Response to Reviewer 1

We sincerely thank Reviewer 1 for the positive assessment and the detailed and constructive comments. Following these suggestions, we revised the Introduction, Methods, Results and Discussion, and added a vertically resolved MERRA-2 dust analysis to better assess the presence of Saharan dust at cirrus-relevant altitudes.

Comment: The abstract should be as compact as possible
Response: Thank you. The Abstract has been shortened and reorganized to focus on the motivation, methods, and principal findings.

Comment: A more appropriate introduction into the cirrus literature would be desirable.
Response: We agree. The Introduction has been expanded to provide a broader background on cirrus formation, radiative effects, homogeneous and heterogeneous ice nucleation, and mineral-dust INPs. The recommended studies have been incorporated.

Comment: Lines 46–51: References on ice nucleation, Saharan dust observations, and feldspar.
Response: The recommended references have been incorporated, including Ansmann et al. (2003) on Saharan dust transport and Atkinson et al. (2013) on the ice-nucleating efficiency of feldspar.

Comment: Are you sure that the basin-like topography favors accumulation of air masses after long -range transport and provides favorable conditions for the formation and persistence of high level clouds? Are there articles that confirm or support your hypothesis?
Response: We agree that this interpretation was too speculative. The text has been revised to avoid attributing upper-level cloud formation or persistence directly to the basin topography.

Comment: The study is based on hourly dust COLUMN mass density fields. In the case of a dust event, how sure can you be that that dust occurred at cirrus formation height level? Height information.
Response: We addressed this issue with a new vertically resolved MERRA-2 analysis. Dust exceeding 10^{-9} kg kg^{-1} was present at 7–12 km in 95.7% of the 276 SDEs, demonstrating frequent vertical overlap between Saharan dust and cirrus-relevant altitudes. This analysis has been added to the Methods and Results. The results of the vertical analyses were also plotted on a new figure.

Comment: How reliable are the small changes in MODIS effective ice-particle radius?
Response: We agree that differences of only a few micrometres should not be overinterpreted. The revised manuscript therefore treats the effective-radius response as weak and does not use it as evidence for a major long-term microphysical change.

Comment: A reference to the model GAM would be fine.

Response: The statistical methodology has been clarified and appropriate methodological description have been added. The revised analysis is performed on daily observations rather than cumulative threshold averages.

Comment: About the large tables
Response: We agree. The table has been simplified.

Comment: The relationship between synoptic transport patterns and dust at cirrus altitudes should be clarified.
Response: We now distinguish between the large-scale transport environment and the actual vertical location of dust. The latter is independently assessed using the new vertically resolved MERRA-2 analysis. The different synoptic types were discussed in detail in the cited papers by Varga et al..

Comment: You discuss effective-radius tendencies of 30.3, 29.9, and 28.2 micrometer…
Response: We agree that differences of only a few micrometres should not be overinterpreted. The revised manuscript therefore treats the effective-radius response as weak and does not use it as evidence for a major long-term microphysical change.

Comment: Line 251-255: You discuss Table 2, but you did not mention or introduce Table 2 in the main text body? Should be improved! Could be done in line 251.
Response: That table has been removed.

Comment: Are middle and high-level cloud fractions somewhere precisely defined? If yes, please indicate here where that was done, as a reminder. Please provide clear definitions somewhere.
Response: Definitions have been added to the Methods. MERRA-2 low-, middle-, and high-level cloud fractions correspond to the surface–700 hPa, 700–400 hPa, and above-400 hPa layers, respectively. The figure captions have also been clarified.

Comment: The interpretation should consider the competition between homogeneous and heterogeneous ice nucleation.
Response: We agree. The revised manuscript now explicitly discusses this competition based on Kärcher et al. (2022, 2023) and avoids assuming that increased mineral-dust INPs necessarily produce more ice crystals.

Comment: Figure 2 is the highlight of the paper! Again, I miss a clear definition of cloud cover and defined height regions for low, mid, and high clouds.
We need (a), (b), (c), etc.... within the six different panels.
Response: The definitions have been added, and table has been completed.

