along this rapid pathway, its relative contribution compared with European continental pathway into the Arctic increases toward higher latitudes, accounting for 25.5% of trajectories reaching 66°N and more than 50% of those reaching 80°N. This pathway also enters the Arctic at lower altitude and with warmer, more humid air than the European continental pathway. Besides, dust poleward transport is negatively correlated with the North Atlantic Oscillation, confined to specific season, February and March. These results identify a recurrent rapid North Atlantic transport pathway linking Saharan dust sources with the Arctic, with potential influence on Arctic mixed-phase clouds and climate.

1 Introduction

The Arctic atmosphere is strongly influenced by air masses transported from lower latitudes, including aerosols that can modify the regional energy balance and cloud properties (Bony et al., 2006; Soden and Held, 2006; Stone et al., 2007; Taylor et al., 2013; Graversen et al., 2014; Philipp et al., 2020). Mineral dust is among the most important aerosol species because it both absorbs and scatters radiation and acts as an efficient ice-nucleating particle (INP), thereby influencing the phase, lifetime, and radiative properties of Arctic mixed-phase clouds (DeMott et al., 2003). Remote deserts, particularly the Sahara, are major external sources of Arctic mineral dust (Kok et al., 2021; Breider et al., 2014), especially during spring when poleward transport from the midlatitudes is most active (Groot Zwaartink et al., 2016). The climatic influence of these transport events therefore depends not only on how much dust reaches the Arctic, but also on how rapidly, and in what particle-size and mineralogical form, it is delivered.



Transport time is a key factor controlling which mineral dust particles survive long-range transport to the Arctic. Coarse particles experience much stronger gravitational settling than fine aerosols and are therefore less likely to survive slow long-range transport. Saharan mineral dust is of particular interest since it contains K-feldspar-bearing particles, which are among the most efficient atmospheric ice-nucleating particle (INP) components (Atkinson et al., 2013). Arctic mixed-phase clouds are especially sensitive to variations in INP supply, and recent observations show that Saharan dust outbreaks can produce substantially higher INP concentrations than non-Saharan aerosol populations at mixed-phase cloud temperatures (Ansmann et al., 2023; Patnaude et al., 2025). Rapid transport may therefore increase the probability that these coarse, ice-active particles reach the Arctic before gravitational removal.

Saharan dust reaches Europe and the Arctic through multiple transport pathways, including westward export across the Atlantic, transport into the Mediterranean, advection toward northern Europe, and episodic poleward transport over the North Atlantic (Kok et al., 2021; Groot Zwaaftink et al., 2016). Among these pathways, rapid North Atlantic intrusions have attracted increasing attention because favorable synoptic conditions can transport Saharan dust to high latitudes within only a few days (Francis et al., 2018, 2022; Varga et al., 2021). These studies have substantially improved our understanding of individual rapid-transport events and their meteorological drivers. They also provide a foundation for investigating broader characteristics of the rapid pathway, including its geographical source dependence, recurrence across years and source regions, and its relationship with large-scale atmospheric circulation.

Here we combine source-restricted GEOS-Chem simulations with satellite observations to characterize the March 2022 rapid transport event and identify its transport characteristics. We then use a full-Sahara HYSPLIT trajectory experiment to examine the recurrence of the pathway across different Saharan source regions and multiple years. Finally, we combine Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis with the North Atlantic Oscillation (NAO) index to investigate the large-scale circulation associated with rapid Saharan dust transport to the Arctic.

2 Data and Methods

2.1 GEOS-Chem simulations and dust diagnostics

The GEOS-Chem global chemical transport model (version 13.4.0, Bey et al. (2001)), driven by MERRA-2 meteorological fields (Gelaro et al., 2017), is used to simulate the March 2022 dust event. Simulations are performed at $2^\circ \times 2.5^\circ$ horizontal resolution with 47 vertical levels using the aerosol-only configuration and are integrated from January 2021 through May 2022. Dust emissions are calculated online using the Dust Entrainment and Deposition (DEAD) mobilization scheme (Zender et al., 2003) together with the Goddard Chemistry Aerosol Radiation and Transport (GOCART) source function (Chin et al., 2004; Ginoux et al., 2001). Two paired simulations are conducted under identical meteorological fields, model configuration, and integration period. The GLOBAL simulation includes dust emissions from all source regions, whereas the AFRICA simulation retains emissions only within 20°W – 54°E and 37°S – 40°N , with emissions elsewhere set to zero. Daily 00:00 UTC output is used for the event analyses.



Total dust aerosol optical depth (AOD) is calculated as the sum of archived dust bins 1–7, and coarse dust AOD as the sum of bins 5–7 (particle diameter $>1\ \mu\text{m}$). The modeled African contribution is diagnosed as the ratio of AFRICA to GLOBAL dust AOD for both total and coarse dust. To characterize changes in particle-size distribution, the coarse-to-total dust AOD fraction is calculated as coarse dust AOD divided by total dust AOD and compared between the background period (1–13 March) and the event period (15–21 March 2022). Because this quantity is based on AOD, it represents the relative optical contribution of coarse dust rather than particle number or mass fraction.

