Responses

Reviewer-1:

The manuscript is, to my opinion, (almost) ready for publication.
The authors present a unique approach to document the impact of Saharan dust on cirrus formation. And they consider long data time series covering more than 20 years. The results are rather clear and well presented and discussed.
For me, the study is a significant and unique contribution to the literature and thus a highlight paper.

Reponse: We sincerely thank the reviewer for the very positive assessment of our revised manuscript and for recognizing the improvements made in response to the previous comments. We are particularly grateful for the encouraging recommendation regarding the manuscript's suitability for publication in ACP and its potential consideration as a highlight paper. We also appreciate the additional constructive suggestions, which have helped us further improve the clarity, scientific context, and presentation of our findings. We have carefully addressed all remaining comments, as detailed in our point-by-point responses below.

Comment: Lines 65: I would use 'strong' words here: …nucleation at MUCH lower ice supersaturation than required for homogeneous freezing and may thereby SIGNIFICANTLY modify ice crystal populations.

Response: We agree with the reviewer and have strengthened the wording to better emphasize the importance of heterogeneous ice nucleation by mineral dust.

Lines 65-68:
"The presence of mineral dust can promote heterogeneous ice nucleation at much lower ice supersaturation than required for homogeneous freezing and may thereby significantly modify ice crystal populations and the optical and radiative properties of cirrus clouds (Kok et al., 2023; Storelvmo, 2017)."

Comment: To my opinion, the 'exciting' Figure 1 is poorly introduced and discussed. A few more sentences would be good. What about the vertical dust profile in this case? The cloud structures point to a DIBS ?, similar to the DIBS case shown in Ansmann et al., 2019), and the event shown in Figure 1 belongs to the Type-2 class, right? All this is missing, to my opinion.

Response: We thank the reviewer for this valuable suggestion. We have expanded the introduction and discussion of Figure 1 to highlight the spatial correspondence between Saharan dust transport and extensive cirrus cloud shields. We also discuss the resemblance of these cloud structures to dust-infused baroclinic storm (DIBS) systems described by Ansmann et al. (2019). However, we avoid assigning a definitive DIBS classification without event-specific vertical and dynamical verification.
And yes, these events have been Type-2 episodes. Description of Type-2 events have been also completed with the reference to Figure 1.

Lines 82-87:
"Figure 1 illustrates several examples of extensive upper-level cloud shields occurring in association with Saharan dust transport over Europe. The spatial organization of these cloud systems resembles the dust-infused baroclinic storm (DIBS) structures described by Ansmann et al. (2019), in which mineral dust is transported into the upper troposphere within dynamically active weather systems. Such situations provide a physically plausible environment for dust–cirrus interactions, particularly when ascending air masses transport mineral particles into ice-supersaturated layers. Nevertheless, the satellite imagery alone does not establish the vertical overlap between dust and cirrus or demonstrate dust-induced ice nucleation."

Lines 107-11: New figure caption:
Figure 1. Examples of extensive upper-level cloud shields associated with Saharan dust transport over Europe on 22 April 2022, 6 May 2022, and 13 April 2026. Upper panels show NASA Terra/MODIS true-colour imagery, while lower panels show the corresponding MERRA-2 dust column mass density distributions. The illustrated cloud structures exhibit similarities to dust-infused baroclinic storm systems, although their classification and vertical dust–cloud overlap are not established by these images alone. The 2026 case is included for illustration and is not part of the 2001–2025 statistical analysis.

Lines 279-280:
"(The Saharan dust events illustrated in Figure 1 are representative examples of Type 2 synoptic situations, characterized by dust transport associated with Mediterranean cyclones.)"

Comment: Lines 210-214: You introduce the two-sided Mann-Whitney U test and the Benjamini-Hochberg false discovery rate (FDR) procedure without providing any references. Are these methods so well known that we do not need references anymore?

Response: We agree and have added the original references for the Mann–Whitney U test and the Benjamini–Hochberg false discovery rate procedure.

Lines 235-242:
"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 (Mann and Whitney, 1947). 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 (Benjamin and Hochberg, 1995). Group medians were used to characterize the magnitude of the observed differences."

Mann, H. B. and Whitney, D. R.: On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other, The Annals of Mathematical Statistics, 18, 50–60, https://doi.org/10.1214/aoms/1177730491, 1947.

