Q# refer to questions by the reviewers, **A#** refer to our replies to the corresponding question, **line number** mentioned in our replies refer to the revised version of manuscript.

Boxho et al. "Quantifying Southern Hemisphere dust sources during the Last Glacial-Interglacial Transition using rare earth elements in the EPICA Dome C ice core"
Reviewed by Austin Carter

The authors have done a nice job addressing most of the feedback I have provided in my initial review as well as the feedback from the other reviewer. The new introduction is very well written and frames the context for the paper nicely, and the discussion sections are also outlined better. Thank you for making these revisions. I believe this is an exciting manuscript that cleverly uses rare earth element concentrations and an unmixing algorithm to resolve dust provenance at EPICA Dome C (EDC) across the Last Glacial-Interglacial Transition. The authors show very clearly that dust sourced to the EDC during times older than ~14.5 kyr BP are dominated by stable high-latitude source regions, specifically and overwhelmingly from Patagonia with secondary input from New Zealand. The authors also show that for times younger than ~14.5 kyr BP there is a shift toward increased and erratic contributions of dust from low-latitude sources (Australia, South Africa, and the Puna Altiplano Plateau). The results from this work are interesting to me and will be of interest to others as well. My comments below are predominantly minor, but I have some more major comments with respect to Fig. 2 and Sr-Nd isotope compositions of dust. It is for this reason only I request major revisions, however, after these are addressed along with the minor corrections, I believe this work will be close to ready for publication.

We would like to thank Austin Carter for the time and effort he dedicated to this second review. In what follows, we did our best to accommodate his remarks and comments.

Below are my suggestions, which I hope will improve the manuscript further:

Q1: L25: The authors appear to refer to New Zealand as a low-latitude source here but everywhere else refer to it as a high-latitude source, which should be revised.
A1: This was a mistake on our part; New Zealand is indeed included alongside Patagonia as a high latitude PSA. This has been corrected in the abstract.

Q2: L31: It might be clearer to say something like this: "This transition in dust sources to EDC is supported by our modeled Sr-Nd isotope compositions of dust, which also align with…"
A2: We thank the reviewer for this helpful suggestion and have revised the text accordingly.

Q3: L125: Perhaps clarify "our database" as "our provenance database" or something to that effect.
A3: We thank the reviewer for this helpful suggestion and have revised the text accordingly.

Q4: L177-178: It might help to clarify here that you are ranking in order from greatest to least contribution (i.e., Rank 1 to Rank 7). I think it's implied but would be useful to be explicit how you are ranking.
A4: We agree that this clarification improves readability and have revised the text accordingly by adding: "*...in order from greatest to least contribution (i.e., Rank 1 to Rank 7)...*".

Q5:L262-264: If rounding to the third decimal place, then the 87Sr/86Sr ratios for the LGM should be ~0.709 (not ~0.708) based on Delmonte et al. (2004a). Please also add a reference to Delmonte et al. (2007) for the Holocene data. Importantly, it should be noted here that the isotope composition of dust for the LGM and Holocene at EDC are sparse (n=2 for each interval). Furthermore, the isotopic differences in LGM vs. Holocene dust at EDC are not very large and can be fully captured in your EDC model for the LGM alone. I think if using these data in your argument, it would be very important to be clear that while yes there is support for a shift in dust provenance, the data is sparse and the changes are subtle. Personally, I agree that this is a limitation that your high-resolution dataset is able to resolve better and makes much more powerful, so you could reiterate that point here or elsewhere.

A5: We thank the reviewer for these valuable comments. We have corrected the LGM $^{87}Sr/^{86}Sr$ value to ~0.709. While Delmonte *et al.,* (2004a) report a value of ~0.708 in the abstract, recalculation of the mean value from the data presented in their Table 1 yields 0.70882, which we round to 0.709. We have also added the reference to Delmonte *et al.,* (2007) for the Holocene isotope data.

