Response to Reviewers

First and foremost, we would like to thank the reviewers for their time and feedback. Please find our responses below to each major/minor comment.

Anonymous Referee #2

The manuscript on the evaluation and characterization of particles deposited on the Huascarán Glacier in the Cordillera Blanca, Peru, is well written and detailed. Furthermore, it provides information on the morphology and chemical composition of particulate matter from 1960-2015.

Nevertheless, detailed comments and questions are listed below:

(1) In the first paragraph, it would be beneficial to further improve and expand the list of different effects of particulate matter in the atmosphere as an example: ocean productivity, human health, reduce solar radiation....

Mineral dust does indeed play many important roles that we did not explicitly mention in the introduction. We were trying to keep the background details relevant to how particulate matter influences albedo (Lines 28-30) and its impact on glaciers (Lines 30-33), though we agree there are still merits to highlighting other ways in which dust is significant.

We plan to appended the following to the first paragraph: "Mineral dust is also a key player in many other parts of the Earth system (Knippertz and Stuut, 2014 and references therein). For example, particles in the atmosphere serve as cloud condensation nuclei and therefore influence cloud albedo and precipitation dynamics (Nenes et al., 2014). Additionally, the deposition of mineral dust over terrestrial ecosystems can act as a natural fertilizer for chemically depleted soils (e.g., Bristow et al., 2010; Yu et al., 2015; Besl, 2022) while deposition across marine environments affects ocean productivity (Jickells et al., 2014). Particulate matter also has significance for respiratory health in people, as demonstrated by increased mortality rates during dust events in Europe, Asia, and Africa (Morman and Plumlee, 2014; Perez et al., 2008; Lopez-Villarrubia et al., 2010; Chan et al., 2008)."

(2) Line 57: I would highly recommend to change the use of To our knowledge, to In this study,.

We have changed the line to read: "In this study, we report …".

(3) On the mineral identification: Although the methodology and the references on which the mineral classification is based are cited, the manuscript does not specify the final classification criteria or the used

elemental ratios to assign particles to the different mineral groups. Those ratios may be subtle to different interpretations, providing them would improve the transparency of the methodology and facilitate the reader's understanding of the final mineral classification. So, I highly recommend to attach a table in the supplementary material describing and fixing those elemental ratios for each mineral class.

We used a combination of five independent algorithms to identify each mineral, and each algorithm assigns a mineralogy based on a completely different set of EDS net intensity ratios, atomic percentages, or spectral characteristics. It would be impossible to communicate every classification criterion in a simple table, but we can provide a table that clarifies the metrics used by each algorithm to identify mineralogy. We plan to add a reference in the main text to the updated supplementary materials, which will contain the following table:

Table S1. *Details on the mineral classification algorithms used in the text, including relevant classification criteria, benefits, and individual limitations.*

Algorithm	**Algorithm Type**	**Classification Criteria**	**Benefits**	**Limitations**
Donarummo et al. (2003)	Sorting Scheme	Net intensity	Fast algorithm; designed for, and commonly used in, ice core studies	Restricted to aluminosilicates; many “Unknown” classification nodes
Kandler et al. (2011)	Comparative Criteria	Atom percent relative abundance	44 mineral groups, including quartz, salts (e.g., NaCl), and mixtures	Mostly broad mineral groups, not necessarily specific minerals
Panta et al. (2023)	Comparative Criteria	Atom percent relative abundance	23 mineral classes, including simple minerals such as quartz and calcite	Cannot differentiate plagioclase solid solution or mafic minerals (pyroxene, amphibole, etc)
Severin (2004)	Dichotomous Key	EDS full spectrum	Includes 182 reference mineral spectra; very easy to use	Requires access to information in Severin (2004), usually in the form of a hard copy of the book; qualitative only; can be subjective and cannot be automated
Weber (2025)	Ensemble Machine Learning Classifier	Net intensity	Provides probability table; can recognize palygorskite and can differentiate plagioclase solid solution series and is trained to recognize certain mafic minerals (e.g., pyroxenes)	Restricted primarily to aluminosilicates

All of these algorithms (with the exception of the Severin dichotomous key) were applied to the EDS data using the open source MATLAB functions provided by Weber (2025) at https://github.com/weber1158/eds-classification. The outputs were cross-referenced with one another and with the Severin dichotomous key to determine the most likely mineral for each particle. The limitations presented in the table clarify the importance of relying on more than just one algorithm to determine mineralogy.

(4) To facilitate comparison with previous work done in the topic, it would also be beneficial to complement the results and discussion sections with comparisons to other studies, highlighting similarities and differences in particle size distributions, particle shapes, and mineralogical composition. Such comparisons would strengthen the interpretation of the data and help better constrain the relative contributions of long-range transported North African dust versus locally sourced dust.