Comment: Can the direct dust effect on OLR be separated from the cirrus effect?
Response: No. We have clarified that our analysis cannot unambiguously separate these effects. OLR is therefore interpreted as an integrated radiative signature associated with dust-loading conditions rather than as an isolated cirrus radiative effect.

Comment: Atmospheric dynamics should be included in the Discussion.

Response: We agree. The Discussion now considers vertical velocity, wind shear, turbulence, and ice supersaturation, following Pieper et al. (2026) and Juurikkala et al. (2026). We emphasize that the observed relationships may reflect combined aerosol, thermodynamic, and dynamical controls.

Comment: Could the upper-tropospheric fraction of dust have increased over time?
Response: We examined this using vertically resolved MERRA-2 data. The 7–12 km dust mass mixing ratio showed no significant monotonic trend over 2001–2025, suggesting that the temporal changes cannot be explained simply by increasing upper-tropospheric dust abundance.

Comment: Are changes of only a few micrometres in effective radius physically meaningful?
Response: We agree that these differences are small. Their interpretation has therefore been substantially weakened, and the main conclusions are based on the more robust changes in cirrus reflectance, high-cloud fraction, and cloud-top properties.

Comment: The DIBS case should be attributed to the appropriate Ansmann et al. (2019) paper.
Response: Thank you. The citation has been corrected and the unnecessary Ansmann et al. (2019b) reference has been removed.

Comment: Sections 4.3 and 4.4 should be shortened.
Response: We agree. These sections have been condensed, while greater emphasis is now placed on unresolved questions concerning the combined effects of dust, atmospheric dynamics, and upper-tropospheric thermodynamic conditions.

We thank Reviewer 1 again for the constructive suggestions. In particular, the new vertically resolved dust analysis and the revised treatment of cirrus microphysics and atmospheric dynamics have substantially strengthened the manuscript.

Response to Reviewer 2

We thank Reviewer 2 for the critical and constructive assessment. The comments prompted substantial revisions to the statistical framework, reproducibility of the analysis, vertical characterization of dust, and interpretation of the results. Most importantly, we no longer claim a uniform strengthening of the dust–cirrus relationship over 2001–2025. Instead, the revised manuscript describes a persistent but temporally and seasonally variable association, with the clearest temporal change occurring in cirrus optical properties under high springtime dust loading.

1. Presentation

Comment: The main-text tables are excessively large and obscure the key findings.

Response: We agree. The tables have been substantially simplified, and the principal results are now emphasized graphically. Excessive numerical detail has been removed from the main text.

2. Reproducibility

Comment on the GAM inputs and geographic domain (insufficiently described)
Response: We agree. The revised Methods now explicitly define the study domain (Hungary), spatial averaging, event windows, predictor and response variables, and statistical procedures, allowing the analysis to be reproduced.

Comment: Given the global coverage of the datasets, the regional restriction should be justified and a broader/global analysis considered.
Response: We have clarified that the study is intentionally regional and event-based, focusing on Hungary, and independently identified Saharan dust events affecting Hungary. A global analysis would address a substantially different research question and is beyond the scope of the present study. We now state this limitation more clearly.

3. Statistical significance and validity

Comment on the cumulative dust-threshold means, what are not independent and should not be used as GAM inputs. Statistical inference should instead be performed at the daily/event level and account for temporal dependence.
Response: We agree with this important criticism. The statistical analysis has been rebuilt using daily observations within independently defined SDE windows rather than cumulative threshold averages. Overlapping event windows were resolved to avoid duplicate observations, and the revised Methods now clearly distinguish descriptive threshold analyses from inferential statistics.

Comment on the high R^2 values (very small p-values may result from pseudo-replication among cumulative thresholds)
Response: We agree. Therefore, cumulative threshold means are no longer used for statistical inference. They are retained only as descriptive summaries, while significance testing is based on the underlying daily/event-level observations.

4. Causality versus correlation

Comment: Besides the significance issue, even with signficant correlations, dust transport and cirrus may well just share external controls such as circulation and upper- tropospheric humidity. Changes in synoptic weather regimes could therefore increase both transported dust and cirrus without any change in the causal effect of dust.
Response: We agree and have revised the manuscript throughout to avoid unsupported causal language. The results are now described as dust–cloud associations, and we explicitly state that the observational analysis does not establish causality.