We agree that the available Sr-Nd isotope measurements for the LGM and Holocene at EDC are limited in number and that the isotopic differences between the two intervals are relatively subtle. To better reflect this limitation, we have revised the text to explicitly acknowledge the sparse isotopic dataset and to emphasize that evidence for a provenance shift was previously based on relatively few measurements. We further highlight that one of the strengths of our study is the higher temporal resolution provided by the REE record, which allows to resolve these changes in provenance better than using the available isotopic data alone. Here is the revised paragraph: "*For instance, Delmonte et al. (2004a) reported $^{87}Sr/^{86}Sr$ ratios of ~0.709 and ε_{Nd} values ranging from -1.66 to -2.46 for LGM dust at EDC, whereas Holocene dust typically displays more radiogenic $^{87}Sr/^{86}Sr$ ratios (~0.710) and more negative ε_{Nd} values (-4.51 to -5.68) (Delmonte et al., 2007). Similar shifts in dust isotopic composition observed in Holocene dust from the Vostok ice core further support the hypothesis of a change in source regions (Basile et al., 1997; Delmonte et al., 2008). However, the available Sr-Nd isotope data for both the LGM and Holocene at EDC remain sparse, and the isotopic differences between these intervals are relatively subtle. Nevertheless, these observations are consistent with a change in dust provenance, which can be investigated in greater detail using the higher-resolution REE record presented here.*"

Q6: L264-266: This sentence and corresponding references confuse me. To my knowledge, there are no Sr-Nd isotope data on ice core dust from the LGM at Vostok, so I'm not sure that a "shift" can be determined. Also, while there are two data points from the Holocene at Vostok, these come from Delmonte et al. (2007) and not either of the references listed. Please double check this.

A6: We thank the reviewer for pointing out this ambiguity. In Delmonte *et al.,* 2002, the author had already noted a similar pattern between the Vostok and EDC ice cores in terms of the decline in the dust concentration ratio between the Last Glacial Maximum and the Holocene. This similarity in the dust mass profile of these two ice cores, combined with the shifts in isotopic values measured at EDC for this glacial-interglacial transition and at Vostok for other similar, older glacial and interglacial transition periods (Delmonte *et al.,* 2007), led to the hypothesis put forward by Basile *et al.,* 1997, of a shift in dust provenance. So, for more clarity, we adapted the text (see corrections in A5).

Q7: L266-268: Do you mean larger variability in the Holocene compared to the LGM across all sites in East Antarctica? It would be helpful to clarify what is being compared.

A7: We corrected the sentence with more details by: "*This Holocene change is also accompanied by a much greater variability in the Nd-Sr signature than during LGM, as observed in both the ice core dust and modern dust including those from Berkner Island as reported in Figure 2.*"

Q8: L284-289: I think this is a fair point on the limitation of measured isotopic data. Alternatively, it might also be fair to mention the limitations of the modeled isotopic data. For example, these seem to hinge on accurately determining both the mean Sr and Nd concentration and isotope composition for each PSA, which inherently have wide ranges.

A8: We agree that the modeled isotopic compositions are also subject to uncertainties, because they depend on the postulated mean Sr and Nd concentrations and isotopic compositions assigned to each PSA, which may exhibit substantial variability. However, we would like to emphasize here that the modeled Sr-Nd isotopic compositions are not used here as an independent provenance proxy. Rather, they serve as a check for our REE-based provenance estimates. For this reason, this section discusses the strengths and limitations of measured isotopic data as a provenance tracer. Nevertheless, we have clarified in the manuscript that the calculated isotopic signatures represent "expected" compositions derived from the modeled source contributions and end-member characteristics, and should therefore be interpreted in light of the variability associated with those end-member values.

Q9: L288 + L470: I appreciate the wording change from "continuous" to "quasi-continuous." I think the word "continuous" to me was initially ambiguous because it was unclear if the measurements themselves were continuous (i.e., continuous flow analysis) or if the temporal resolution was essentially continuous. While the former is not true, the latter appears to be so as detailed nicely in L110–115. For added clarity, maybe somewhere in L110-115 it would be useful to mention that given the high temporal spacing the dataset therefore represents a near continuous record, but I leave that up to the authors' discretion.