2.2 Satellite Observations

The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) and Multi-angle Imaging SpectroRadiometer (MISR) products are used to provide independent observational constraints on the March 2022 event. CALIOP Level-2 Vertical Feature Mask and 5-km Aerosol Profile Version 4.51 products are sampled along representative segments on 14, 15, and 19 March 2022. Aerosol subtype information is obtained from the feature mask, while the corresponding 532-nm total backscatter coefficient is taken from the aerosol-profile product (Kim et al., 2018). The selected curtains represent successive observations along the candidate source-to-Arctic region. MISR Version 23 aerosol retrievals provide an independent constraint in the Arctic Svalbard area. Retrievals are collocated with the selected Arctic area sampling using $\pm 1^\circ$ spatial and $\pm 6\ \text{h}$ temporal criteria. The product provides AOD_{550} and fractional contributions from nonspherical and large-mode aerosol components (Garay et al., 2020). A conservative large-plus-nonspherical indicator is calculated for each pixel as the smaller of large-mode AOD and nonspherical AOD divided by total AOD. These properties are interpreted as being consistent with coarse mineral dust but are not treated as a unique source attribution.

2.3 Full-Sahara HYSPLIT Trajectory Analysis

To evaluate the source-region dependence, recurrence, and preferred transport pathways of rapid Saharan dust transport toward the Arctic without relying on a single release point, we perform a full-Sahara forward-trajectory experiment using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler and Hess, 1998). A regular 2° grid comprising 286 release locations spans 15°N – 35°N and 15°W – 35°E , providing broad coverage of the major Saharan source region. Trajectories are initialized daily at 00:00 UTC during March of each year from 2005 to 2025, with a starting height of 1000 m above ground level, and are integrated forward for 120 h using 1° Global Data Assimilation System (GDAS) meteorological fields. Trajectory endpoints and associated meteorological variables are recorded hourly. For each release location and date, we define the air mass as having reached the Arctic as long as at least one point along its trajectory reaches or exceeds 66°N within 120 h. The Arctic-reaching density is then calculated as the number of successful trajectories divided by the total number of quality-controlled releases from that location.

To characterize the major transport pathways connecting the Sahara with the Arctic, all trajectories reaching 66°N within 120 h are further classified according to the location at which they first cross 50°N . Trajectories whose first 50°N crossing occurs west of 0° longitude are assigned to the North Atlantic (NA) branch, representing predominantly oceanic transport through the North Atlantic sector, whereas trajectories crossing 50°N at or east of 0° are assigned to the European continental



(EU) branch. This branch definition provides a consistent geographical criterion for separating the two dominant northward transport routes before they enter the Arctic. The same classification is applied to trajectories reaching progressively higher latitude thresholds of 66°, 70°, 75°, and 80°N within 120 h. At each threshold, the relative contribution of the NA and EU branches is calculated as the fraction of Arctic-reaching trajectories assigned to each branch. This analysis quantifies how the relative importance of the two transport pathways changes as trajectories penetrate progressively farther into the Arctic.

To further characterize the atmospheric conditions under which the two pathways enter the Arctic, meteorological variables sampled by HYSPLIT directly from the GDAS meteorological fields along each trajectory are extracted, including relative humidity, specific humidity, air temperature, and trajectory height.

2.4 Rapid North Atlantic pathway and the North Atlantic Oscillation

To describe how efficiently Saharan dust is transported polarward along the North Atlantic pathway, we compare the dust loading near the entrance of the pathway with that farther north. We define the pathway entrance as a narrow latitude band at 39–40°N, where dust transported from the Sahara enters the North Atlantic pathway. The downstream region extends from 40 to 70°N and represents the region through which dust is subsequently transported toward the Arctic. Both regions are restricted to 40°W–5°E, following the North Atlantic transport corridor identified in our trajectory analysis.

We then define a dust transport ratio as

$$R_{DT} = \frac{AOD_{40-70^{\circ}N}}{AOD_{39-40^{\circ}N}}, \quad (1)$$

where the $AOD_{40-70^{\circ}N}$ is the mean dust AOD over the downstream North Atlantic region (40–70°N) and the $AOD_{39-40^{\circ}N}$ is the mean dust AOD near the pathway entrance (39–40°N). This ratio compares how much dust is found farther north with how much dust is available at the entrance of the pathway. This indicator allows us to compare the strength of northward Saharan dust transport with the NAO index and to test whether different NAO conditions are associated with more or less efficient dust transport along the North Atlantic pathway. Monthly dust AOD is obtained from MERRA-2 (Gelaro et al., 2017), and monthly NAO indices are obtained from the NOAA Climate Prediction Center.

3 Results

3.1 March 2022 Event: Enhanced coarse-dust contribution during Arctic transport

The GEOS-Chem GLOBAL simulation reproduces the evolution of the March 2022 Saharan dust outbreak (Fig.1a). Dust emissions intensified over northern Africa during 14–16 March and were transported northward across the eastern Atlantic and western Europe. By 19 March, enhanced dust AOD extended into the Norwegian Sea and the European Arctic, reaching the Svalbard area. The event gradually weakened after 21 March as the plume dispersed over the Arctic Ocean.