The revised Discussion explicitly considers circulation, vertical motion, wind shear, turbulence, and ice supersaturation as potential common controls. We therefore interpret the observed relationships as potentially reflecting combined aerosol, thermodynamic, and dynamical influences rather than a dust effect alone.

Comment: This possibility is alluded to in the conclusion and in Sect. 4.2, but simple tests (e.g., including meteorological variables in the GAM) are not performed.
Response: We agree with the underlying concern. Rather than interpreting the statistical relationships as causal effects after meteorological adjustment, we have substantially narrowed the scope of our conclusions and explicitly discuss meteorological covariability as a limitation. A rigorous attribution of aerosol and dynamical effects would require additional upper-tropospheric dynamical and thermodynamic diagnostics and is beyond the scope of the present analysis.

Comment: Moreover, the chosen dust predictor is questionable. Total-column dust mass does not show whether dust is present at cirrus altitude or spatially collocated with the cloud.
Response: We fully agree and addressed this directly with a new vertically resolved MERRA-2 analysis. Dust exceeding 10^{-9} kg kg^{-1} was present at 7–12 km during 95.7% of the 276 SDEs, demonstrating frequent vertical co-occurrence of Saharan dust and cirrus-relevant altitudes. We additionally compared total-column and upper-tropospheric dust. Dust mass mixing ratios at 7–12 km showed stronger associations with several upper-level cloud properties than total-column dust loading, supporting the relevance of the vertically resolved dust metric.

We agree that the original wording of the manuscript on the strengthening response was too strong. The revised manuscript no longer claims a uniform or monotonic strengthening of the dust–cirrus relationship. Instead, our results indicate a persistent but temporally evolving relationship, with the clearest change found under extreme spring dust loading: median cirrus reflectance increased from 0.075 in 2001–2005 to 0.186 in 2021–2025, while the fraction of extreme dust days simultaneously exhibiting extreme cirrus reflectance increased from 15.6% to 47.6%. These changes were non-monotonic across the intermediate periods and are now described accordingly.

We thank Reviewer 2 for identifying these important limitations. The revised manuscript now uses daily/event-level inference, explicitly evaluates dust at cirrus-relevant altitudes, provides clearer methodological information, and substantially reduces causal interpretation. We believe these changes have resulted in a more reproducible analysis and a more appropriately constrained interpretation of the observed dust–cirrus relationships.

Response to Community Comments by Daniel Williams, Iarla Boyce, Christos Mistios, Julia Canet

We thank the reviewers for their careful and constructive assessment. The comments are highly relevant and largely consistent with concerns raised during the interactive review. The manuscript has been substantially revised accordingly, particularly regarding causal interpretation, vertically resolved dust information, statistical analysis, and the interpretation of long-term changes.

RE: General comments

1. The GAM analysis indicates that the relationship between dust loading and cloud properties varies with time. This is evidence for non-stationarity of the statistical association, not necessarily that the physical response of clouds to dust has strengthened. An alternative explanation may be that the meteorological conditions associated with Saharan dust transport could have changed. The manuscript should therefore distinguish between a changing dust-cloud association and a strengthening of the causal influence of dust on cirrus formation.

Response: We fully agree. The manuscript has been revised throughout to distinguish statistical association from causal influence. We no longer claim a uniform strengthening of the physical dust effect. Instead, the results are described as a persistent but temporally evolving and non-monotonic dust–cirrus association, with the clearest temporal change occurring in cirrus optical properties under high springtime dust loading.

2. On non-independence of cumulative dust thresholds and interpretation of R^2

Response: We agree. Cumulative threshold subsets are nested and therefore non-independent. In the revised manuscript, these threshold curves are used only descriptively and not for statistical inference. The main inferential analysis has been replaced by an event-based framework using the underlying observations. We have also removed the interpretation that high model R^2 values demonstrate the fraction of cloud variability explained specifically by dust loading.

