# Authors' Responses to the Reviewers' Comments

First and foremost, we would like to sincerely thank the reviewers and the editor for their valuable comments, constructive suggestions, and critical assessments, which have greatly contributed to improving our manuscript.
Below, we provide detailed point-by-point responses to all comments and questions raised. As the manuscript has undergone substantial revision, and several reviewers raised overlapping concerns, it would not be practical to use different colours in the tracked-changes manuscript to indicate which modifications were made in response to specific reviewers' comments. Therefore, to facilitate the review process, we have reproduced relevant excerpts from the revised manuscript within our detailed responses, highlighting these passages in blue.

**All revisions and modifications are clearly indicated in the uploaded tracked-changes version of the manuscript.**

# Response to Reviewer 1

**General impression:**
**The manuscript is well written. It deals with a careful and very detailed analysis of long-term dust and cirrus data sets. The data base contains 276 Saharan dust events and covers the years from 2001-2025. A clear impact on cirrus properties by Saharan dust was found and thus a dust impact on ice cloud formation and development in the upper troposphere. This is a valuable contribution to the cirrus research branch.**
**Minor revisions may further improve the paper.**

**Response:** 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:

Lines 9-20: *"Saharan mineral dust is an important source of ice-nucleating particles, yet the long-term evolution of its relationship with upper-tropospheric ice clouds remains poorly constrained. Here, we investigate dust–cloud interactions over Hungary during 2001–2025 using MERRA-2, MODIS, and HIRS data, focusing on 276 independently identified Saharan dust events (SDEs). Vertically resolved MERRA-2 dust fields were used to quantify mineral dust at 7–12 km, allowing cloud properties to be compared between SDEs with different*

*upper-tropospheric dust abundances and low-dust reference conditions. SDEs with high Dust7–12 were characterized by enhanced cirrus reflectance and high-cloud fraction and by higher, colder cloud tops in all seasons. The response was particularly coherent in spring, when cirrus reflectance and high-cloud fraction were 272% and 133% higher, respectively, effective ice particle radius was 7.2% smaller, and outgoing longwave radiation was 14.4% lower than under low-dust conditions. Springtime five-year composites showed no monotonic increase in Dust7–12, whereas the cirrus-reflectance enhancement increased from 143% in 2001–2005 to 398% in 2021–2025. These results indicate an increasingly pronounced springtime cirrus optical response during SDEs containing substantial dust at cirrus-relevant altitudes, while other cloud properties exhibit more variable long-term behaviour."*

**Comment: Introduction: A more appropriate introduction into the cirrus literature would be desirable.**
**Please check the Meteorological Monographs, Special Issue, and here, e.g., Heymsfield et al., Met. Monographs, DOI: 10.1175/AMSMONOGRAPHS-D-16-0010.1**
**Please check the book: Lynch et al., Cirrus, 2002, Oxford University Press, see chapter 2: K. Sassen: Cirrus clouds, a modern perspective, …… and all the references in this chapter.**
**One of the pioneering cirrus articles is from 1986: Kuo-Nan Liou, Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective, Review Article in Monthly Weather Review , 114, 1986, https://doi.org/10.1175/1520-0493(1986)114<1167:IOCCOW>2.0.CO;2**

**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 in Lines 29-30:

Lines 29-30: *"Their radiative effect depends strongly on cloud altitude, optical thickness, ice crystal concentration, particle size and habit, and may therefore range from shortwave cooling to pronounced longwave warming (Heymsfield et al., 2017; Liou, 1986)."*

**Comment: In addition, there are many modelling papers, please check papers of Kaercher et al., Jensen et al., Spichtinger et al.. in ACP and JGR, partly given in the references of the papers, listed next:**
**Important papers on dust INP parameterization:**
**DeMott, P. J. et al., Predicting global atmospheric ice nuclei distributions and their impacts on climate, P. Natl. Acad. Sci. USA, 107, 11217–11222, https://doi.org/10.1073/pnas.0910818107, 2010.**
**DeMott, P. J. et al., Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles, Atmos. Chem. Phys., 15, 393–409, https://doi.org/10.5194/acp-15-393-2015, 2015.**
**Niemand et al., Parameterization of immersion freezing on mineral dust particles: an application in a regional scale model, J. Atmos. Sci., 69, 3077–3092, 2012**
**Ullrich et al., A new ice nucleation active site parameterization for desert dust and soot, J. Atmos. Sci., 74, 699–717, 2017.**

**Response:** The mentioned papers have been discussed and cites in the revised manuscript in Lines 83-91:

*"Mineral dust is particularly relevant in this context because it represents one of the most important atmospheric sources of ice-nucleating particles, although its activity depends strongly on particle concentration, mineralogical composition, temperature, and nucleation mode (DeMott et al., 2003, 2010; Niemand et al., 2012; Ullrich, 2017). Model simulations therefore indicate that the response of cirrus clouds to mineral dust is not necessarily monotonic: enhanced heterogeneous nucleation may modify or suppress subsequent homogeneous freezing, while variations in vertical velocity and supersaturation can substantially change the resulting ice crystal population (Kärcher et al., 2022, 2023). Assessing dust–cirrus interactions thus requires consideration not only of atmospheric dust loading, but also of whether mineral dust reaches cirrus-forming altitudes and encounters thermodynamic and dynamical conditions favourable for heterogeneous ice nucleation."*

**Comment: Important INP review papers:**
**Kanji et al., Chapter 1: Overview of ice nucleating particles, Meteor Monogr. Am. Meteorol. Soc., 58, 1–33, https://doi.org/10.1175/amsmonographs-d-16-0006.1, 2017.**
**Knopf, D. A. and Alpert, P. A.: Atmospheric ice nucleation, Nat. Rev. Phys., 5, 203–217, https://doi.org/10.1038/s42254-023-00570-7, 2023.**
**Recently published simulation papers (the references contain many relevant papers since 2000):**
**Kärcher, B., DeMott, P. J., Jensen, E. J., and Harrington, J. Y.: Studies on the Competition Between Homogeneous and Heterogeneous Ice Nucleation in Cirrus Formation, J. Geophys. Res.-Atmos., 127, e2021JD035805, https://doi.org/10.1029/2021JD035805, 2022.**
**Kärcher, B., Jensen, E. J., Pokrifka, G. F., and Harrington, J. Y.: Ice Supersaturation Variability in Cirrus Clouds: Role of Vertical Wind Speeds and Deposition Coefficients, J. Geophys. Res.-Atmos., 128, e2023JD039324, https://doi.org/10.1029/2023JD039324, 2023.**
**Please check the papers of Krämer et al. , cirrus aircraft observations, overview papers!**
**Krämer et al., A microphysics guide to cirrus clouds – Part 1: Cirrus types, Atmos. Chem. Phys., 16, 3463–3483, https://doi.org/10.5194/acp-16-3463-2016, 2016.**
**Krämer et al., A microphysics guide to cirrus – Part 2: Climatologies of clouds and humidity from observations, Atmos. Chem. Phys., 20, 12569–12608, https://doi.org/10.5194/acp-20-12569-2020, 2020.**
**Krämer et al., A microphysics guide to cirrus – Part 3: Occurrence patterns of cloud particles, Atmos. Chem. Phys., 25, 13563–13583, https://doi.org/10.5194/acp-25-13563-2025, 2025.**

**Response:** The mentioned papers have been discussed and cites in the revised manuscript in Lines 63-74:

*"Cirrus clouds also encompass a wide variety of formation pathways and microphysical states, ranging from in situ cirrus formed directly at low upper-tropospheric temperatures to liquid-origin cirrus developing from the glaciation of pre-existing mixed-phase clouds (Krämer, 2016, 2020; Krämer et al., 2025). Their formation is critically controlled by temperature, ice supersaturation, vertical motion, and the availability and ice-nucleating ability of aerosol particles. Consequently, relatively small changes in the thermodynamic environment or aerosol population may alter ice crystal number concentrations and cloud optical properties, with potential consequences for cirrus persistence and radiative effects (Kanji et al., 2017; Knopf and Alpert, 2023).*

*A central challenge in representing cirrus clouds in atmospheric models is the competition between homogeneous freezing and heterogeneous ice nucleation. Homogeneous freezing of solution droplets generally requires high ice supersaturation and can produce large numbers of ice crystals, whereas heterogeneous nucleation on ice-nucleating particles can initiate ice formation at lower supersaturation and modify the subsequent evolution of the cloud (Kärcher et al., 2022, 2023).”*

**Comment: Line 46: The used reference should be substituted by Hoose and Moehler 2012, Kanji et al. 2017, and Knopf and Alpert, 2023. With respect to dust, often cited papers are: DeMott et al., 2010, 2015, Niemand et al., 2012, Ullrich et al., 2017**