Comparison between the GLOBAL and AFRICA simulations shows that the Arctic dust enhancement is associated with African emissions (Fig.1a–d). On 19 March, the Africa-only simulation reproduces nearly the entire dust plume over the North Atlantic and European Arctic. Within the Svalbard area, African emissions accounts for 95.2% of the total dust AOD during



the event period (15–21 March) and 98.0% on the peak day (20 March), indicating that the simulated Arctic dust enhancement is dominated by African sources (Fig.1e and f).

The event is also characterized by a marked increase in the relative contribution of coarse dust aerosol. Relative to the background period (1–13 March), total dust AOD over the Svalbard area increases by a factor of 3.8 during the event, whereas coarse dust AOD increases by a factor of 9.0. Consequently, the coarse-to-total dust AOD fraction increases from 3.56% to 8.39%, reaching 2.35 times its background value. This enhancement is dominated by African dust emissions. The African contribution to coarse dust AOD increases from 61.0% during the background period to 95.4% during the event and reaches 98.9% on the peak day. These results indicate that the March 2022 event not only increases dust loading over the Arctic but also substantially shifts the dust size distribution toward a greater coarse-particle contribution.

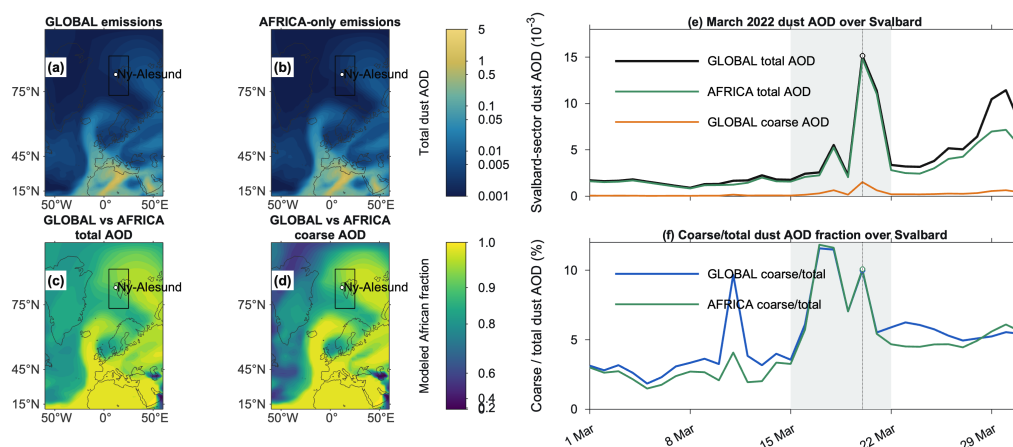


Figure 1. GEOS-Chem simulation of the Arctic dust event in March 2022. (a) Total dust AOD from the GLOBAL emission simulation on 19 March 2022, shown on a logarithmic color scale. (b) Corresponding total dust AOD from the AFRICA-only emission simulation. (c) Modeled African contribution to total dust AOD, calculated as the ratio between AFRICA-only and GLOBAL-only. (d) Simulated African contribution to coarse dust AOD, calculated from the corresponding coarse-mode AOD ratio. The black box in Figure a to d marks the Svalbard area (5–25°E, 74–82°N), and the white point denotes Ny-Ålesund. (e) Time series of dust AOD over the Svalbard area during March 2022. Black, green, and orange lines show GLOBAL total dust AOD, AFRICA-only total dust AOD, and GLOBAL coarse dust AOD, respectively. (f) Time series of the GLOBAL (blue) and AFRICA-only (green) coarse-to-total dust AOD fraction over the Svalbard area during March 2022. The shaded interval indicates the main event period (15–21 March), and the vertical line marks the peak day (20 March).

3.2 Satellite Observations Supporting the Event Evolution

Satellite observations provide an independent evaluation of the simulated transport pathway and aerosol characteristics during the March 2022 event. Based on the simulated event evolution, CALIOP overpasses were selected over the Saharan source region on 14 March (Fig.2a), the eastern North Atlantic on 15 March (Fig.2b), and the northern North Atlantic on 19 March



135 (Fig.2c). The CALIOP Vertical Feature Mask classified the observed aerosol layers at these locations as dust or dust-related
 aerosol types. These observations represent different stages of the simulated transport pathway rather than continuous tracking
 of a single air mass, but together they are consistent with the modeled northward progression of the dust intrusion. Near the
 Arctic endpoint, independent information on aerosol properties is provided by MISR observations over the Svalbard region
 during 20 - 21 March (Fig.2d). The retrievals show enhanced nonspherical and large-mode aerosol fractions (0.627 and 0.333,
 140 respectively), together with a mean AOD of 0.210, consistent with the presence of coarse mineral dust near Svalbard. Figure
 2e summarizes the locations of these satellite observations relative to the simulated dust transport pathway, illustrating their
 spatial correspondence with successive stages of the event.