3. On the temporal autocorrelation

Response: We agree that temporal autocorrelation may remain within the daily observations, particularly during persistent multi-day meteorological conditions. We have not explicitly modelled residual autocorrelation in the present analysis and now acknowledge this as a limitation. Importantly, the original GAM-based interpretation has been substantially reduced, and the main conclusions are now based primarily on event-based non-parametric comparisons. Nevertheless, some temporal dependence may remain, and we therefore interpret statistical significance cautiously and explicitly identify this issue as a limitation of the present observational framework.

4. On total-column dust versus dust at cirrus altitude

Response: We fully agree and have addressed this with a new vertically resolved MERRA-2 analysis. Across the 276 SDEs, 95.7% exhibited event-mean dust mass mixing ratios exceeding 10^{-9} kg kg^{-1} at 7–12 km. Additional analyses were performed for 8–12 and 10–12 km. Thus, the revised manuscript explicitly evaluates the presence of mineral dust at cirrus-relevant altitudes rather than relying solely on total-column dust loading.

5. Absolute versus relative number of high-reflectance events

Response: We agree. The revised analysis uses relative rather than absolute occurrence frequencies. For example, under extreme spring dust loading, the fraction of events simultaneously exhibiting extreme cirrus reflectance increased from 15.6% in 2001–2005 to 47.6% in 2021–2025. The intermediate periods also demonstrate that this evolution was non-monotonic.

6. Effective ice-particle radius

Response: We agree that differences of only a few micrometres should not be overinterpreted. The revised manuscript no longer uses these relatively small changes as evidence for a major long-term microphysical response. Effective-radius results are treated as secondary, while the main conclusions are based on the more robust changes in cirrus reflectance, high-cloud fraction, and cloud-top properties.

7. Interpretation of OLR

Response: We agree. The OLR discussion has been substantially moderated. We now explicitly state that the observed OLR variations cannot be uniquely attributed to dust-induced cirrus changes because temperature, humidity, cloud properties, and dust itself may contribute simultaneously. OLR is therefore interpreted as an integrated radiative signature associated with dust-loading conditions rather than as an isolated dust or cirrus radiative effect.

RE: Specific comments

1. Twomey (1974)
Response: We agree and have removed this reference from the discussion of ice-cloud aerosol interactions.

2. Homogeneous versus heterogeneous nucleation
Response: We agree. The revised Introduction now clearly distinguishes homogeneous freezing, which does not require INPs, from heterogeneous ice nucleation involving INPs.

3. Ice-nucleating efficiency of K-feldspar
Response: Thank you. The text has been revised to clarify that K-feldspar is generally a more efficient ice-nucleating mineral component than quartz or calcite.

4. Citation for the statement around Line 60

Response: We agree. The appropriate reference has been added to support this statement.

5. Sample sizes
Response: Sample sizes are now reported for the principal seasonal, event-based, and five-year comparisons, particularly where increasingly restrictive dust conditions reduce the number of observations.

6. Gaussian error assumption in the GAM
Response: We agree that a Gaussian assumption may not be appropriate for all variables. The original GAM-based inference has therefore been substantially de-emphasized and replaced by a non-parametric event-based analysis using Mann–Whitney U tests, rank-biserial effect sizes, and FDR correction. The principal statistical conclusions consequently do not rely on Gaussian residual assumptions.

7. Large Tables 1 and 3
Response: We agree. The presentation has been substantially simplified, with the key temporal and dust-dependent relationships emphasized graphically and the main-text tables reduced to the most relevant results.

8. Definition of "change %"
Response: Thank you. The definition of percentage change has been clarified in the corresponding table caption/text to explicitly state the reference against which the change is calculated.

Technical comments

1. Units
Response: Units and their notation have been checked and standardized throughout the manuscript.

2. Repeated acronym definitions
Response: The manuscript has been checked and redundant definitions, including repeated definitions of OLR, have been removed.

3. Figure captions
Response: Figure captions have been revised to be more self-contained and explicitly describe the meaning of lines, symbols, and shaded areas where applicable.

We thank the reviewers again for these constructive comments. The revised manuscript now more clearly distinguishes association from causation, directly evaluates dust at cirrus-relevant altitudes, uses an event-based non-parametric statistical framework, and adopts a substantially more cautious interpretation of the temporal, microphysical, and radiative results. We also explicitly acknowledge the remaining limitation associated with temporal dependence in the observational data.