A9: We thank the reviewer for his suggestions. We agree that explicitly linking the high temporal resolution of the dataset to its near-continuous character improves clarity. Accordingly, we have revised the text in lines 110‑115 to state: "*The dataset spans from the late MIS 3 to the late Holocene (33.699 to 2.852 kyr BP). Except for the interval between 21.7 and 27.3 kyr BP, where only four samples were available, the record can be considered quasi-continuous owing to its high temporal resolution, with an average spacing of approximately 100 years (60‑140 years between adjacent samples). The age model follows the EDC3 chronology (Parrenin et al., 2007). Each sample integrates between 2‑3 years of deposition during the Holocene and 4‑5 years during the LGM.*"

Q10: L367-368: The second and third driver appear to be competing with each other a bit with one seeming to argue for shorter and the other longer residence times. The second driver is an important point but may be more related to dust flux than provenance. This is shown nicely in Fig. S2. If I am mistaken, it could be helpful to elaborate on why this second driver would result in increased variability of dust after 14.5 kyr BP.

A10: We agree that the link between increased wet scavenging and enhanced provenance variability was not sufficiently explained. Our reasoning is that wet scavenging is, by nature, intermittent and highly variable in both space and time. As hydrological cycling intensified between 18 and 14.5 kyr BP, variations in precipitation patterns along transport pathways likely resulted in differential removal of dust originating from distinct source regions. Consequently, wet scavenging may have influenced not only the overall dust flux reaching EDC but also the relative contributions of individual dust sources, thereby contributing to the increased variability observed in the provenance record. We have revised the text to clarify this point and to better distinguish this mechanism from the changes in transport trajectories discussed in the third driver. The text related to the second driver says: "*Second, rising temperatures and enhanced wet scavenging along transport after increased during the HS1 and later reducing airborne particle lifetime and the efficiency of long-range dust transport (Lambert et al., 2008; Markle et al., 2018). Because wet scavenging is inherently intermittent and spatially heterogeneous, changes in precipitation patterns may have differentially affected dust transported from distinct source regions, thereby contributing not only to lower dust fluxes but also to greater temporal variability in the relative source contributions recorded at EDC*".

Q11: L370-373 + L403-404: These two sentences seem to be at odds with each other. The former argues for a northward shift in moisture sources, whereas the latter hints at southward shift, unless I am misinterpreting the sentences.

A11: We thank the reviewer for highlighting this potential ambiguity. The northward shift referred to in lines 370–373 concerns the inferred position of the moisture source regions supplying precipitation to Antarctica, as derived from deuterium-excess records (Fig S3C). In contrast, the southward (poleward) shift discussed in lines 403–404 refers to the mean position of the Southern Westerly Winds belt. These two variables are related but do not necessarily evolve in the same direction, as they reflect different aspects of the Southern Hemisphere climate system. To avoid confusion, we have revised the text to explicitly distinguish between shifts in moisture source regions and shifts in the SWW belt. The text related to the third driver says: "*Third, a lengthening of transport trajectories associated with changes in the location of the moisture source regions supplying Antarctic precipitation, as inferred from deuterium-excess values after 14.5 kyr BP (Figure S3; Stenni et al., 2010)*."

Figure 1:

Q12: In the caption, I would suggest mentioning LGIT something like "Evolution of dust PSA contributions to EDC ice core across the Last Glacial-Interglacial Transition between…"

In addition, I recommend adding labels for MIS3, LGM, HS1, ACR, YD, Early and Middle Holocene. This does not need to be shaded bars like in Fig. 4 and 6, rather a semi-thick vertical black line at each time boundary would be helpful. I realize this will make the figure busier, but I do think it will guide the reader through your temporal discussion and really highlight changes within each timestep.

It would also be helpful in the caption to elaborate a bit more on the ranking technique and to clarify that there is a total of seven PSAs with only six being shown, excluding CWA.