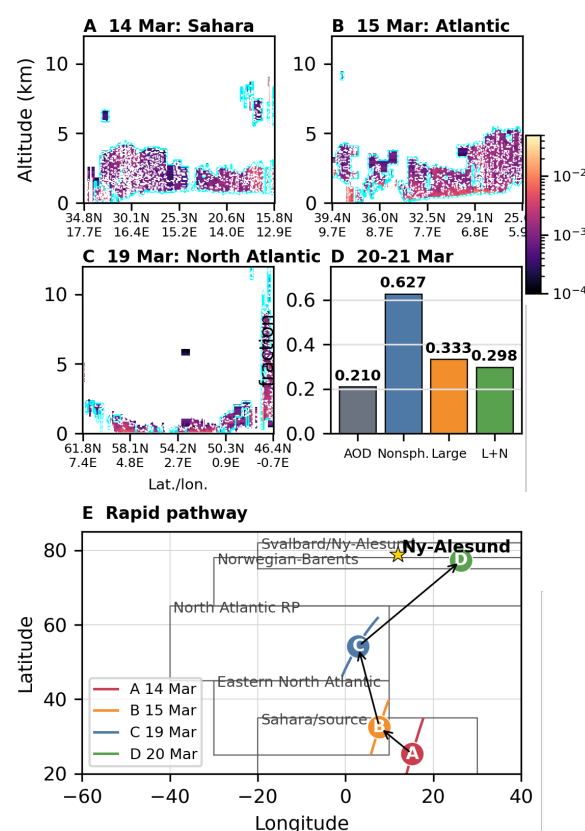


Figure 2. Satellite observations of the March 2022 aerosol intrusion. (a–c) Selected CALIOP V4.51 overpasses sampled successive stages of the event over the Saharan source region on 14 March, the eastern North Atlantic on 15 March, and the northern North Atlantic on 19 March. The colorbar denotes the 532-nm total backscatter coefficient from the 5-km Aerosol Profile product, with aerosol subtype information from the Vertical Feature Mask product. (d) MISR Version 23 retrievals in the Svalbard sector during 20–21 March, summarized from three swaths and 105 collocated pixels. (e) Locations of the selected CALIOP overpasses and the Arctic MISR retrievals.



3.3 Spatial Variability and Recurrence of Arctic-Reaching Transport

The dust intrusion in March 2022 demonstrates that Saharan dust can rapidly reach the Arctic, but its broader significance depends on whether similar transport recurs under different source locations and atmospheric conditions. To address this question, we extend the analysis using a full-Sahara HYSPLIT trajectory experiment covering March 2005–2025 (Method in Sec.2.3). The results show that five-day Arctic accessibility is strongly dependent on release location (Fig. 3a, b). Among all trajectories, those originating from the northern Sahara are most likely to reach the Arctic region (north of 66°N). In contrast, trajectories released from the central and southern Sahara rarely reach 66°N within 120 hours (Fig. 3b).

Across all 186,186 trajectories, 2,135 reach 66°N within five days. Among these trajectories, 545 (25.5%) follow the North Atlantic (NA) branch and 1,590 (74.5%) follow the European continental (EU) branch (Fig. 3c). Although lower frequent than the EU branch, the NA branch forms a distinct and recurrent transport pathway linking northwestern Africa with the Arctic. The trajectory-density fields show that the NA branch crosses the eastern North Atlantic before turning poleward, whereas the EU branch propagates through the Mediterranean and continental Europe.

Both the number of Arctic-reaching trajectories and their route composition vary substantially from year to year (Fig. 3d). The dust intrusion in March 2022 falls within the range of previously sampled transport configurations rather than representing an exceptional event. The trajectory experiment therefore demonstrates recurrence of the North Atlantic pathway but provides no evidence for a long-term increase in its occurrence. Recurrence of the pathway also does not imply equally frequent or equally intense dust transport in every year.

Additional diagnostics further distinguish the two transport branches (Fig. 3e, f). The fraction of trajectories assigned to the NA branch increases from 25.5% at 66°N to 30.3% at 75°N, exceeding 50% at 80°N. This pattern indicates that the NA branch becomes increasingly important for transport into the higher Arctic. In addition, the two branches differ in the thermodynamic properties of the air masses entering the Arctic. At 66°N, relative humidity is nearly identical between the two pathways (86.3% and 86.9%, respectively). However, air masses transported along the North Atlantic pathway reach this latitude at a lower altitude than those following the European continental pathway (5.13 km vs. 6.58 km) and exhibit substantially higher specific humidity (1.30 g kg⁻¹ vs. 0.63 g kg⁻¹). Together with their higher temperature, these results indicate that the North Atlantic pathway transports Saharan dust into the Arctic within a lower-altitude, warmer, and moister air mass than the European continental pathway.

3.4 Seasonal window for the rapid North Atlantic pathway

The HYSPLIT experiment shows that the North Atlantic pathway recurs throughout the study period, raising the question of what large-scale atmospheric conditions favor its occurrence. The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric variability over the North Atlantic and strongly influences the strength of the westerlies and meridional air exchange. During its negative phase, weakened zonal flow and enhanced meridional exchange generally favor poleward transport from the subtropical North Atlantic toward the Arctic. We therefore examine whether variability in the rapid North Atlantic pathway is associated with the NAO.