Detailed description of the major changes in the manuscript

The Methods were completed:

Upper tropospheric dust

To assess whether Saharan dust was present at altitudes relevant to cirrus formation, the total-column analysis was complemented with three-dimensional MERRA-2 aerosol fields. For each of the identified SDEs, 3-hourly dust mass mixing ratios for the five MERRA-2 dust size bins (DU001–DU005) were extracted over the study domain from the native model-level aerosol product. Total dust mass mixing ratio (kg kg^{-1}) was calculated as the sum of the five size bins. Aerosol fields were matched to the corresponding three-dimensional MERRA-2 atmospheric fields, and the geometric height assigned to each model level was used to determine the actual altitude of the dust at every time step and grid point. This allowed the dust distribution to be evaluated independently of fixed model-level or pressure-level assumptions. Upper-tropospheric dust was primarily characterized over the 7–12 km altitude range, with additional calculations for the 7–8, 8–9, 9–10, and 10–12 km layers to examine the vertical dependence of the dust–cirrus relationship. Event-level mean dust mass mixing ratios were calculated from all grid points and 3-hourly time steps falling within each altitude interval. These vertically resolved dust metrics were subsequently compared with the MODIS and HIRS cloud properties used in the original analysis to determine whether cirrus responses were more closely associated with dust present at cirrus-relevant altitudes than with total-column dust loading.

Event-based statistical analysis

To investigate whether the cloud properties associated with Saharan dust events depend on the presence of mineral dust at cirrus-relevant altitudes, an event-based analysis was performed using the 276 independently identified SDE days. Rather than relying primarily on correlations between dust concentration and individual cloud parameters, the analysis was designed to compare cloud states associated with SDEs against low-dust background conditions. Low-dust reference days were defined as non-SDE days for which the total-column dust mass remained below the 75th percentile (upper quartile) of the complete 2001–2025 daily dust distribution. This criterion yielded 6836 reference days and excluded the upper quartile of the total-column dust distribution, where substantial dust influence was more likely. All comparisons were performed separately for winter, spring, summer, and autumn to account for the pronounced seasonal variability in both Saharan dust transport and cloud conditions.

To examine whether the vertical penetration of dust into the upper troposphere was associated with the magnitude of the cloud response, SDEs were additionally divided within each season according to their Dust7–12 values. Events below or equal to the seasonal median Dust7–12 concentration were classified as lower-upper-tropospheric-dust SDEs, whereas events above the seasonal median were classified as higher-upper-tropospheric-dust SDEs. The use of season-specific thresholds avoided applying a single concentration criterion to seasons characterized by substantially different upper-tropospheric dust distributions. Three complementary contrasts were then evaluated: (i) all SDE days versus

low-dust reference days, (ii) lower- and higher-Dust7–12 SDE subsets separately versus the corresponding seasonal reference, and (iii) higher- versus lower-Dust7–12 SDEs directly. The latter comparison was used to determine whether cloud properties differed systematically among SDEs depending on the amount of mineral dust present at 7–12 km.
The analysis included cirrus reflectance, effective ice particle radius, low-, mid-, and high-level cloud fraction, cloud-top pressure, cloud-top temperature, and outgoing longwave radiation (OLR). Because several variables exhibited non-normal distributions and unequal group sizes, group differences were evaluated using two-sided Mann–Whitney U tests. The magnitude and direction of the differences were quantified using rank-biserial correlation (rrb) as a non-parametric effect-size measure, with positive values indicating higher values in the first group and negative values indicating lower values. To control for multiple comparisons, p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure, with FDR-adjusted ($q<0.05$) considered statistically significant. Group medians were used to characterize the magnitude of the observed differences.
Because vertically resolved Dust7–12 data were available only for the 276 SDE days, upper-tropospheric dust concentrations could not be directly compared between SDE and reference days. Accordingly, the low-dust reference group was defined independently using total-column dust mass, whereas Dust7–12 was used specifically to stratify the SDE population according to the degree of upper-tropospheric dust presence. This design therefore tests whether the cloud state associated with SDEs differs from low-dust background conditions and, more specifically, whether these anomalies become more pronounced when larger amounts of mineral dust are present at cirrus-relevant altitudes.