Benjamini, Y. and Hochberg, Y.: Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing, Journal of the Royal Statistical Society: Series B, 57, 289–300, https://doi.org/10.1111/j.2517-6161.1995.tb02031.x, 1995.

Comment: Line 559: Did you introduce somewhere: INP (ice nucleating-particles)? and Line 576: Now you can use INP instead of ice-nucleating particles…

Response: Thank you for pointing this out. We have introduced the abbreviation INP at its first occurrence and standardized its use throughout the manuscript.

Line-51:
"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 (INPs) can initiate ice formation at lower supersaturation and modify the subsequent evolution of the cloud (Kärcher et al., 2022, 2023)."

Comment: Line 585 (Section 4.4 on mixed phase clouds): … future investigations…

I obviously forgot to mention during the last review round that already several studies exist in this dust MPC research field and thus should be included in the references.

Response: We agree that the role of mineral dust in mixed-phase cloud glaciation is already supported by substantial observational evidence. We have revised Section 4.4 to acknowledge these findings and to clarify that further investigations are needed specifically to quantify their relevance to the cloud anomalies identified in our study.

Lines 636-643:
"The positive relationship observed between atmospheric dust loading and middle-level cloud fraction is therefore noteworthy. Previous studies have demonstrated the importance of Saharan dust for heterogeneous ice formation in European cloud systems (Seifert et al., 2010), while recent findings indicate that dust-driven droplet freezing can explain cloud-top phase in the northern extratropics (Villanueva et al., 2025). Although our datasets do not allow direct identification of mixed-phase cloud processes, these findings provide a physically plausible context for the observed dust-associated middle-cloud anomalies. Further investigations combining vertically resolved cloud-phase observations with thermodynamic profiles would be needed to quantify the contribution of mineral dust to these regional cloud changes."

Villanueva, D., Stengel, M., Hoose, C., Bruno, O., Jeggle, K., Ansmann, A., and Lohmann, U.: Dust-driven droplet freezing explains cloud-top phase in the northern extratropics, Science, 389, 521–525, https://doi.org/10.1126/science.adt5354, 2025.

Reviewer-3

I am satisfied that the revised paper has substantially improved it's treatment of the statistical analysis presented. I am also satisfied that the language has been appropriately

moderated when discussing implications of statistical association. The addition of vertically resolved dust information strengthens the physical relevance of the analysis, while the expanded discussion more clearly acknowledges the limitations of attributing the observed cloud changes to dust.

My original concerns have therefore been largely addressed, and I recommend acceptance subject to minor revisions.

Response: We sincerely thank the reviewer for the positive assessment of the revised manuscript and for acknowledging the improvements in the statistical analysis, the incorporation of vertically resolved dust information, and the more cautious interpretation of dust–cloud associations. We appreciate the remaining constructive suggestions, which have helped us further improve the clarity, methodological transparency, and literature context of the manuscript. Our point-by-point responses are provided below.

Comment: 1. Please reconcile the median dust mass mixing ratio reported in Section 3.2.2 (9.63×10^{-8} kg kg^{-1}) with the statement that only 48.6% of events exceeded 10^{-8} kg kg^{-1}. These appear inconsistent.

Response: We thank the reviewer for identifying this inconsistency. The reported value of 9.63×10^{-8} kg kg^{-1} was a typographical error; the correct median event-mean dust mass mixing ratio for the 7–12 km layer is 9.63×10^{-9} kg kg^{-1}. This is consistent with the finding that 134 of the 276 events (48.6%) exceeded 10^{-8} kg kg^{-1}. We have corrected the value in Section 3.2.2 and checked the reported dust concentrations for consistency.

Lines 318-320:
"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^{-9} kg kg^{-1} (Figure 3)."

Comment: 2. Please clarify whether the 276 SDE days represent separate dust outbreaks or include consecutive days within individual outbreaks, and explain any implications for the independence assumed in the statistical tests. Sample sizes for the seasonal and five-year subsets would also be helpful.

Response: We thank the reviewer for requesting this clarification. The dataset comprises 276 distinct Saharan dust events (SDEs), rather than 276 individual dusty days. Some events extended over multiple consecutive days, but each was treated as a single event in the analysis. We have clarified this distinction in Section 2.4 to avoid confusion regarding the sampling units and statistical independence. The seasonal and five-year sample sizes reported in Table 1 likewise refer to distinct SDEs.