**Response:** The recommended references have been incorporated:

Lines 66-70: *“Consequently, relatively small changes in the thermodynamic environment or aerosol population may alter ice crystal number concentrations and cloud optical properties, with potential consequences for cirrus persistence and radiative effects (Kanji et al., 2017; Knopf and Alpert, 2023).”*

Lines 83-86: *“Mineral dust is particularly relevant in this context because it represents one of the most important atmospheric sources of ice-nucleating particles, although its activity depends strongly on particle concentration, mineralogical composition, temperature, and nucleation mode (DeMott et al., 2003, 2010; Niemand et al., 2012; Ullrich, 2017).”*

**Comment: Lines 46–51: Line 48: The first lidar network paper reporting a Saharan dust outbreak towards Central Europe (in October 2001) was published in 2003 (Ansmann et al., 2003). Could be mentioned!**

**Response:** The recommended references have been incorporated:

Lines 92-94: *“In this context, Saharan mineral dust plays a particularly important role (Ansmann et al., 2019; Seifert et al., 2023; Weger et al., 2018). During long-range transport events, large quantities of mineral dust can reach Europe, including Central Europe (Ansmann et al., 2003; Pey et al., 2013; Rogora et al., 2004; Salvador et al., 2022; Varga, 2020).”*

**Comment: Line 51: Here one should mention the paper of Atkinson et al., 2013, highlighting the feldspar impact.**

**Response:** The recommended references have been incorporated:

Lines 94-97: *“Mineral aerosol particles, especially those rich in K-feldspar, quartz and calcite, are known to act as highly efficient heterogeneous ice nuclei under the low-temperature conditions of the upper troposphere (Atkinson et al., 2013; Chatziparaschos et al., 2023; Harrison et al., 2019; Hoose et al., 2008; Hoose and Möhler, 2012; Seifert et al., 2010).”*

**Comment: Lines 86-88: 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:

Lines 162-167: *"2.1. Study area*
*The study focuses on Hungary, located in the Carpathian Basin, Central Europe (all of the analyses were conducted using the shapefile defining the national borders). Due to its geographical location, the region is situated at the intersection of several major atmospheric circulation systems, where Atlantic, Mediterranean, and continental influences all play important roles. The region is particularly sensitive to Saharan dust intrusions, which occur most frequently and intensely during the spring and summer seasons (Varga, 2020)."*

**<u>Comment:</u> Line 92: 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? To my opinion, Saharan dust loading is usually confined to the height range from the surface to 6 km height (over Europe), and the upper troposphere is often not affected by Saharan dust. However, cirrus preferably starts formation close to the tropopause (in situ cirrus). Any comment on this would be good!**
**Does MERRA-2 provide height information about dust loading? … so that on could check how often the upper troposphere is dust-loaded or dust-free when MERRA 2 indicates a dust event in terms of dust column mass concentration.**

**<u>Response:</u>** We fully agree with the reviewer that column-integrated dust mass density alone cannot establish whether Saharan dust reaches cirrus-forming altitudes. To address this important limitation, we have substantially extended our analysis by incorporating vertically resolved MERRA-2 dust mass mixing ratios, which demonstrate that Saharan dust was present at upper-tropospheric altitudes during nearly all investigated dust events. Specifically, 95.7% of the 276 independently identified Saharan dust events exhibited mean dust mass mixing ratios exceeding $10^{-9}$ kg $kg^{-1}$ within the 7–12 km layer, while 81.2% exceeded this threshold even at 10–12 km. These findings provide direct evidence from the reanalysis data that Saharan dust frequently reaches cirrus-relevant altitudes over Central Europe, although its presence at these levels does not necessarily imply that dust particles actively participated in ice nucleation.
This analysis has been added to the Methods and Results. The results of the vertical analyses were also plotted on a new figure.

Methods:
Lines 173-188: "*The threshold-based analysis extends this approach by progressively selecting days exceeding different column-dust levels, thereby characterizing dust-load-dependent cloud responses and their evolution across consecutive five-year periods without relying on a single arbitrary dusty-day threshold. Finally, vertically resolved MERRA-2 dust mass mixing ratios at 7–12 km were used to determine whether mineral dust was actually present at cirrus-relevant altitudes and whether cloud properties were more closely associated with upper-tropospheric dust than with total-column loading. Thus, these metrics address complementary aspects of the problem—event occurrence, total dust burden, dust-*

*load dependence, and vertical dust–cloud co-occurrence—rather than representing alternative definitions of the same quantity."*

Lines 223-235: *"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.*

Lines 290-298: *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.*

*Results*

## *3.2.2. 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.*

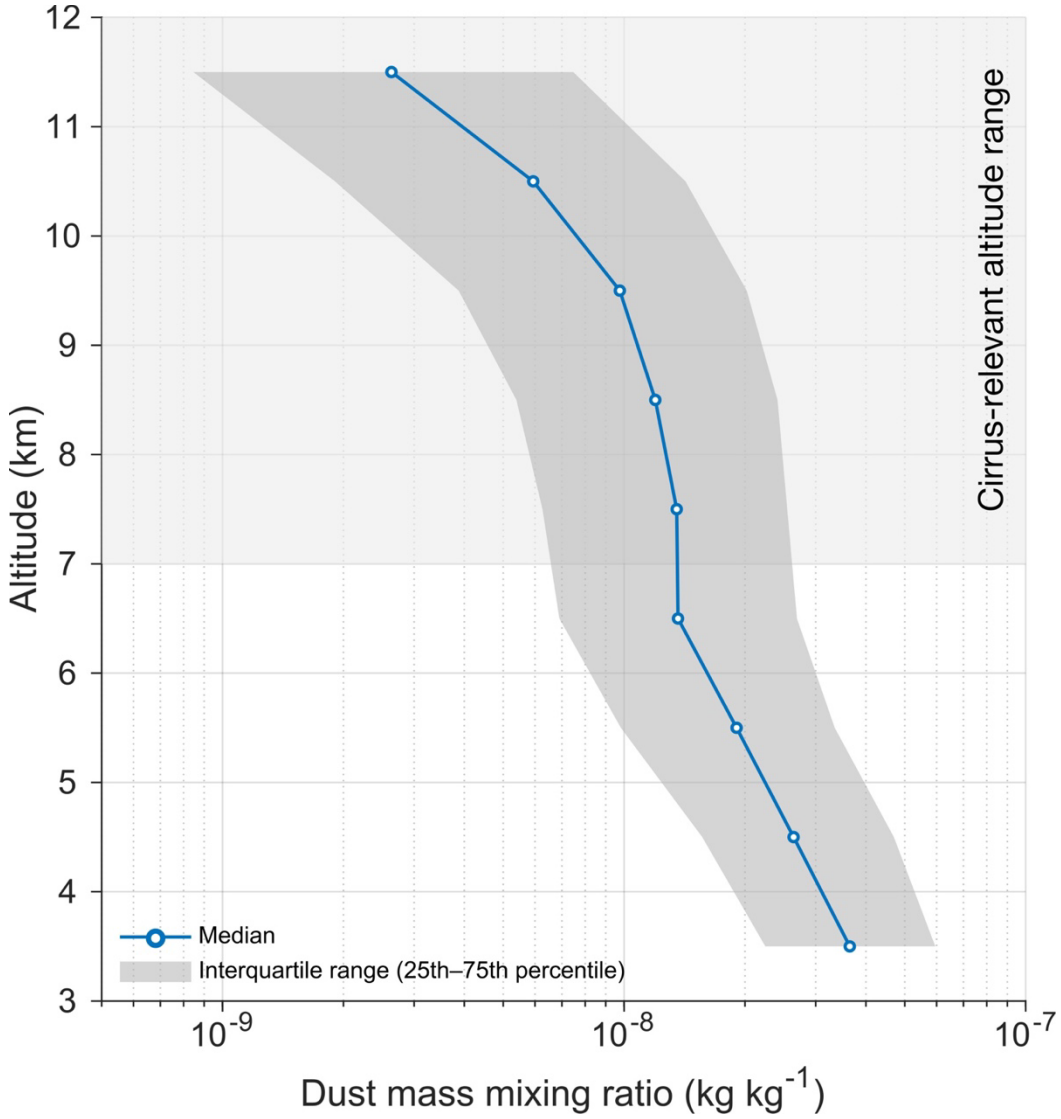


***Figure 3. Vertical distribution of Saharan dust during the 276 identified SDEs. (The line shows the median MERRA-2 dust mass mixing ratio, with the shaded envelope representing the interquartile range, while the shaded 7–12 km layer indicates cirrus-relevant altitudes.)***

**Comment: Lines 102-107: Later on, you show effective radius plots (Figure 2) in which the effective radius changes by a few micrometers within 20-25 years. How accurate are these MODIS retrieval products? I think some uncertainty bars in Figures 2d,e,f would solve the problem, whether the trends are trustworthy or not.**

Response: We agree that relatively small changes in MODIS-derived effective ice-particle radius should be interpreted with caution, particularly because satellite retrievals are subject to uncertainties associated with cloud optical thickness, cloud heterogeneity, particle shape assumptions, and retrieval conditions.