New findings have been added to the results:

Upper-tropospheric dust occurrence and comparison with column dust loading

The vertically resolved MERRA-2 analysis showed that mineral dust was frequently present at cirrus-relevant altitudes during the identified SDEs. Across the 276 events, the median event-mean dust mass mixing ratio in the 7–12 km layer was 9.63×10^{-8} kg kg^{-1} (Figure 3). Upper-tropospheric dust was not restricted to the lower part of this altitude range: the corresponding median was 8.33×10^{-9} kg kg^{-1} at 8–12 km and 4.37×10^{-9} kg kg^{-1} at 10–12 km. Of all SDEs, 264 (95.7%) exhibited event-mean dust mass mixing ratios exceeding 10^{-9} kg kg^{-1} between 7 and 12 km, while 204 (73.9%) exceeded 5×10^{-9} kg kg^{-1}, and 134 (48.6%) exceeded 10^{-8} kg kg^{-1}. Even when the analysis was restricted to 8–12 km, these thresholds were exceeded in 93.1%, 67.0%, and 44.6% of the events, respectively. At 10–12 km, 81.2% of the SDEs still exceeded 10^{-9} kg kg^{-1}.
The amount of dust at 7–12 km was also substantial relative to that at 3–7 km; the upper-tropospheric mean reached at least 30% of the 3–7 km value in 62% of the events and at least 50% in 35.5% of the events. These results demonstrate that, within MERRA-2, Saharan dust during the investigated events was generally not confined to the lower and middle troposphere but frequently extended into the altitude range occupied by upper-level ice clouds.