Lines 208-211:
"The statistical analysis was based on 276 distinct Saharan dust events (SDEs) identified during 2001–2025. Individual events occasionally extended over several consecutive days; however, each multi-day episode was treated as a single observational unit, using event-aggregated atmospheric variables. Thus, the sample size of 276 refers to independent dust

episodes rather than individual dusty days. The seasonal and five-year event counts are summarized in Table 1."

Comment: 3. Please clarify how the high-dust subsets and corresponding reference conditions were defined across the five-year periods. The reported increase in cirrus-reflectance enhancement should be accompanied by uncertainty estimates or explicitly described as a descriptive finding.

Response: We thank the reviewer for this suggestion. We have expanded the methodological description to clarify the definition of high-upper-tropospheric-dust SDE subsets and the corresponding low-dust reference conditions used in the five-year comparisons. We also agree that the increase in cirrus-reflectance enhancement should not be interpreted as a statistically established temporal trend without a dedicated uncertainty analysis. Accordingly, we now explicitly describe the five-year changes as descriptive differences between period-specific median values.

Lines 217-222:
"For the five-year comparisons, the high-Dust7–12 SDE subsets were defined using the season-specific median thresholds calculated from the complete 2001–2025 SDE dataset. These thresholds were kept constant across the five consecutive periods to ensure a consistent classification of upper-tropospheric dust abundance. Low-dust reference conditions were identified using the fixed 75th-percentile threshold of the complete daily dust column distribution, excluding identified SDE days. For each five-year period, only reference days belonging to the corresponding period and season were included in the comparison."

Lines 385-389:
"In contrast, the descriptive comparison of five-year median values indicated a pronounced increase in the cirrus-reflectance anomaly associated with high-Dust7–12 SDEs. Relative to the corresponding low-dust reference conditions, median cirrus reflectance was 143% higher in 2001–2005 and 398% higher in 2021–2025. These values describe differences between the investigated five-year subsets and should not be interpreted as evidence of a statistically significant temporal trend, as uncertainty estimates for the between-period changes were not calculated."

Lines 693-696:
"The descriptive five-year springtime comparison suggested a more pronounced cirrus-reflectance enhancement during high-Dust7–12 SDEs in the later part of the study period. The relative difference from low-dust reference conditions increased from 143% in 2001–2005 to 398% in 2021–2025. However, this temporal pattern is based on period-specific median comparisons and does not establish a statistically significant long-term trend."

Comment: 4. Section 4.1 would be improved by greater engagement with existing literature. A number of factual claims are made without adequate citation.

Response: We agree with the reviewer that Section 4.1 would benefit from stronger connections to the existing observational and modelling literature. We have revised the discussion and added references supporting the statements concerning the vertical transport

of Saharan dust, its potential contribution to heterogeneous ice nucleation, and the sensitivity of dust-associated cloud properties to thermodynamic and dynamical conditions. These additions also help distinguish established physical mechanisms from the statistical associations identified in our study.

Lines 449-450:
"Although long-range Saharan dust transport over Europe is most commonly associated with the lower and middle troposphere, with elevated dust layers frequently occurring at approximately 3–4 km altitude (Ansmann et al., 2003; Seifert et al., 2010), this typical transport level should not be interpreted as an upper limit to the vertical extent of mineral dust."

Lines 453-457:
"Consequently, dust layers and detectable mineral dust have repeatedly been observed in the upper troposphere, including at altitudes approaching or overlapping those characteristics of cirrus clouds (Ansmann et al., 2019; Weger et al., 2018; Seifert et al., 2023). Such vertical transport is particularly relevant for cirrus formation because mineral dust can provide INPs capable of initiating heterogeneous ice nucleation under suitable thermodynamic conditions (DeMott et al., 2003; Kärcher et al., 2022)."

Lines 498-502:
"The pronounced seasonal differences are also consistent with previous modelling studies demonstrating that the microphysical response of cirrus clouds to mineral dust depends strongly on the competition between heterogeneous and homogeneous ice nucleation, as well as on vertical velocity and ice supersaturation (Kärcher et al., 2022, 2023). Consequently, similar upper-tropospheric dust concentrations may be associated with different cloud properties under different meteorological conditions. This dependence provides an important context for interpreting the seasonal variability observed in our analysis."