In the revised manuscript, we have therefore placed greater emphasis on the statistical robustness and seasonal consistency of the observed differences rather than interpreting small changes in effective radius as direct evidence of dust-induced ice nucleation. Conventional uncertainty estimates or error bars cannot be directly assigned to the values presented in the dust-threshold-based diagrams, as these values represent statistical summaries of observations grouped according to predefined dust-loading thresholds rather than individual measurements with directly quantifiable uncertainties.

Lines 272-276: *"The cirrus reflectance dataset was used to characterize variations in the optical reflectivity of high-level ice clouds, while the ice cloud effective particle radius variable provided estimates of the effective size of ice crystals within cirrus clouds. (MODIS-derived effective ice-particle radii are subject to retrieval uncertainties associated with cloud optical thickness, ice crystal shape assumptions, and cloud heterogeneity, which should be considered when interpreting small differences of a few micrometres, particularly in long-term comparisons.)"*

**Comment: A reference to the model GAM would be fine.**
Response: We thank the reviewer for this suggestion. However, we would like to clarify that the Generalized Additive Model (GAM) has been completely removed from the revised manuscript following a substantial revision of the statistical methodology. The revised analysis is now based on daily observations rather than cumulative dust-threshold averages, and alternative statistical approaches have been implemented and described in detail in the Methods section. Consequently, a reference to GAM is no longer applicable, as this modelling approach is not used anywhere in the revised study:

## *"2.4. 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 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."*

**Comment: Lines 157-164: Here again, do you have the potential to check how often dust was present at heights above 7-8 km when the dust column mass density threshold was exceeded? Mattis et al., JGR, 2008 provide height resolved statistics on Saharan dust events over Germany? Please check that paper!**

**Response:** We thank the reviewer for this valuable suggestion. As explained in our response to an earlier comment, we have substantially extended our analysis to explicitly investigate the vertical distribution of Saharan dust using the vertically resolved MERRA-2 dust mass mixing ratio fields. This additional analysis allowed us to determine how frequently Saharan dust reached the upper troposphere, particularly the 7–12 km altitude range relevant to cirrus cloud formation. Our results demonstrate that dust was present at these altitudes during nearly all investigated Saharan dust events, providing important additional evidence beyond the column-integrated dust mass density data used in the original manuscript. The methodology and results of this vertical analysis are now described in detail in the revised manuscript.

**Comment: Tables 1,2, and 3: I always ask myself in case of large and complex tables, what is the key information here? And this key information should be visualized! Readers are attracted by good section headlines and by figures, not by long tables. The tables could be**

**moved into the Appendix section or in a Supplementary unit. I leave that open to the authors, what to do with the tables.**

**Response:** We agree. The tables have been simplified.

**Table 1. Seasonal and total frequency and intensity of Saharan dust events (SDEs) over the Carpathian Basin during the 2001–2025 period.**

| | Winter | | Spring | | Summer | | Autumn | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| Timeframe | SDEs | Dust mass | SDEs | Dust mass | SDEs | Dust mass | SDEs | Dust mass | SDEs | Dust mass |
| | (n) | (avg.) [g $m^{-2}$] | (n) | (avg.) [g $m^{-2}$] | (n) | (avg.) [g $m^{-2}$] | (n) | (avg.) [g $m^{-2}$] | (n) | (avg.) [g $m^{-2}$] |
| **2001-2005** | 3 | 0.009 | 18 | 0.011 | 11 | 0.007 | 8 | 0.005 | 40 | 0.009 |
| **2006-2010** | 12 | 0.006 | 18 | 0.007 | 10 | 0.005 | 8 | 0.005 | 48 | 0.006 |
| **2011-2015** | 12 | 0.006 | 25 | 0.007 | 16 | 0.003 | 7 | 0.004 | 60 | 0.005 |
| **2016-2020** | 10 | 0.004 | 26 | 0.008 | 16 | 0.003 | 9 | 0.005 | 61 | 0.006 |
| **2021-2025** | 5 | 0.006 | 29 | 0.008 | 19 | 0.007 | 14 | 0.005 | 67 | 0.007 |
| **Total** | **42** | **0.006** | **116** | **0.008** | **72** | **0.005** | **46** | **0.005** | **276** | **0.006** |

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.

**Comment: Lines 215-216: It would be nice to have a sketch to illustrate high and low pressure systems and resulting air mass transport features of types 1,2, and 3. But then the question arises, the meteorological pattern leading to types 1, 2 and 3 belong to the main Saharan dust layer? And the main Saharan dust layer is typically below 6 km above Central**

**Europe. How is then the link between the air mass transport pattern and the cirrus formation event, mainly taking place above 8 km height?**
**It would be interesting to have even a class (some kind of type 4) without any dust, i.e., a dust-free class, i.e., MERRA indicates upper tropospheric (sulfate) aerosol background conditions and thus homogeneous freezing conditions?**

**Response:** We thank the reviewer for these suggestions. We now clearly distinguish between the large-scale atmospheric transport patterns and the actual vertical distribution of Saharan dust. The latter is independently assessed using the newly incorporated vertically resolved MERRA-2 dust mass mixing ratio data, allowing us to evaluate the presence of dust at cirrus-forming altitudes. The different synoptic transport types have already been discussed in detail in the cited studies by Varga et al., which provide the relevant meteorological context.

Regarding the suggested additional dust-free category (Type 4), we would like to emphasize that the synoptic classification is specifically intended to distinguish between different atmospheric circulation patterns associated with Saharan dust transport. Therefore, a dust-free category would not be directly comparable to the existing transport types. Nevertheless, dust-free reference conditions are extensively considered throughout the revised manuscript. Although they are not included as a separate synoptic type, low-dust reference periods are repeatedly incorporated into the analyses of the other atmospheric and cloud-related variables, providing a baseline against which the characteristics of Saharan dust events are evaluated. Thus, the revised study explicitly addresses dust-free background conditions through multiple statistical comparisons, without introducing an additional category into the synoptic classification.

**Comment: Line240-242: You discuss effective-radius tendencies of 30.3, 29.9, and 28.2 micrometer. Is it really possible to derive effective radius information with an accuracy of better than 1 micrometer. For me, all the values just show effective radii around 30 micrometer and thus rather constant microphysical properties over the 25 years.**

**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: Line 323: 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.

Lines 246-272: *"In MERRA-2, low-, middle-, and high-level cloud fractions correspond to clouds occurring between the surface and 700 hPa, 700 and 400 hPa, and above 400 hPa, respectively. These pressure ranges approximately correspond to altitudes of 0–3 km, 3–7 km, and >7 km, although their actual geometric heights vary with atmospheric conditions."*

**Comment: Lines 336-338: Is that statement in line with simulations of Kaercher et al., 2022 (heterogeneous versus homogeneous ice nucleation, the paper is mentioned above)? Usually, simulation show that more ice crystals are produced in homogeneous freezing processes than in heterogeneous ice nucleation processes.**

**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.

Lines 71-74: *A central challenge in representing cirrus clouds in atmospheric models is the competition between homogeneous freezing and heterogeneous ice nucleation. Homogeneous freezing of solution droplets generally requires high ice supersaturation and can produce large numbers of ice crystals, whereas heterogeneous nucleation on ice-nucleating particles can initiate ice formation at lower supersaturation and modify the subsequent evolution of the cloud (Kärcher et al., 2022, 2023).*
*(…)*
Lines 83-91: *Mineral dust is particularly relevant in this context because it represents one of the most important atmospheric sources of ice-nucleating particles, although its activity depends strongly on particle concentration, mineralogical composition, temperature, and nucleation mode (DeMott et al., 2003, 2010; Niemand et al., 2012; Ullrich, 2017). Model simulations therefore indicate that the response of cirrus clouds to mineral dust is not necessarily monotonic: enhanced heterogeneous nucleation may modify or suppress subsequent homogeneous freezing, while variations in vertical velocity and supersaturation can substantially change the resulting ice crystal population (Kärcher et al., 2022, 2023). Assessing dust–cirrus interactions thus requires consideration not only of atmospheric dust loading, but also of whether mineral dust reaches cirrus-forming altitudes and encounters thermodynamic and dynamical conditions favourable for heterogeneous ice nucleation.*