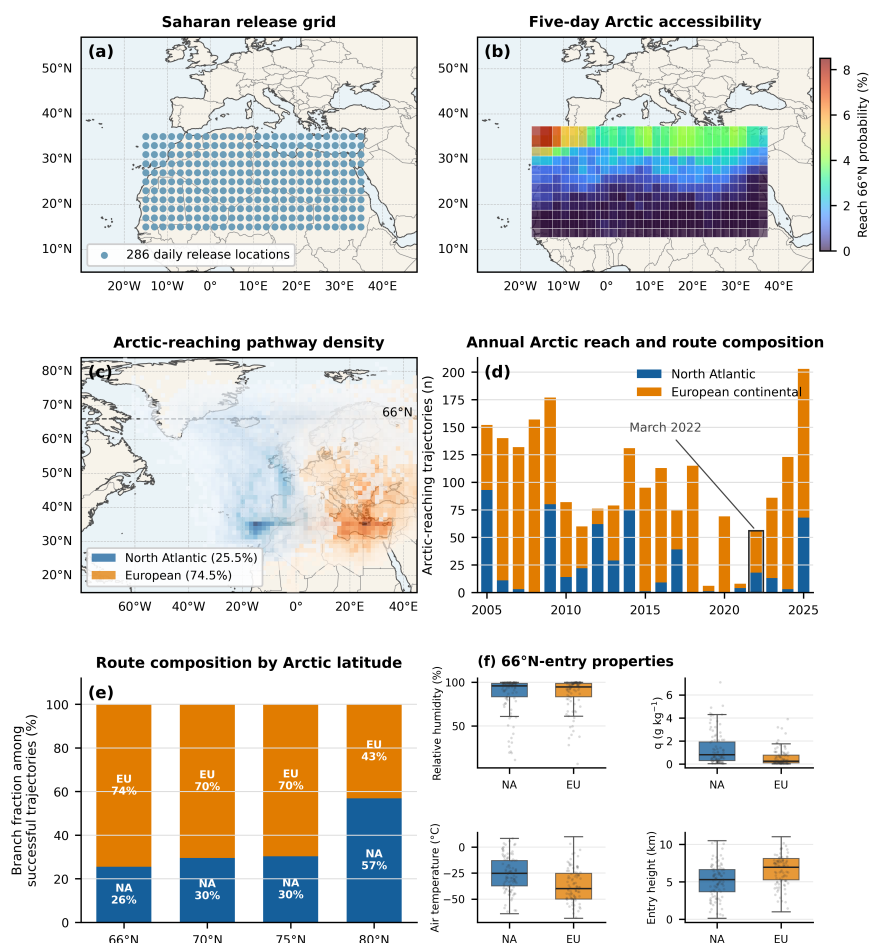


Figure 3. (a) The 286 daily release locations on the $2^\circ \times 2^\circ$ Saharan grid. (b) Probability that trajectories released from each grid cell reach 66°N within 120 h during March 2005–2025. (c) Density of all trajectories reaching 66°N within 120 h, classified into the North Atlantic and European continental branches according to the longitude of their first crossing of 50°N (west of 0° for the North Atlantic branch and east of or at 0° for the European continental branch). (d) Annual number and branch composition of trajectories reaching 66°N within 120 h. (e) Fraction of trajectories assigned to each branch among all trajectories reaching the specified latitude threshold (%) of 66°, 70°, 75°, and 80°N within 120 h. (f) Relative humidity, specific humidity, air temperature, and trajectory height at the point reaching 66°N for the North Atlantic (NA) and European continental (EU) branches (Method Sec.2.3).



To quantify transport along the pathway, we define a regional dust transport ratio (R_{DT}) using MERRA-2 dust AOD. The relationship between R_{DT} and the NAO exhibits pronounced seasonality. Although negative correlations occur in most months, only February ($r = -0.447$) and March ($r = -0.425$) remain statistically significant (Fig. 4a). To test whether these relationships could arise from common long-term changes in the NAO and R_{DT} , we repeated the analysis after removing linear trends from both variables. The March correlation remains essentially unchanged after detrending ($r = -0.430$), indicating that the relationship primarily reflects interannual covariability rather than a shared long-term trend.

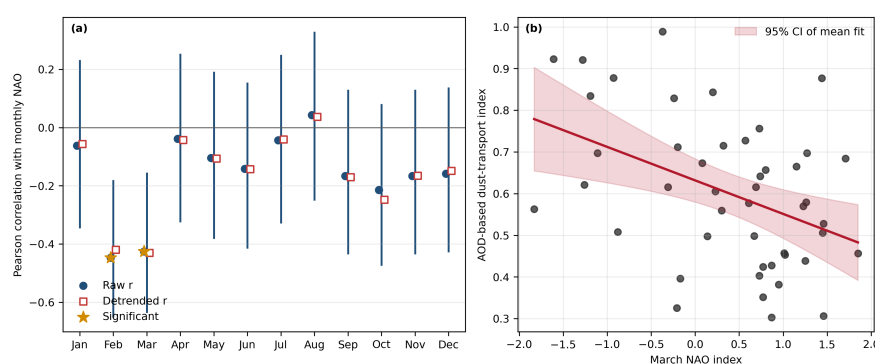


Figure 4. Monthly dust-transport relationships with the North Atlantic Oscillation (NAO). (a) Pearson correlation between the normalized monthly dust transport ratio (Method 2.4) and the corresponding monthly NAO index during 1980–2025. Filled circles show raw correlations, open squares show correlations after linear detrending, vertical lines show 95% confidence intervals, and stars identify months significant correction. (b) March normalized dust transport ratio versus March NAO, with linear regression and the 95% confidence interval of the mean fit. The March relationship is $r = -0.425$ ($p = 0.0032$), remains $r = -0.430$ after detrending.