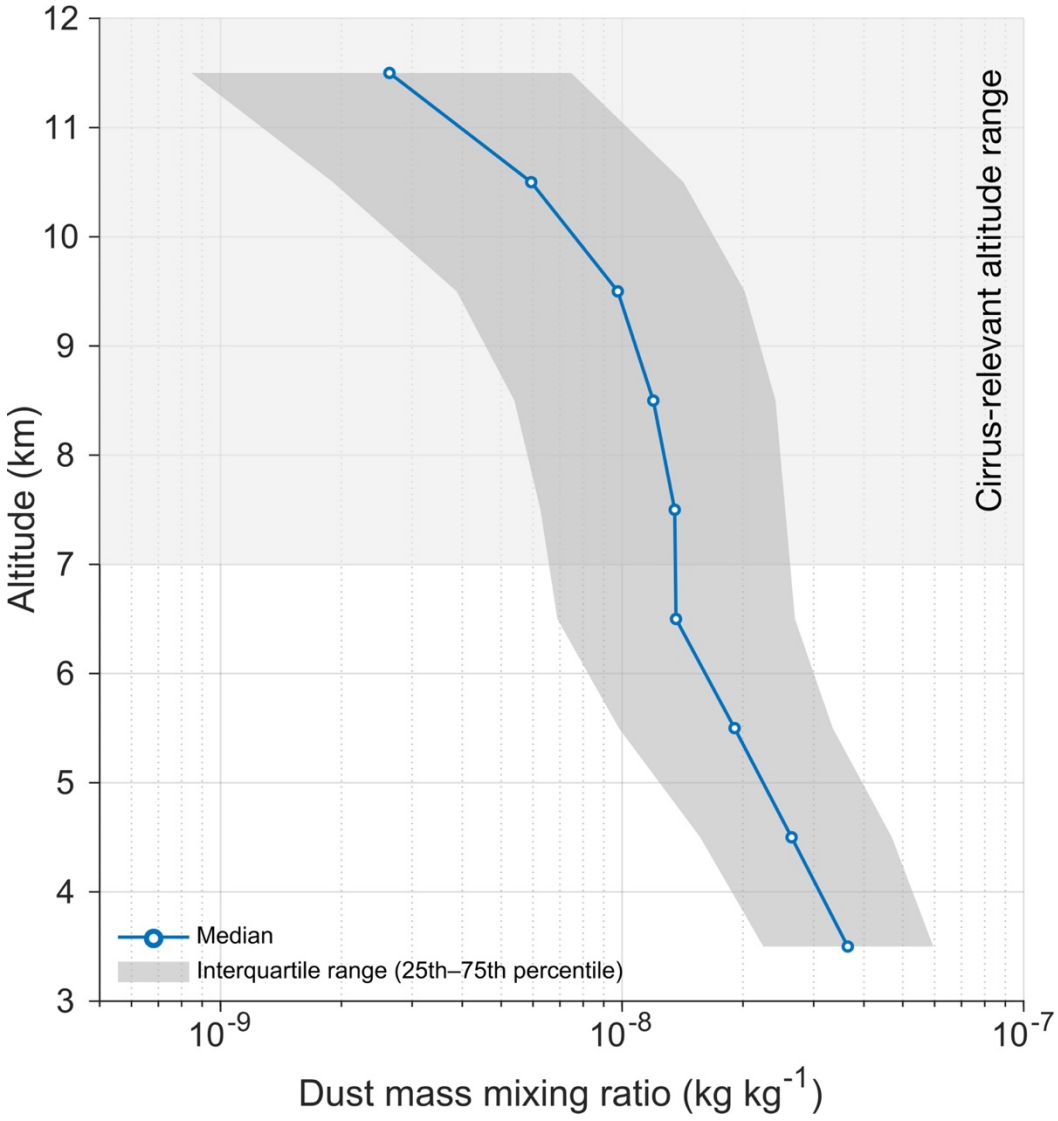

Figure 3. Vertical distribution of Saharan dust during the 276 identified SDEs. (The line shows the median MERRA-2 dust mass mixing ratio, with the shaded envelope representing the interquartile range, while the shaded 7–12 km layer indicates cirrus-relevant altitudes.)

Seasonal cloud-property differences associated with upper-tropospheric dust during SDEs

The event-based analysis revealed pronounced seasonal differences in cloud and radiative properties between Saharan dust events and low-dust reference conditions (Table 2). The differences were particularly marked for SDEs characterized by above-median dust concentrations in the 7–12 km layer. Across all seasons, these high-Dust7–12 events were associated with significantly enhanced cirrus reflectance and high-cloud fraction, together with substantially lower cloud-top pressure and temperature. Most of these differences remained highly significant after FDR correction and were accompanied by moderate to large rank-biserial effect sizes.

The largest overall contrasts were observed during winter and spring. In winter, high-Dust7–12 SDEs showed particularly large differences in high-cloud fraction, cloud-top properties, and OLR relative to low-dust reference conditions. Spring exhibited a similarly coherent pattern, with enhanced cirrus reflectance and high-cloud fraction and reduced cloud-top pressure, cloud-top temperature, and OLR. A significant reduction in effective ice particle

radius was also detected in spring, whereas particle-size differences were not statistically significant in the other seasons. Summer exhibited smaller cirrus and radiative differences, although high-cloud fraction and cloud-top properties remained significantly different from reference conditions. During autumn, the largest differences were observed in high-cloud fraction and cloud-top pressure and temperature.

Direct comparison of SDEs with above- and below-median Dust7–12 concentrations showed that the differences were not restricted to the contrast between SDE and reference conditions. Higher upper-tropospheric dust concentrations within SDEs were accompanied by significantly greater cirrus reflectance and high-cloud fraction during winter and spring. Spring high-Dust7–12 events additionally showed significantly smaller effective ice particle radii and lower OLR than lower-Dust7–12 events. During summer, the most pronounced within-SDE difference occurred in high-cloud fraction, whereas autumn showed the clearest differences in cloud-top pressure and temperature. Thus, the seasonal analysis identified distinct cloud-property differences not only between SDEs and low-dust background conditions but also according to the amount of mineral dust present within the 7–12 km layer during the events.

Table 2. Relative changes in cloud and radiative properties during high-Dust7–12 SDEs compared with low-dust reference conditions.