**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.

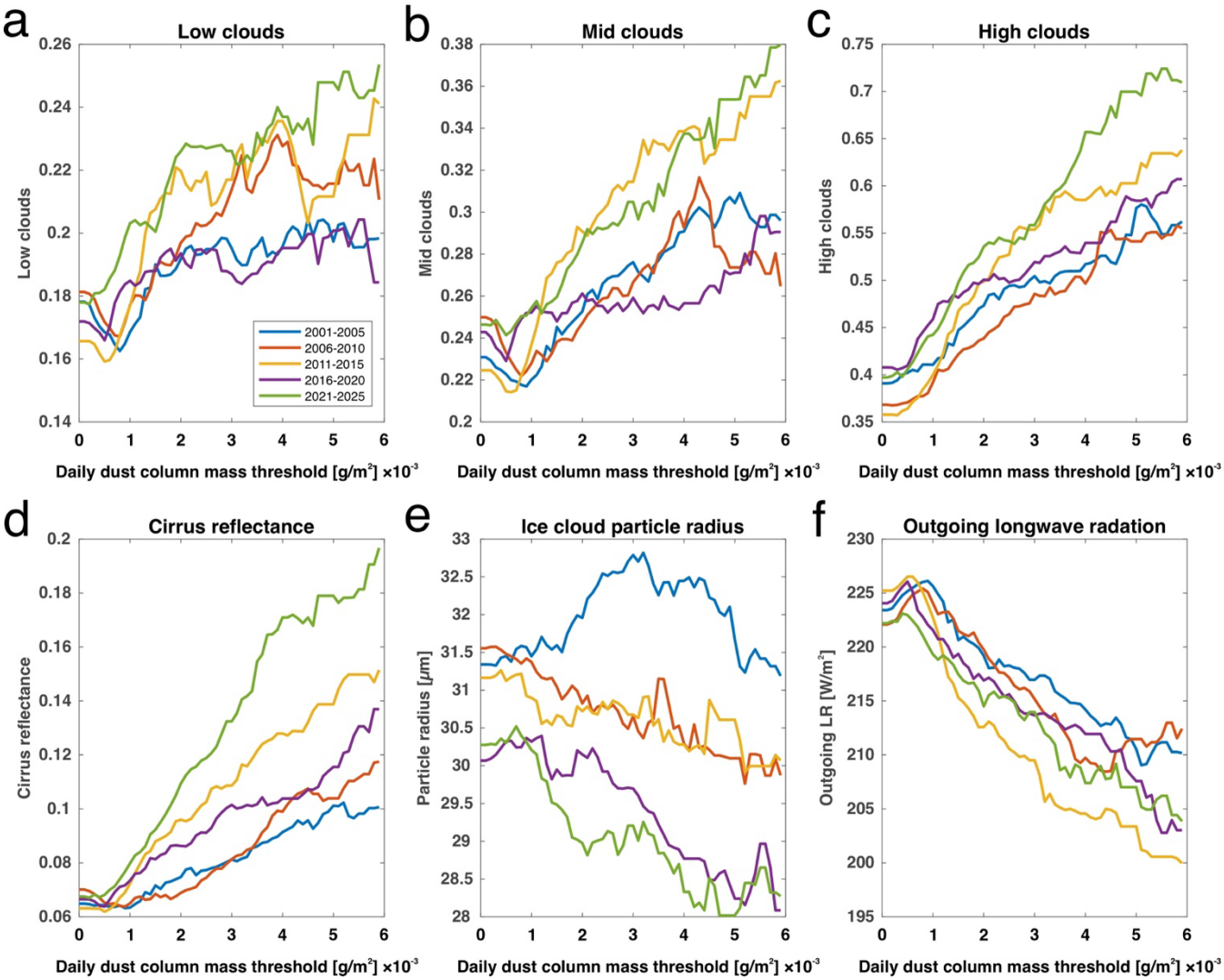


***Figure 4. Variations in the investigated atmospheric and cloud-physical parameters as a function of daily dust column mass density thresholds during 2001–2025, presented for consecutive five-year periods. Panels show (a) low-, (b) middle-, and (c) high-level area-averaged cloud fractions, (d) cirrus reflectance, (e) ice-cloud effective particle radius, and (f) outgoing longwave radiation.***

**Comment: Figure 2e (ice cloud particle radius). This effective radius information is probably related to the cirrus top region. In the virga zone, the effective radius is probably larger than 100 microns. Again, the range of values from 28 to 33 micrometer is so small and uncertainty bars are missing! Can we trust the trends in the different figures?**

**Response:** We thank the reviewer for this important observation. We agree that MODIS-derived effective ice-particle radii primarily characterize the radiatively relevant portion of the observed ice clouds and should not be interpreted as representative of the entire vertical cloud structure, particularly the virga region, where substantially larger ice particles may occur.

We also acknowledge that the relatively small variations in effective radius (approximately 28–33 µm) must be interpreted with caution, as MODIS retrievals are subject to uncertainties associated with cloud optical thickness, ice crystal shape assumptions, and cloud

heterogeneity. These uncertainties may be comparable to the observed differences of a few micrometres.

Importantly, the statistical methodology and the corresponding figures have been substantially revised. The original threshold-based analysis has been replaced by comparisons based on daily observations, with statistical significance assessed using the Mann–Whitney U test and adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate procedure. The revised results indicate that statistically significant differences in effective ice-particle radius are primarily confined to spring, whereas the differences observed in other seasons are not statistically significant.

We emphasize that statistical significance does not eliminate the inherent uncertainties of satellite retrievals. Consequently, we do not interpret the small effective-radius differences as conclusive evidence of dust-induced changes in ice-crystal size or as proof of heterogeneous ice nucleation. Instead, these results are presented as complementary, seasonally specific observations supporting the broader dust–cirrus associations identified in the study. The corresponding limitations have been clarified in the revised manuscript.

**Comment: Figure 2f (outgoing longwave radiation): You were able to clearly separate the dust impact on the outgoing IR radiation fluxes from the respective cirrus impact on the outgoing IR radiation? Please comment on that within the discussions presented in lines 347-365 (Sect. 3.5).**

**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.

Lines 1125-1132: *"Across all five-year periods, progressively higher dust-loading thresholds were associated with lower OLR values. The magnitude and absolute level of this response varied among periods, with particularly low OLR values under high dust-loading conditions during 2011–2015 and 2016–2020. These results demonstrate a persistent dust-load dependence of springtime OLR, but do not indicate a uniform monotonic strengthening of the relationship over the full 25-year period.*
*It should be noted that the observed OLR response cannot be attributed exclusively to dust-associated changes in cirrus, because mineral dust itself contributes to the longwave radiative balance. The OLR variations are therefore interpreted here as an integrated radiative signature associated with dust-loading conditions rather than as an isolated cirrus radiative effect."*

**Comment: Lines 373-379: Please check the papers of Pieper et al. (2026) (observations) and Juurikkala et al. (2026) (simulations) regarding the impact of atmospheric dynamics (wind shear, turbulence, and consequences for updraft strength and related supersaturation strength) on ice crystal nucleation! The fundamental question is: Is the enhanced INP number concentration responsible for all the trends in your results? Or is that related to changes in the dynamics when Saharan dust events occur. With other words, please include the dynamics aspect in your 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.

Lines 1192-1222: *"The pronounced seasonal differences further suggest that upper-tropospheric dust abundance alone is insufficient to determine the cloud response. In summer, enhanced Dust7–12 was most clearly associated with increased high-cloud fraction, whereas autumn exhibited particularly pronounced differences in cloud-top pressure and temperature. Such differences are consistent with the strong dependence of ice-cloud formation on the thermodynamic and dynamical environment. Temperature, ice supersaturation, vertical motion, and moisture availability may determine whether mineral dust reaching 7–12 km can effectively participate in ice formation and how the resulting cloud field develops. The seasonal dependence therefore provides an important indication that the observed dust–cloud relationship is conditional on the atmospheric environment.*
*The vertically resolved results also help explain why relationships based on total-column dust loading were comparatively weak. Total-column dust combines aerosol located at very different altitudes, much of which may have limited relevance to upper-tropospheric ice-cloud formation. Consequently, a strong SDE can exhibit high column-integrated dust loading while containing relatively little mineral dust near cirrus-forming levels. Explicit consideration of Dust7–12 reduces this vertical mismatch and reveals substantially clearer differences between events characterized by relatively low and high upper-tropospheric dust abundance. This emphasizes the importance of representing aerosol vertical distribution, rather than column loading alone, when investigating mineral dust–cirrus interactions.*
*Nevertheless, the observed differences should not be interpreted as direct evidence of dust-induced ice nucleation. Saharan dust reaching the upper troposphere is transported by atmospheric circulation that simultaneously determines vertical motion, humidity, temperature, and cloud formation. The high-Dust7–12 and low-Dust7–12 SDE subsets may therefore also represent different meteorological regimes. The present results demonstrate that upper-tropospheric dust occurrence is closely associated with distinct cloud states, but separating direct aerosol microphysical effects from the meteorological conditions responsible for both vertical dust transport and cloud development requires additional thermodynamic and dynamical information.*
*The complementary total-column threshold analysis also indicated increasing middle-level cloud fraction at higher dust-loading thresholds, suggesting that the observed relationships are not restricted to the classical cirrus altitude range. This suggests that the influence of Saharan dust may extend beyond classical cirrus formation and potentially affect cloud systems developing within the mixed-phase temperature regime. The temporal evolution of the dust–cloud relationship cannot be interpreted solely in terms of changes in mineral-dust INP availability. Cirrus nucleation and subsequent cloud development are also strongly controlled by the dynamical environment, including vertical velocity, wind shear, turbulence, and the associated variability in ice supersaturation. Recent observations of dusty cirrus and large-eddy simulations indicate that changes in turbulence and updraft strength can substantially modify ice crystal nucleation, cloud structure, and persistence even under comparable aerosol conditions (Juurikkala et al., 2026; Pieper et al., 2026). Thus, the observed changes in cirrus properties during Saharan dust events may reflect a combined*