Dust studies for the tropical Andes are extremely scarce (Gilardoni et al., 2022), and so we are quite limited in our ability to compare our results with previous work (which highlights the novelty of our study). The only other ice core mineral dust study that explicitly identifies mineral particles is from Lindau et al. (2021), which we mention in Lines 441-444 in the manuscript. They used micro-Raman to identify 630 mineral grains in a firn core from Nevado Illimani (Bolivia) and found that phyllosilicates are sorted by means of wet deposition. There are a few studies that discuss size distributions (e.g., dos Reis et al., 2022), but the size distributions are categorized according to very wide bin sizes (<2 µm, 2-10 µm, 20-60 µm, etc.). Also, until now there have been no studies that discuss particle shapes in the tropical Peruvian Andes.

In contrast, there is a lot of information in the literature about dust from African source regions. Formenti et al. (2011) provides a good overview of what is known. For instance, they cite numerous studies that examined illite/kaolinite ratios across North Africa, all of which report ratios between 0 and 2 (see their Table 2a). Figure 10 in the manuscript shows how our results compare to various African sources according to the work of Caquineau et al. (1998, 2002). Scheuvens and Kandler (2014) provide insights into the median aspect ratio (AR) of particles from North Africa, which ranges from about 1.6 to 1.9, but the way they calculate AR is very different than how we calculate AR using the automated process provided by Fiji-ImageJ (Schindelin et al., 2012). That is, we calculate AR as the length of a particle's major axis divided by the length of its minor axis, while Scheuvens and Kandler (2014) calculate AR as four-times the particle's long axis divided by the product of the two-dimensional area multiplied by pi. Huang et al. (2020) and Panta et al. (2023), however, calculate AR in the same way as we do in our study. Panta et al. (2023) characterized 300,000 freshly emitted dust particles from the Moroccan Sahara using SEM and identified a median AR of 1.46, which is consistent with the median AR of 1.42 that we observed in the ice core record. However, Huang et al. (2020) compared the ARs of African dust particles reported across the literature and found that the median AR of North African dust increases significantly during long-range transport due to the preferential settling of spherical particles, from about 1.60 over the source regions to 1.90 after long-range transport. Thus, the ARs of dust particles in the ice core from Peru are inconsistent with long-range transport from Africa. There is not much information in the literature regarding the circularity of African dust particles, although one study by Varga et al. (2021) measured the circularity of dust transported from Africa to Iceland and found median values between 0.75 and 0.80, which is consistent with what we noted in the ice core record. We plan to add this discussion on AR and circularity to the revised manuscript.

(5) The manuscript shows a good correlation between the abundance of kaolinite detected in the ice core, and regional deforestation rates. It would also be interesting to investigate whether the relative abundance of specific mineral groups (e.g., montmorillonite, mica, kaolinite, or oligoclase) correlates with the

frequency of North African dust events affecting the region during the same period. Such an analysis could provide additional evidence supporting the contribution of long-range transported Saharan dust to the mineral assemblages identified in the ice core.

Such an analysis was attempted in the first author's dissertation: that is, trying to correlate the abundance of individual mineral species with aerosol optical depth (AOD) data for North Africa collected with the MODIS sensor aboard NASA's Terra satellite (Weber, 2026). Unfortunately, because the mineralogical data were sampled at multiannual resolution (5-yr intervals), and the MODIS data begin in the year 2000, we cannot draw any meaningful statistical conclusions about the relationship. At 5-yr resolution, the temporal overlap is just four data points: 2000-2004, 2005-2009, 2010-2014, and 2015-2018. If the mineralogical data were annual, then we would have 19 data points to compare with the AOD data. A higher temporal-resolution sampling study is needed to test this relationship in detail. It is not possible to "up-sample" the mineralogical data to annual resolution because that would require interpolation, which would be statistically erroneous in this case because the interpolated data points would be completely artificial and not necessarily reflective of reality. In the conclusions section we intend to add a statement regarding the need for higher-resolution sampling to improve our understanding of dust seasonality and its relationships to various climatological and environmental phenomena.

(6) Finally, I would like to congratulate the authors on this valuable work and the results presented. This study provides important new insights into the characterization of mineral dust transported to the tropical Andes and offers valuable information that will support future studies on dust sources, transport pathways, and environmental change.

We greatly appreciate these kind words. It is our hope that these data will be beneficial to the broader atmospheric science community and not just those interested in ice core records. We thank the reviewer for their constructive feedback and their thoughts.

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