The rapid North Atlantic pathway therefore appears to be associated with a distinct late-winter to early-spring window rather than representing either an isolated March event or a year-round transport regime. This timing coincides with the seasonal increase in northward Saharan dust activity toward Europe and the North Atlantic during spring, with recent climatological analyses identifying March as a particularly active month for Saharan dust intrusions into Europe (Merdji et al., 2023; Ilieva et al., 2025). The NAO, meanwhile, exerts strong control on the strength and position of the North Atlantic jet and storm tracks and thereby reorganizes large-scale zonal and meridional atmospheric transport (Hurrell, 1995). Our significant negative correlations in February and March indicate that, specifically for the North Atlantic pathway identified here, more negative NAO conditions are associated with circulation states that more efficiently transfer Saharan dust from the subtropical North Atlantic toward higher latitudes. The February–March maximum may therefore reflect a seasonal coincidence between increasing Saharan dust availability and NAO-related circulation configurations favorable for rapid poleward transport. This interpretation is consistent with the recurrent trajectory pathway identified independently by the HYSPLIT analysis. The quantitative contribution of this pathway to the total Saharan dust burden in the Arctic, however, remains uncertain and will require additional observational constraints.



195 4 Discussion

4.1 Will Rapid North Atlantic Transport Become More Favorable in a Warming Climate?

An important question raised by this study is whether rapid Saharan dust transport to the Arctic may become more frequent under continued global warming. Arctic amplification has been proposed to modify northern hemisphere atmospheric circulation through changes in the jet stream, planetary-wave propagation, and blocking frequency, potentially favoring stronger meridional exchanges between mid-latitudes and the Arctic (Francis and Vavrus, 2012; Cohen et al., 2020). Such circulation changes could increase opportunities for rapid poleward transport from North Africa. However, this hypothesis remains debated. Other studies argue that observational evidence for systematic circulation changes is weak and that long-term trends in large-scale circulation indices such as the NAO remain small or statistically insignificant (Barnes, 2013; Screen and Blackport, 2019).

Our results provide additional evidence relevant to this discussion. The dust transport ratio exhibits a significant relationship with the NAO only during February and March, indicating that the influence of large-scale circulation on Saharan dust transport is strongly season dependent. This seasonality is physically plausible. February and March coincide with active Saharan dust emissions, an active North Atlantic storm track, and frequent meridional exchanges, providing favorable conditions for rapid poleward transport. Outside this late-winter period, these factors become progressively less synchronized, weakening the circulation–transport relationship.

More broadly, our results suggest that the influence of Arctic amplification on atmospheric circulation may not be best evaluated using annual or year-round averages alone. Previous studies have emphasized that the atmospheric response to Arctic amplification is highly season dependent and can vary substantially among circulation regimes, contributing to the continuing debate over whether Arctic warming systematically alters midlatitude circulation (Barnes and Screen, 2015; Screen and Blackport, 2019; Cohen et al., 2020). The distinct February–March transport window identified here suggests that focusing on dynamically active seasons may provide a more sensitive framework for detecting future circulation changes associated with Arctic warming.

4.2 Why Rapid Transport Matters?

The importance of the rapid pathway lies not simply in transporting Saharan dust to the Arctic, but in transporting it within only a few days. Gravitational settling, turbulent mixing, and wet scavenging continuously remove coarse mineral dust during long-range transport. A transport timescale of approximately five days therefore substantially reduces the time available for these removal processes compared with slower transport pathways. Consistent with this interpretation, the March 2022 event is accompanied by an increase in the simulated coarse-dust AOD fraction together with enhanced large-mode and nonspherical aerosol signatures observed by MISR near Svalbard. These independent observations support the interpretation that rapid transport increases the probability that coarse mineral dust survives transport to high latitudes.

To examine whether the observed shift toward a larger coarse-dust contribution could also influence Arctic cloud radiation, we performed event-specific sensitivity experiments using the Community Atmosphere Model Single Column Model (SCAM). Only the initial partitioning between fine- and coarse-mode dust AOD is varied, while the total initial dust AOD and the

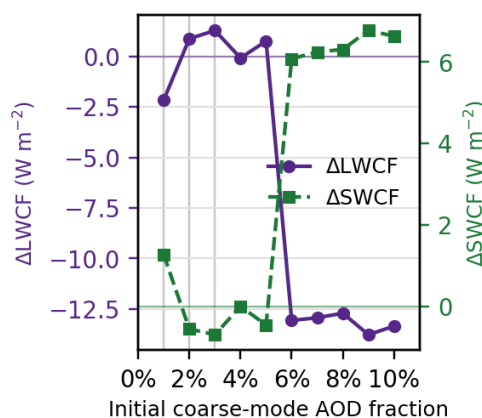


Figure 5. SCAM-simulated cloud radiative response to dust AOD partitioning. The horizontal axis shows the prescribed initial coarse-mode dust AOD fraction, expressed as a percentage of the total dust AOD. The vertical axes show the changes in longwave cloud radiative forcing (LWCF, left axis) and shortwave cloud radiative forcing (SWCF, right axis) relative to the control state. The control state is defined as the mean of the simulations with fine-mode AOD fractions of 97–99%, corresponding to coarse-mode fractions of 1–3%. Solid purple circles denote ΔLWCF , and dashed green squares denote ΔSWCF . The total initial dust AOD was kept approximately constant among the experiments, while the aerosol size partitioning was varied. The simulations used the relaxed event-specific Ny-Ålesund IOP for the March 2022 Sahara dust intrusion (Model details see Appendix A).