*influence of mineral-dust availability and concurrent changes in upper-tropospheric dynamics rather than an aerosol effect alone."*

**Comment: Line 382: You are using dust column values! Maybe the dust fraction (contribution to the column value) for the upper troposphere increased with 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: Line 388: Again, the effective radius changes are so small! Is it really possible to retrieve this property so precisely over 25 years and for different dust column mass values? Are all the trends trustworthy? Do changes of a few micrometers rather than by 20-50 micrometers or even more, indicate different formation conditions? To my opinion, changes by 2 micrometer with inceasing dust column mass and variations by 3 micrometer withing 25 years indicate more or less unchanged cirrus conditions from 2001 to 2025! Please defend your position and comment on this!**

**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.

Lines 1514-1520: *"The five-year springtime analysis further revealed that these cloud changes were not accompanied by a monotonic increase in upper-tropospheric dust loading. Instead, the relative cirrus-reflectance enhancement during high-Dust7–12 SDEs increased from 143% in 2001–2005 to 398% in 2021–2025, whereas high-cloud fraction and cloud-top properties showed persistent but non-monotonic anomalies and effective ice particle radius exhibited greater temporal variability. Collectively, the results indicate increasingly frequent Saharan dust intrusions and a more pronounced springtime cirrus optical response during SDEs containing substantial dust at cirrus-relevant altitudes, rather than a uniform strengthening across all investigated cloud and radiative properties."*

**Comment: Line 468: DIBS was obviously presented in Ansmann et al. (2019a), not in the Ansmann et al. (2019b) conference paper. In the 2019a paper, the entire lidar/radar approach is described as well. So, Ansmann et al. (2019b) is not needed.**

**Response:** Thank you. The citation has been corrected and the unnecessary Ansmann et al. (2019b) reference has been removed.

*Direct observational evidence for this mechanism was provided by (Ansmann et al., 2019) using combined lidar and radar measurements over Cyprus. The authors found a close correspondence between predicted INP concentrations and observed ice crystal concentrations within Saharan dust-containing middle- and upper-tropospheric cloud layers. The investigated cirrus clouds formed at altitudes between 8 and 11 km and temperatures ranging from −35 to −57 °C, and in several cases the observed ice crystal concentrations could be fully explained by the available dust-derived INPs. Particularly noteworthy is the "dust-*

*infused baroclinic storm" (DIBS) case described by the authors, in which a North African dust outbreak injected large quantities of Saharan dust into the upper troposphere. The resulting dust-enriched cirrus system could be tracked for more than 3,500 km from the Mediterranean to Central Asia, and the study concluded that mineral dust substantially contributed to the persistence and longevity of the cirrus cloud system. Similar dust-cirrus interactions were described in detail by other (Central) European studies (Seifert et al., 2023; Weger et al., 2018).*

**Comment: Sections 4.3 and 4.4 should be kept short. They are too long and not very interesting. Such a general and extended discussion is not needed in this paper. It would be more interesting to formulate some fundamental questions on future cirrus developments in a changing climate, and leave the answers open to the modelling community in order to find plausible solutions to these questions.**

**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

**This study examines associations between Saharan dust intrusions and upper-tropospheric cloud properties over the period 2001-2025. It makes the strong claim of a strengthening of the dust-cirrus relationship over that relatively short period. In the referee's opinion, the analysis is not reproducible and the manuscript does not demonstrate its main claim. The main concerns are detailed below; in particular, the GAM input may be redundant, and the manuscript repeatedly gives statistical links a causal interpretation which is not corroborated by the observational analysis presented. Furthermore, presenting the results in very large tables makes the demonstration very hard to follow. In light of these issues, I recommend that the paper be rejected at this stage.**

**Response:** 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.

**Comment: Presentation – The paper's tables contain roughly 500 populated entries that cannot be interpreted efficiently. Table 1 is particularly overloaded and split across pages, while Table 3 presents excessive numerical precision and many repetitive significance**

**values. The authors should substantially simplify the main-text tables. In their present form, the tables obscure the 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.

**Table 1. Seasonal and total frequency and intensity of Saharan dust events (SDEs) over the Carpathian Basin during the 2001–2025 period.**

| | Winter | | Spring | | Summer | | Autumn | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Timeframe** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** |
| | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** |
| **2001-2005** | 3 | 0.009 | 18 | 0.011 | 11 | 0.007 | 8 | 0.005 | 40 | 0.009 |
| **2006-2010** | 12 | 0.006 | 18 | 0.007 | 10 | 0.005 | 8 | 0.005 | 48 | 0.006 |
| **2011-2015** | 12 | 0.006 | 25 | 0.007 | 16 | 0.003 | 7 | 0.004 | 60 | 0.005 |
| **2016-2020** | 10 | 0.004 | 26 | 0.008 | 16 | 0.003 | 9 | 0.005 | 61 | 0.006 |
| **2021-2025** | 5 | 0.006 | 29 | 0.008 | 19 | 0.007 | 14 | 0.005 | 67 | 0.007 |
| **Total** | **42** | **0.006** | **116** | **0.008** | **72** | **0.005** | **46** | **0.005** | **276** | **0.006** |

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.

**Comment: Reproducibility – The paper never states exactly what the GAM inputs are or over which geographic domain the averages are calculated: it is unclear whether the**

**domain is Hungary, the Carpathian Basin, or another Central European region, and no spatial mask is defined. Under these conditions, the analysis cannot be reproduced. Given that the datasets have global coverage, the authors should also justify the regional restriction and demonstrate whether the reported relationship persists in a broader or global analysis, which would improve sampling and establish its generality.**

**Response:** 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. 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.

Lines 162-167: "***2.1. Study area***
*The study focuses on Hungary, located in the Carpathian Basin, Central Europe (all of the analyses were conducted using the shapefile defining the national borders). Due to its geographical location, the region is situated at the intersection of several 165 major atmospheric circulation systems, where Atlantic, Mediterranean, and continental influences all play important roles. The region is particularly sensitive to Saharan dust intrusions, which occur most frequently and intensely during the spring and summer seasons (Varga, 2020)."*

**Response:** We thank the reviewer for this suggestion. However, we would like to clarify that the Generalized Additive Model (GAM) has been completely removed from the revised manuscript following a substantial revision of the statistical methodology. The revised analysis is now based on daily observations rather than cumulative dust-threshold averages, and alternative statistical approaches have been implemented and described in detail in the Methods section. Consequently, a reference to GAM is no longer applicable, as this modelling approach is not used anywhere in the revised study:

Lines 282-446:

## *"2.4. 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 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."*

## 3. Statistical significance and validity

**Comment: Statistical significance and validity – Section 2.4 appears to describe cumulative threshold curves: days above a high dust threshold also contribute to means at every lower threshold. If these threshold means are used as GAM inputs, adjacent thresholds largely correspond to the same daily data and are not independent. This "replication" could be the reason for the large R2 values and very small p-values. If cumulative means are indeed used, appropriate statistical tests should be performed; the inference should be rebuilt at the daily or event level, accounting for temporal autocorrelation and using block-based uncertainty estimates.**

**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: Causality versus correlation – 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.

