

Review: Strengthening dust-cirrus relationships over Central Europe (2001-2025)

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Summary

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 however, 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.

General Comments

1. The GAM analysis indicates that the relationship between dust loading and cloud properties varies with time. This is evidence for non-stationarity of the statistical association, not necessarily that the physical response of clouds to dust has strengthened. An alternative explanation may be that the meteorological conditions associated with Saharan dust transport could have changed. The manuscript should therefore distinguish between a changing dust-cloud association and a strengthening of the causal influence of dust on cirrus formation.
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 R^2 values. If instead the thresholds define non-overlapping dust-loading bins, please state this explicitly. Secondly, the statement that high adjusted R^2 demonstrates that dust loading explains a substantial fraction of cloud variability is inaccurate. The reported R^2 describes the complete model defined on Line 125, not just dust loading.
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.

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.
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.
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.
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.

Specific Comments

1. Line 29: Twomey (1974) deals with liquid-cloud-aerosol interactions. I would suggest removing this reference.
2. Line 45: Homogeneous nucleation does not require INPs. The authors may want to distinguish between homogeneous and heterogeneous nucleation.
3. Line 50: K-feldspar is a more efficient ice nucleator compared to calcite and quartz. Clarifying the relative efficiencies would improve the statement.
4. Line 60: This statement could do with a citation. Varga (2020) is cited for a similar statement later in the manuscript.
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.
6. Line 125: If the $+\epsilon$ 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.
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.

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

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.
2. Some acronyms are defined multiple times in the manuscript, particularly OLR.
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.

This review was conducted as a joint exercise for the 2026 EGU Peer Review Training.