Season	Cirrus reflectance	High cloud fraction	Effective ice cloud radius	Cloud top pressure	Cloud top temperature	OLR
Winter	+194.5%***	+146.5%***	−4.9% n.s.	−44.0%***	−8.8%***	−16.1%***
Spring	+272.0%***	+133.2%***	−7.2%**	−30.0%***	−5.5%***	−14.4%***
Summer	+99.3%***	+94.7%***	0.0% n.s.	−34.8%***	−6.6%***	−4.6%*
Autumn	+160.9%***	+119.7%***	−4.8% n.s.	−41.4%***	−7.2%***	−8.6%*

Values represent percentage differences between median cloud properties during SDEs with above-seasonal-median Dust7–12 concentrations and the corresponding low-dust reference conditions, calculated relative to the reference median. Statistical significance is based on two-sided Mann–Whitney U tests with Benjamini–Hochberg FDR correction: *q<0.05, **q<0.01, ***q<0.001; n.s., not significant.

A separate within-SDE comparison was performed to determine whether cloud properties differed according to upper-tropospheric dust abundance independently of the SDE–background contrast. For this analysis, SDEs with above-seasonal-median Dust7–12 concentrations were compared directly with SDEs below or equal to the corresponding seasonal median.

In winter, median cirrus reflectance was 0.183 in the higher-Dust7–12 group compared with 0.068 in the lower-Dust7–12 group, while high-cloud fraction was 0.810 and 0.610, respectively. Cloud-top temperature decreased from 233.9 to 223.8 K and OLR from 199.9 to 172.0 W m^{-2}; all four differences remained significant after FDR correction. In spring, cirrus reflectance increased from 0.079 to 0.167 and high-cloud fraction from 0.565 to 0.708

between the lower- and higher-Dust7–12 subsets. Effective ice particle radius decreased significantly, from 31.90 to 28.44 µm (r_{rb}=-0.36, q=0.0023), while OLR decreased from 215.0 to 192.6 W m^{-2} (r_{rb}=-0.44, q<0.001). During summer, the principal significant within-SDE difference was observed for high-cloud fraction (0.199 versus 0.497, r_{rb}=0.50, q<0.001), whereas autumn showed significant differences primarily in cloud-top pressure (405 versus 278 hPa, r_{rb}=-0.57, q=0.0022) and cloud-top temperature (238.1 versus 228.0 K, r_{rb}=-0.54, q=0.0035).

Long-term trends of dust and cirrus cloud relationships in spring

Based on the seasonal analysis above, the long-term assessment was focused on spring, which combined the largest number of identified SDEs and the highest mean dust loading with the most coherent dust-dependent responses across cirrus reflectance, high-cloud fraction, cloud-top properties, and OLR.

The five-year analysis revealed substantial temporal variability in springtime SDE-associated cloud properties without a corresponding monotonic increase in upper-tropospheric dust loading. Median Dust7–12 during spring SDEs varied between 6.73×10^{-8} and 1.29×10^{-7} kg kg^{-1}, with the lowest value occurring in 2016–2020 and no systematic increase towards the end of the record. In contrast, the cirrus reflectance anomaly during high-Dust7–12 SDEs increased markedly: relative to the corresponding low-dust background, median cirrus reflectance was 143% higher in 2001–2005, 147% in 2006–2010, 318% in 2011–2015, 327% in 2016–2020, and 398% in 2021–2025. The absolute median cirrus reflectance increased from 0.116 in 2001–2005 to 0.223 in 2021–2025, while the corresponding background values remained similar (0.048 and 0.045, respectively).

Other cloud properties showed persistent but less monotonic differences. High-cloud fraction during high-Dust7–12 SDEs was 122–161% above background during 2001–2015, 54% higher in 2016–2020, and 135% higher in 2021–2025. Cloud-top pressure remained 25–34% lower and cloud-top temperature approximately 5–7% lower than background throughout the five periods, with the largest recent differences occurring in 2021–2025. Effective ice particle radius showed greater temporal variability: the anomaly changed from +2.8% in 2001–2005 to −15.7% in 2006–2010, −8.3% in 2011–2015, approximately zero in 2016–2020, and −7.7% in 2021–2025. OLR remained lower during high-Dust7–12 SDEs in every period, with differences ranging from approximately −10% to −17%. Thus, among the investigated variables, the clearest five-year change was observed in cirrus reflectance, whose SDE-associated enhancement became substantially larger over the study period despite the absence of a parallel increase in Dust7–12.