Lines 1250-1277:

### *"4.2. Evidence for changing dust–cloud relationships*

*The combined results indicate that the relationship between Saharan dust and upper-level cloud properties over Hungary has evolved during the past 25 years, although this evolution cannot be described as a uniform strengthening across all investigated variables. The clearest long-term change was found in cirrus reflectance, for which the SDE-associated anomaly increased substantially between the beginning and the end of the study period. Together with the increasing frequency of SDEs, this suggests that the long-term evolution involves both more frequent dust intrusions and changes in the optical properties of cirrus associated with high dust loading.*
*The consistency of the event-based comparisons strengthens this interpretation. SDEs with higher upper-tropospheric dust abundance showed more pronounced differences in several cloud properties not only relative to low-dust background conditions, but also relative to SDEs with lower Dust7–12 concentrations. This distinction is important because the latter comparison is restricted entirely to independently identified Saharan dust events and therefore specifically addresses differences associated with the amount of dust reaching cirrus-relevant altitudes. The strongest and most coherent contrasts occurred in winter and spring, while their magnitude and the affected cloud properties varied among seasons.*
*The pronounced seasonal dependence, particularly the coherent response observed in spring, further suggests that the effect associated with dust depends on the thermodynamic state of the atmosphere. Mineral dust can provide efficient ice-nucleating particles, but its influence on cirrus formation requires favourable temperature and ice-supersaturation conditions. Enhanced cirrus reflectance is therefore physically consistent with dust-related modification*

*of ice-cloud formation. However, the weak and seasonally inconsistent response of effective ice particle radius does not provide sufficient evidence for a specific microphysical pathway, and heterogeneous ice nucleation should be regarded as a plausible interpretation rather than a directly demonstrated mechanism.*
*An important limitation is that Saharan dust transport and cloud formation are both closely linked to synoptic meteorological conditions. Moisture transport, vertical motion, temperature, and upper-tropospheric humidity may therefore contribute to the observed associations. Consequently, the results demonstrate a robust dust–cloud association, but do not establish causality. Long-term changes in the occurrence of conditions favourable for ice supersaturation could also contribute to a possible strengthening cirrus response, although such conditions were not directly quantified in this study."*

**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.
This analysis has been added to the Methods and Results. The results of the vertical analyses were also plotted on a new figure.

Methods:
Lines 173-188: "*The threshold-based analysis extends this approach by progressively selecting days exceeding different column-dust levels, thereby characterizing dust-load-dependent cloud responses and their evolution across consecutive five-year periods without relying on a single arbitrary dusty-day threshold. Finally, vertically resolved MERRA-2 dust mass mixing ratios at 7–12 km were used to determine whether mineral dust was actually present at cirrus-relevant altitudes and whether cloud properties were more closely associated with upper-tropospheric dust than with total-column loading. Thus, these metrics address complementary aspects of the problem—event occurrence, total dust burden, dust-load dependence, and vertical dust–cloud co-occurrence—rather than representing alternative definitions of the same quantity.*"

Lin*es 223-235: "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.*

Lines 290-298: *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.*

*Results*

## *3.2.2. 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.*

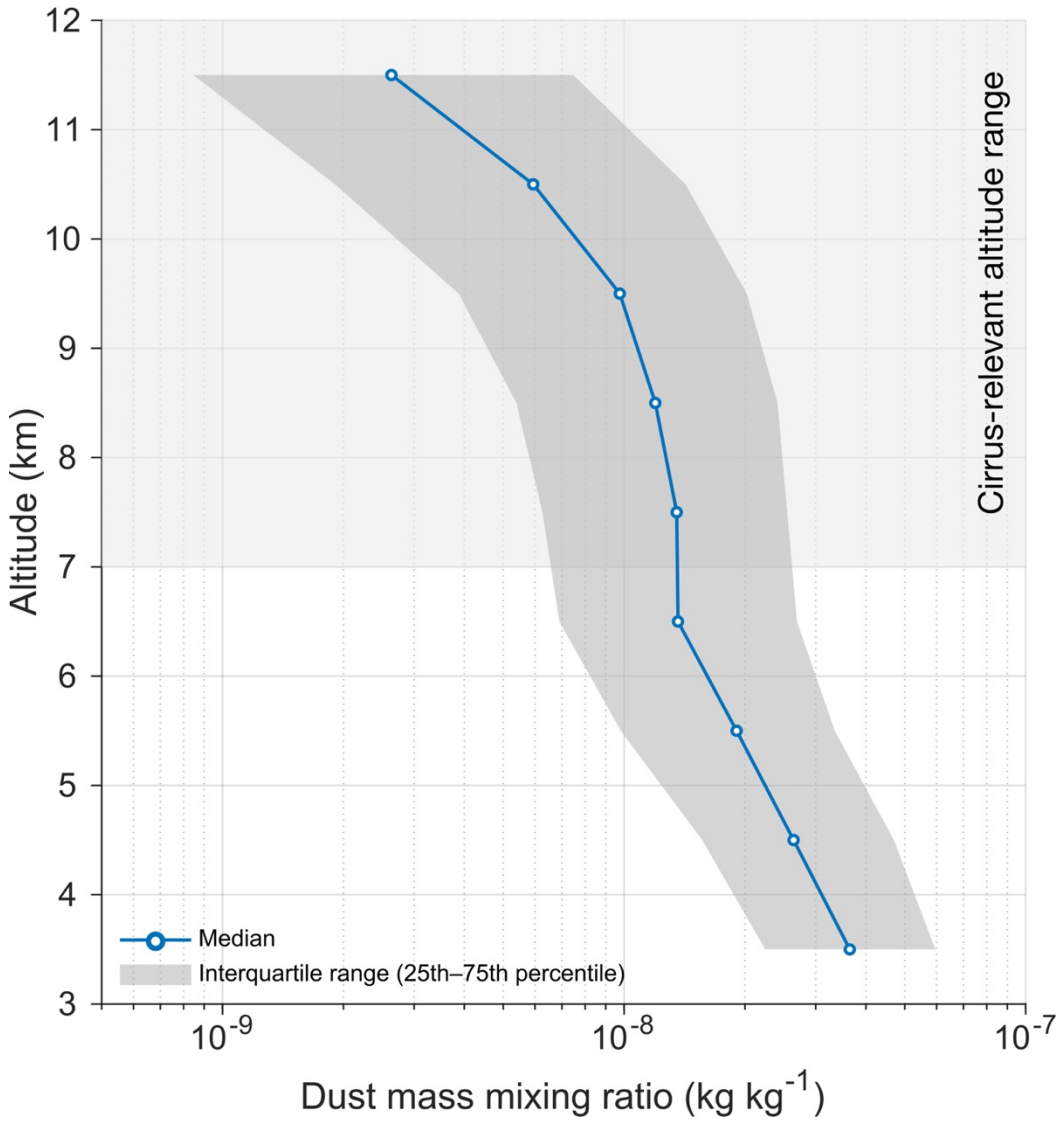


***Figure 3. Vertical distribution of Saharan dust during the 276 identified SDEs. (The line shows the median MERRA-2 dust mass mixing ratio, with the shaded envelope representing the interquartile range, while the shaded 7–12 km layer indicates cirrus-relevant altitudes.)***

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

**Comment: This submitted manuscript investigates the long-term influence of Saharan dust, which is a known driver of aerosol-cloud interactions, on cloud formation over the Carpathian Basin in central Europe. A collection of satellite observations, reanalysis and record data is used to study intrinsic and radiative cloud properties, with their analysis suggesting a strong link between dust events and seasonal weather in recent years. The work is of scientific interest howeve,r there is overly strong causal language used when describing statistical associations, especially when discussing dust loading's effect on cloud properties. The current manuscript is not sufficiently convincing to justify the strong interpretations present. There is not adequate treatment of confounding variables in the analysis, particularly meteorological covariation. We would recommend major revisions to address the concerns outlined below.**

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

**Comment: 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.

Lines 602-657:

*"3.3. 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 $6.73\times10^{-8}$ and $1.29\times10^{-7}$ 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.*

*As a complementary analysis independent of the vertically resolved SDE stratification, the longer-term behaviour was also examined using progressively restrictive total-column dust-loading thresholds applied to the complete daily dataset (Figure 4). Middle- and high-level cloud cover fractions generally increase with increasing dust column mass density, whereas low-cloud fraction shows neither a consistent dust-load dependence nor a systematic temporal pattern. The relationship is most pronounced for high clouds, for which higher dust-loading thresholds are associated with larger cloud fractions in nearly all five-year periods. Differences among the periods are also evident, with the largest high-cloud fractions occurring under the highest dust-loading conditions in the later part of the record. During 2021–2025, high-cloud fractions associated with the highest dust loads were approximately 1.5 times those observed during 2001–2005."*

Lines 1535-1574:

*"The event-based analysis of 276 independently identified Saharan dust events provided further evidence for a systematic dust–cirrus association. SDEs were characterized by significantly enhanced cirrus reflectance and high-cloud fraction and by higher and colder cloud tops, with the most coherent response occurring in spring. These patterns were consistently supported by event–background comparisons, effect-size estimates, and direct comparisons between SDEs with lower and higher upper-tropospheric dust concentrations. The vertically resolved analysis showed that the strongest cloud anomalies occurred during SDEs with enhanced mineral dust concentrations at 7–12 km. Relative to low-dust reference conditions, high-Dust7–12 SDEs were characterized by substantially greater cirrus reflectance and high-cloud fraction and by higher and colder cloud tops in all seasons. The response was particularly coherent in spring, when cirrus reflectance and high-cloud fraction were 272% and 133% higher, respectively, while effective ice particle radius was 7.2% smaller and OLR 14.4% lower than under low-dust conditions. The direct comparison between SDE subsets further showed significantly smaller ice particle radii during high- than during low-Dust7–12 spring events.*
*The five-year springtime analysis further revealed that these cloud changes were not accompanied by a monotonic increase in upper-tropospheric dust loading. Instead, the relative cirrus-reflectance enhancement during high-Dust7–12 SDEs increased from 143% in 2001–2005 to 398% in 2021–2025, whereas high-cloud fraction and cloud-top properties showed persistent but non-monotonic anomalies and effective ice particle radius exhibited greater temporal variability. Collectively, the results indicate increasingly frequent Saharan dust intrusions and a more pronounced springtime cirrus optical response during SDEs containing substantial dust at cirrus-relevant altitudes, rather than a uniform strengthening across all investigated cloud and radiative properties."*