remaining meteorological, surface, and aerosol background conditions are kept approximately unchanged (Detailed model settings are provided in the Appendix). The prescribed coarse-mode AOD fraction ranges from 1% to 10%, spanning the change simulated by GEOS-Chem from a background coarse-dust AOD fraction of 3.56% to an event-period value of 8.39%.

The SCAM experiments indicate a nonlinear cloud-radiative sensitivity to this change in dust size partitioning (Fig. 5). Relative to the control state, defined as the mean of the simulations with coarse-mode fractions of 1–3%, simulations with coarse-mode fractions of approximately 6–10% produced a decrease in longwave cloud radiative forcing (LWCF) of approximately 13 W m^{-2} and an increase in shortwave cloud radiative forcing (SWCF) of approximately 6 W m^{-2} . These changes correspond to a weakening of the cloud longwave greenhouse effect together with a partial reduction in the shortwave cooling effect, yielding a combined cloud-radiative anomaly of approximately -7 W m^{-2} .

The abrupt response emerging near a coarse-mode fraction of approximately 5–6% further suggests that the modeled cloud-radiative response is nonlinear rather than proportional to the imposed change in aerosol size distribution. These simulations are not intended to reproduce or attribute the total radiative effect of the March 2022 dust event. Instead, they isolate the sensitivity of the modeled cloud-radiative response to the shift in dust size distribution and indicate that a change within the range simulated during the observed event is sufficient to produce a substantial radiative response under the prescribed meteorological conditions.



Besides, unlike continental transport through Europe, the North Atlantic pathway is associated with persistent transport over the ocean, where air masses may acquire relatively warm, moist marine characteristics together with increased sea-salt aerosol, while experiencing less influence from continental anthropogenic aerosols such as sulfate (Quinn et al., 2022; Schmale et al., 2021). Consequently, rapid transport may alter not only the size distribution of dust reaching the Arctic but also the thermodynamic environment and aerosol mixture encountered by Arctic clouds. Such changes have the potential to influence cloud formation through multiple pathways, including aerosol hygroscopicity, cloud condensation nuclei, and ice-nucleating particles (Atkinson et al., 2013; Kanji et al., 2017). Future work combining source-tagged dust simulations, mineralogical observations, and Arctic cloud-process measurements will be required to determine whether rapid transport measurably alters mixed-phase cloud evolution and regional radiation.

5 Conclusions

We identify a recurring North Atlantic rapid pathway that transports Saharan dust to the Arctic. During the dust intrusion in March 2022, GEOS-Chem simulations attribute more than 95% of both total and coarse dust aerosol optical depth (AOD) over the Svalbard area to African emissions. Satellite observations from CALIOP and MISR independently support the simulated transport pathway and the occurrence of the Arctic dust intrusion.

The event was characterized by a pronounced enhancement of coarse dust. Relative to the background period, total dust AOD increased by a factor of 3.8, whereas coarse dust AOD increased by a factor of 9.0, with the coarse-dust AOD fraction increasing to 2.35 times its background value. Together, the simulations and satellite observations suggest that rapid transport favors the delivery of a larger coarse-particle contribution to the Arctic.

Sahara-wide HYSPLIT trajectory experiments show that the North Atlantic rapid pathway recurs throughout 2005–2025 and mainly originates from the northern and northwestern Sahara. Although it accounts for only about one quarter of Arctic-reaching trajectories at 66°N, its relative contribution increases toward higher Arctic latitudes. Compared with the European continental pathway, the North Atlantic rapid pathway also delivers dust within warmer, more moisture-rich lower-tropospheric air masses. Finally, a regional dust transport ratio is significantly associated with the NAO only during February and March, identifying a distinct late-winter window favorable for rapid Saharan dust transport. These results suggest that future changes in Arctic dust transport should be considered in the context of seasonally dependent atmospheric circulation and their potential influence on the cloud-relevant properties of mineral dust reaching the Arctic.

Data availability. The CALIOP data used in this study are available from the NASA Langley Atmospheric Science Data Center (ASDC) through NASA Earthdata. The analysis uses the CALIPSO Level-2 Vertical Feature Mask product (CAL_LID_L2_VFM-Standard-V4-51), available at https://search.earthdata.nasa.gov/search?q=CAL_LID_L2_VFM-Standard-V4-51, and the CALIPSO Level-2 5-km Aerosol Profile product (CAL_LID_L2_05kmAPro-Standard-V4-51). The specific CALIOP granules analyzed in this study correspond to 14, 15, and 19 March 2022, , available at https://search.earthdata.nasa.gov/search?q=CAL_LID_L2_05kmAPro-Standard-V4-51.