**Comment: 2. The GAM analysis would be strengthened by having several aspects of its implementation clarified. Firstly, if each threshold represents all days exceeding that value, neighbouring threshold estimates will be based on strongly overlapping sets of observations and therefore cannot be treated as statistically independent. This would compromise the notably low p-values and high R2 values. If instead the thresholds define non-overlapping dust-loading bins, please state this explicitly. Secondly, the statement that high adjusted R2 demonstrates that dust loading explains a substantial fraction of cloud variability is inaccurate. The reported R2 describes the complete model defined on Line 125, not just dust loading.**

**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.
We thank the reviewer for this suggestion. However, we would like to clarify that the Generalized Additive Model (GAM) has been completely removed from the revised manuscript following a substantial revision of the statistical methodology. The revised analysis is now based on daily observations rather than cumulative dust-threshold averages, and alternative statistical approaches have been implemented and described in detail in the Methods section.

Lines 207-221: *Beyond the analysis of discrete dust events, the relationship between atmospheric dust loading and cloud properties was investigated using continuous dust column mass density thresholds. In this approach, progressively restrictive dust-loading thresholds were applied. Because no universally accepted threshold exists for distinguishing dusty and non-dusty conditions across different geographical and climatic environments, and seasons, multiple dust-loading thresholds were applied. Dust column mass density threshold values were systematically varied between 0 and 0.006 g $m^{-2}$ in increments of 0.0001 g $m^{-2}$. For each threshold value, daily mean cloud parameters, including cirrus reflectance, high cloud cover fraction, and effective ice particle radius, were calculated and subsequently analysed seasonally within consecutive five-year time windows across the 2001–2025 study period.*

*This approach enabled the assessment of how different dust-loading regimes are associated with changes in the optical and spatial characteristics of cirrus clouds. To evaluate radiative impacts, the same methodology was applied to ice cloud effective particle radius, cloud fractions (at different heights), outgoing longwave radiation (OLR) data, allowing the investigation of long-term relationships between atmospheric dust loading, cirrus cloud development, and upper-tropospheric radiative processes. While this total-column threshold analysis provides a complementary view of dust-load-dependent cloud variability over the full daily record, the event-based analysis described below focuses specifically on the 276 independently identified SDEs and uses vertically resolved dust information to assess whether mineral dust was present at cirrus-relevant altitudes.*

Lines 282-446:

## *"2.4. 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 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."*

**Comment: 3. The GAM formulation appears to assume independent residuals, but daily cloud, dust, and meteorological conditions are likely to exhibit substantial temporal persistence, particularly during multi-day Saharan dust events. Unaccounted residual autocorrelation can substantially underestimate uncertainty and inflate the significance of the smooth terms and Dust x Time interactions. Please examine and report residual autocorrelation and, where necessary, account for temporal dependence using an appropriate correlation structure or GAM formulation.**

**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 removed, 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.

**Comment: 4. A large column dust burden does not necessarily imply that said dust is available as INPs at cirrus altitude. The manuscript should clarify whether any vertically resolved dust data is available. If not, the framing of dust loading as direct evidence for increased INPs should be softened to an indicative proxy.**

**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.
This analysis has been added to the Methods and Results. The results of the vertical analyses were also plotted on a new figure.

Methods:
Lines 173-188: "*The threshold-based analysis extends this approach by progressively selecting days exceeding different column-dust levels, thereby characterizing dust-load-dependent cloud responses and their evolution across consecutive five-year periods without relying on a single arbitrary dusty-day threshold. Finally, vertically resolved MERRA-2 dust mass mixing ratios at 7–12 km were used to determine whether mineral dust was actually present at cirrus-relevant altitudes and whether cloud properties were more closely associated with upper-tropospheric dust than with total-column loading. Thus, these metrics address complementary aspects of the problem—event occurrence, total dust burden, dust-load dependence, and vertical dust–cloud co-occurrence—rather than representing alternative definitions of the same quantity.*"

Lin*es 223-235: "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.*

Lines 290-298: *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.*

### *3.2.2. 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 $9.63\times10^{-8}$ kg kg$^{-1}$ (Figure 3). Upper-tropospheric dust was not restricted to the lower part of this altitude range: the corresponding median was $8.33\times10^{-9}$ kg kg$^{-1}$ at 8–12 km and $4.37\times10^{-9}$ 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 $5\times10^{-9}$ 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.*

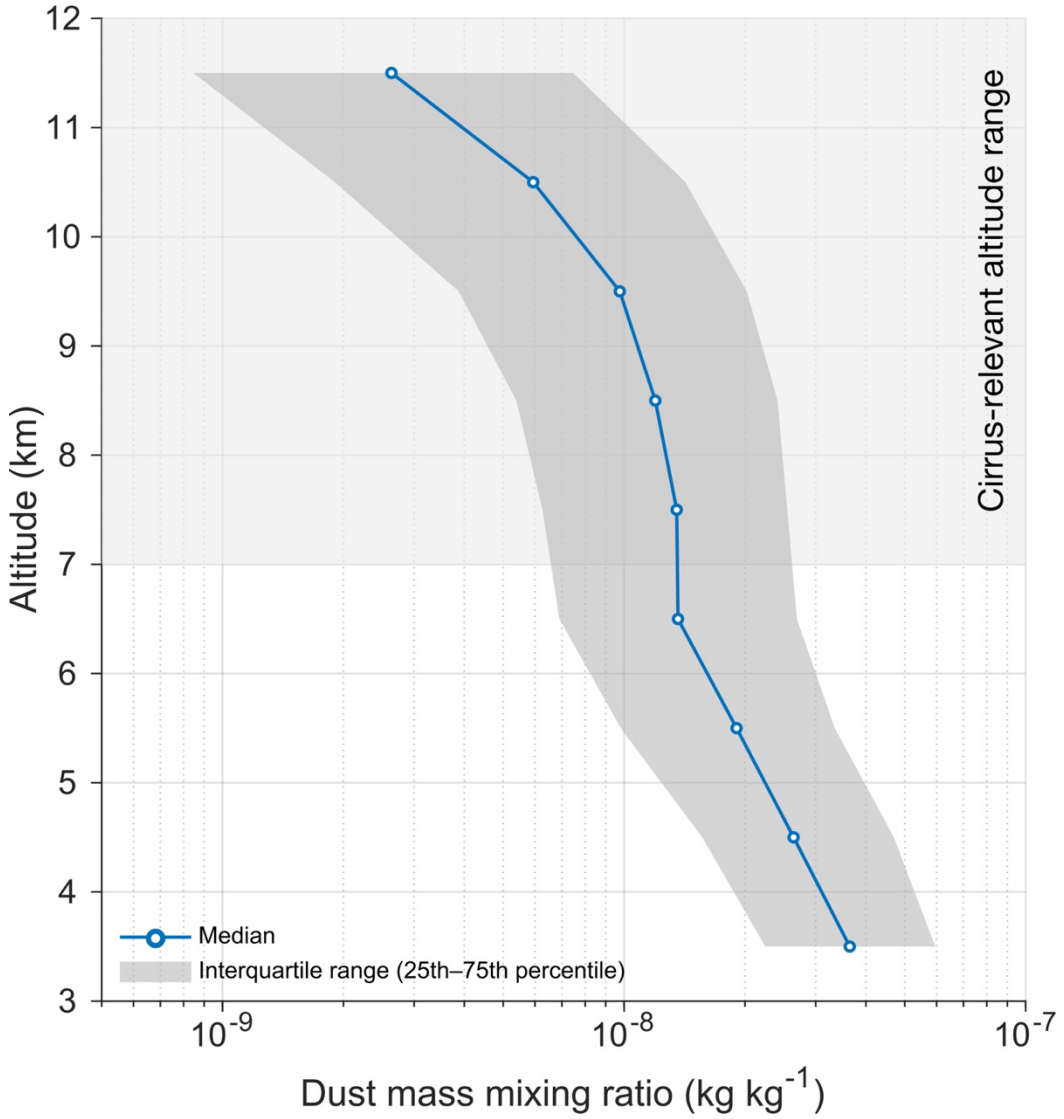


*Figure 3. Vertical distribution of Saharan dust during the 276 identified SDEs. (The line shows the median MERRA-2 dust mass mixing ratio, with the shaded envelope representing the interquartile range, while the shaded 7–12 km layer indicates cirrus-relevant altitudes.)*

**5. The temporal event analysis does not adequately account for an increase in total Saharan dust events. The 73\% increase in the number of high-reflectance events in Table 2 corresponds to essentially no increase in the proportion of high-reflectance events relative to dust events. I would recommend adjusting this analysis to relative rather than absolute counts.**

**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. (See our previus comment on long-term trends and Chapter 3.3. of the revised manuscript)

**Comment: 6. The manuscript repeatedly interprets smaller retrieved ice effective radius under higher dust loading as being consistent with enhanced heterogeneous ice-nucleation. The means of these groups differ from 30.3 to 28.2 µm, a relatively small change in my view. To make this claim the authors should demonstrate that this change is significant relative to documented MODIS retrieval biases and natural variability.**

**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.
In the revised manuscript, we have therefore placed greater emphasis on the statistical robustness and seasonal consistency of the observed differences rather than interpreting small changes in effective radius as direct evidence of dust-induced ice nucleation.
Our revised event-based analysis indicates that statistically significant differences in effective ice-particle radius are primarily confined to spring. During springtime Saharan dust events characterized by high upper-tropospheric dust concentrations (Dust7–12), the median effective radius was 28.44 µm, compared with 30.65 µm under low-dust reference conditions, corresponding to a reduction of approximately 2.22 µm (7.2%; FDR-adjusted $q \approx 0.0012$). Importantly, a separate comparison restricted entirely to independently identified Saharan dust events also revealed a significant difference between high- and low-Dust7–12 conditions (28.44 versus 31.90 µm, respectively; $q \approx 0.0023$).
These two independent group comparisons provide statistical support for a springtime association between enhanced upper-tropospheric dust abundance and smaller retrieved ice-particle radii. However, statistical significance does not eliminate the systematic uncertainties inherent in satellite retrievals, and the observed differences should not be interpreted as precise measurements of dust-induced changes in ice-crystal size.

**Comment: 7. Section 3.5 and 4.4 over interpret the OLR analysis. OLR is strongly affected by atmospheric temperature and humidity profiles, cloud fraction, and cloud top temperature, all of which vary with the meteorological regimes responsible for Saharan dust transport. The analysis demonstrates a dust-OLR association, not the radiative effect. Interpretation in these sections should be substantially moderated.**

**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.

Lines 1524-1529: *"The observed dust-associated variations in cirrus reflectance, high-cloud fraction, and OLR may therefore be considered within this broader context of changing aerosol, cloud, and radiative conditions, although the present regional analysis does not establish a direct connection to hemispheric-scale radiative trends. Our results suggest that Saharan mineral dust at mid-latitudes may influence not only the microphysical properties of*

*clouds but also contribute to upper-tropospheric energy exchange through the radiative effects associated with dust-related high-level ice clouds."*

## RE: Specific comments

**1. Twomey (1974) deals with liquid-cloud-aerosol interactions. I would suggest removing this reference.**
**Response:** We agree and have removed this reference from the discussion of ice-cloud aerosol interactions.

**2. Homogeneous nucleation does not require INPs. The authors may want to distinguish between homogeneous and heterogeneous nucleation.**
**Response:** We agree. The revised Introduction now clearly distinguishes homogeneous freezing, which does not require INPs, from heterogeneous ice nucleation involving INPs.

Lines 71-74:
*"A central challenge in representing cirrus clouds in atmospheric models is the competition between homogeneous freezing and heterogeneous ice nucleation. Homogeneous freezing of solution droplets generally requires high ice supersaturation and can produce large numbers of ice crystals, whereas heterogeneous nucleation on ice-nucleating particles can initiate ice formation at lower supersaturation and modify the subsequent evolution of the cloud (Kärcher et al., 2022, 2023)."*
Lines 83-86:
*"Mineral dust is particularly relevant in this context because it represents one of the most important atmospheric sources of ice-nucleating particles, although its activity depends strongly on particle concentration, mineralogical composition, temperature, and nucleation mode (DeMott et al., 2003, 2010; Niemand et al., 2012; Ullrich, 2017)."*

**3. K-feldspart is a more efficient ice nucleator compared to calcite and quartz. Clarifying the relative efficiencies would improve the statement.**
**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.

Lines 95-108:
*"Mineral aerosol particles, especially those rich in K-feldspar, quartz and calcite, are known to act as highly efficient heterogeneous ice nuclei under the low-temperature conditions of the upper troposphere (Atkinson et al., 2013; Chatziparaschos et al., 2023; Harrison et al., 2019; Hoose et al., 2008; Hoose and Möhler, 2012; Seifert et al., 2010)."*

**4. This statement could do with a citation. Varga (2020) is cited for a similar statement later in the manuscript.**
**Response:** We agree. The appropriate reference has been added to support this statement.

Lines 114-119:
"Previous studies have linked these changes to increasingly meridional atmospheric circulation patterns and a more meandering jet stream, which facilitate long-range dust

transport while simultaneously influencing a wide range of hydrological and thermodynamic processes (Varga, 2020)."

**5. Sample sizes should be reported across dust thresholds, seasons and five-year periods, particularly at the highest dust loadings where relatively few observations may control the inferred response.**

**Response:** We thank the reviewer for this important suggestion. In the substantially revised manuscript, we have explicitly reported the sample sizes associated with the newly introduced vertically resolved MERRA-2 dust analysis, including the seasonal distribution of the investigated Saharan dust events. Furthermore, the original dust-threshold-based approach has been removed from the statistical analyses. All statistical comparisons are now performed using daily observations rather than cumulative threshold-based averages, thereby avoiding the disproportionate influence of the relatively small number of observations at the highest dust loadings. However, the threshold-based diagrams are able to illustrate general patterns and tendencies in the dust–cloud relationships, but are no longer used to establish statistical significance or support quantitative inferences.

Lines 526-537: *"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 $9.63\times10^{-8}$ kg kg$^{-1}$ (Figure 3). Upper-tropospheric dust was not restricted to the lower part of this altitude range: the corresponding median was $8.33\times10^{-9}$ kg kg$^{-1}$ at 8–12 km and $4.37\times10^{-9}$ 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 $5\times10^{-9}$ 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."*

**6. If the +ε error term in the model assumes a Gaussian error, this may be inappropriate for several variables, e.g. effective radius and cloud fraction. I recommend the authors assess the residual distributions for each model and justify the use of a Gaussian family or clarify the use of an alternative family.**

**Response:** We agree that a Gaussian assumption may not be appropriate for all variables. The original GAM-based inference has therefore been removed 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. Tables 1 and 3 are quite large and it is unclear what is supposed to be demonstrated by them. If a trend is being demonstrated a time-series figure may**

**be more appropriate with the tables being moved to an appendix or supplementary material.**

**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.

**Table 1. Seasonal and total frequency and intensity of Saharan dust events (SDEs) over the Carpathian Basin during the 2001–2025 period.**

| | Winter | | Spring | | Summer | | Autumn | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Timeframe** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** | **SDEs** | **Dust mass** |
| | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** | **(n)** | **(avg.) [g m$^{-2}$]** |
| **2001-2005** | 3 | 0.009 | 18 | 0.011 | 11 | 0.007 | 8 | 0.005 | 40 | 0.009 |
| **2006-2010** | 12 | 0.006 | 18 | 0.007 | 10 | 0.005 | 8 | 0.005 | 48 | 0.006 |
| **2011-2015** | 12 | 0.006 | 25 | 0.007 | 16 | 0.003 | 7 | 0.004 | 60 | 0.005 |
| **2016-2020** | 10 | 0.004 | 26 | 0.008 | 16 | 0.003 | 9 | 0.005 | 61 | 0.006 |
| **2021-2025** | 5 | 0.006 | 29 | 0.008 | 19 | 0.007 | 14 | 0.005 | 67 | 0.007 |
| **Total** | **42** | **0.006** | **116** | **0.008** | **72** | **0.005** | **46** | **0.005** | **276** | **0.006** |

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.

**8. Table 3: it is not obvious what the column 'change %' is being calculated from. I presume it is the final minus first column, but this should be made more explicit**

**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. Overall inconsistency in the use of units, with different notations used at times (e.g. ms^-1 versus m/s). Please correct; if using LaTeX the siunitx package can be very useful.**
**Response:** Units and their notation have been checked and standardized throughout the manuscript.

**2. Some acronyms are defined multiple times in the manuscript, particularly OLR.**
**Response:** The manuscript has been checked and redundant definitions, including repeated definitions of OLR, have been removed.

**3. Figure captions should be as explicit as possible. Even if you have a legend, you should still state that 'shaded bars represent X...', which is especially beneficial for those using assistive technology.**
**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.**