MISR Version 23 aerosol retrievals (MIL2ASAE) are available through NASA Earthdata at <https://search.earthdata.nasa.gov/search?q=MIL2ASAE>.

The MERRA-2 data used for the dust-transport analysis are from the monthly aerosol diagnostics collection M2TMNXAER (Version 5.12.4), specifically the 550-nm dust extinction aerosol optical thickness variable DUEXTTAU, available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) at https://disc.gsfc.nasa.gov/datasets/M2TMNXAER_5.12.4/summary.

The monthly North Atlantic Oscillation (NAO) index is available from the NOAA Climate Prediction Center at <https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>.

The processed GEOS-Chem outputs, HYSPPLIT trajectory products, plotting scripts, processed figure data, and supporting documentation required to reproduce the results presented in this study are publicly available from Zenodo under the Creative Commons Attribution 4.0 International (CC BY 4.0) license at <https://doi.org/10.5281/zenodo.21787750> (Ji and Sun, 2026). CALIOP, MISR, and MERRA-2 products are publicly available through NASA Earthdata and require a free Earthdata Login for data access.

Appendix A: SCAM Dust AOD-Partition Sensitivity Experiments

A1 Model configuration

To investigate the sensitivity of Arctic cloud radiative properties to the particle-size distribution of transported Saharan dust, we performed a series of single-column simulations using the Community Atmosphere Model Single Column Model (SCAM). The simulations were driven by an event-specific Ny-Ålesund intensive observation period (IOP) constructed for the March 2022 Saharan dust intrusion. The same thermodynamic, dynamical, surface, and aerosol background conditions were used in all sensitivity experiments.

The model was run with the SCM relaxation option enabled (`scm_relaxation = .true.`). Relaxation was applied to constrain the large-scale thermodynamic environment and reduce the accumulation of spurious drift among the sensitivity simulations. This configuration allows the cloud and radiative responses to changes in aerosol size partitioning to be evaluated under approximately consistent meteorological conditions.

The prescribed aerosol perturbation was applied only to the initial dust size partitioning. Subsequent aerosol transport, sedimentation, activation, and cloud processing were allowed to evolve freely within SCAM. Consequently, the simulated in-cloud aerosol distribution was not artificially constrained to retain the prescribed initial fine- and coarse-mode fractions throughout the simulation.

A2 Dust AOD-partition sensitivity experiments

The sensitivity experiments modified the partitioning of dust aerosol optical depth (AOD) between the fine and coarse modes while keeping the initial total dust AOD approximately constant. The fine- and coarse-mode AOD fractions are defined as

$$f_{\text{fine}} = \frac{\tau_{\text{fine}}}{\tau_{\text{dust}}}, \quad f_{\text{coarse}} = \frac{\tau_{\text{coarse}}}{\tau_{\text{dust}}}, \quad (\text{A1})$$



where

$$\tau_{\text{dust}} = \tau_{\text{fine}} + \tau_{\text{coarse}}, \quad f_{\text{fine}} + f_{\text{coarse}} = 1. \quad (\text{A2})$$

The prescribed fine-mode AOD fraction is varied from 0.90 to 0.99 at intervals of 0.01. The corresponding coarse-mode fraction therefore varied from 0.10 to 0.01.

$$f_{\text{fine}} = 0.90, 0.91, 0.92, \dots, 0.99, \quad (\text{A3})$$

or equivalently,

$$f_{\text{coarse}} = 0.10, 0.09, 0.08, \dots, 0.01. \quad (\text{A4})$$

This range encompasses the change in coarse-dust AOD fraction diagnosed by GEOS-Chem during the March 2022 event over the Svalbard area. The modeled coarse-to-total dust AOD fraction increased from 3.56% during the background period to 8.39% during the event period. The SCAM experiments therefore span both background-like and event-like dust size distribution.

315 **A3 Control definition and radiative diagnostics**

The control state is defined as the mean of the three simulations with fine-mode AOD fractions of 0.97, 0.98, and 0.99, corresponding to coarse-mode fractions of 0.03, 0.02, and 0.01. For each sensitivity experiment, the radiative anomaly is calculated as

$$\Delta X_i = X_i - \bar{X}_{\text{ctrl}}, \quad (\text{A5})$$

320 where X denotes either the longwave cloud radiative forcing (LWCF) or the shortwave cloud radiative forcing (SWCF). The control-state mean is calculated as

$$\bar{X}_{\text{ctrl}} = \frac{1}{3} \sum_{f_{\text{fine}} \in \{0.97, 0.98, 0.99\}} X(f_{\text{fine}}). \quad (\text{A6})$$

The combined cloud radiative forcing anomaly is subsequently calculated as

$$\Delta \text{CRF} = \Delta \text{LWCF} + \Delta \text{SWCF}. \quad (\text{A7})$$

325 *Author contributions.* DJ, XS, and JN conceived and designed the overall study. XS designed and performed the GEOS-Chem simulations. DJ performed the HYSPLIT and SCAM simulations. DJ and XS integrated and analyzed the datasets. DJ prepared the initial draft of the manuscript. All authors reviewed and contributed to the final manuscript.

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