A12: We added each period of time in the bottom of the Figure 1. And we followed your suggestions for a better understanding of the Figure 1, the caption became: "*Evolution of dust PSA contributions to the EDC ice core during the Last Glacial–Interglacial Transition (LGIT; 33.699–2.852 kyr BP; % of total dust deposition for each PSA; Table S2). Bold lines represent a 9-steps moving average. Climate intervals (MIS3, LGM, HS1, ACR, YD*, and Holocene) are indicated along the bottom axis. Central Western Argentina (PSA 7) is omitted because its contribution to the dust assemblage is negligible. Darker shading indicates a higher probability, based on 2000 Monte Carlo simulations, that a source occupies a given rank (Rank 1–7, from greatest to least contribution), providing a measure of the stability of source apportionment through time.*"

Figure 2:

I really appreciate the updates made to this figure. Separating the LGM and Holocene into two panels makes this figure much more legible. Thank you for doing that. Below are additional corrections:

Q13: It would be helpful if the references for the ice core and modern dust data were added in the figure caption both for the reader but also to get properly indexed. The caption for Fig. 2b mentions modern dust from Berkner Island and Holocene dust from Taylor Glacier and Talos Dome. I believe you are also including Holocene dust from Taylor Dome, so that should be stated as well. Additionally, Holocene EDC and Vostok data should be included on Fig. 2b and in Table S5, especially as they are referenced in L262-266 (Delmonte et al., 2007).

A13: We chose to not include the references of ice core and modern dust data in the Figure 2 caption, as it is already very dense in information. We have already created Table S5, which allows the data used and the corresponding time period to be viewed directly.

We have corrected the Taylor Dome name in the caption for Figure 2b. We have also added the values from Delmonte *et al.,* (2007) for the Holocene from the EDC and Vostok ice cores to Table S5 and Figure 2.

Q14: Regarding the Taylor Dome data, it is important to note there are two types of isotopic data presented in Aarons et al., 2016. This includes data on both soluble and insoluble fractions (i.e., filtered ice and dust, respectively). The authors report both in Table S1 and in Fig. 2a and 2b when only the insoluble fractions are relevant to their comparisons. All soluble fractions need to be removed from Fig. 2 and Table S1 because these data are not of dust. Also, it appears that maybe two additional Taylor Glacier samples from Aarons et al. (2017) are missing from the compilation (sample ID P210 and P190) and should be included.

A14: We corrected the Table S5 dataset with the removing of the soluble fraction samples of Aarons *et al.,* (2016) and by the addition of the two missing samples from Aarons *et al.,* (2017). We also corrected the Figure 2 and S5.

Q15: After removing the Taylor Dome data that does not belong on Fig. 2, it becomes more clear that the modern dust from Berkner Island is unique when compared with Holocene ice core dust. All measured data on Panel b with εNd values <-10 come from these samples, which to me highlights a source difference. This is further exemplified if modern dust from Dome A (Du et al., 2018) were included. To my knowledge, there are no published East Antarctic ice core dust records, which contain εNd values <-10. The only ice core dust record that comes to mind, which contains very low εNd values is Holocene data from Siple Dome (Koffman et al. 2021, 2023), but this is not an East Antarctic record, which I think the authors intend on focusing on these. Furthermore, all of these sites (Berkner Island, Siple Dome, and Dome A) highlight ice-free areas of East Antarctica as the most likely dust provenance. This is different from your modeled EDC Holocene data, which appear to be driven by contributions from Southern Africa. Because the manuscript does not focus on the modern and because the modern dust records are observationally different from East Antarctic ice core dust records, I think the inclusion of modern dust on Fig. 2b warrants further discussion. I understand the desire to include more data, but if the authors choose to include it, then it should probably be indicated with a different symbol to not be confused with data from the Middle or Early Holocene.

A15: We thank the reviewer for his suggestion and we used a different symbol for the Berkner Island dataset to distinguish them from the Holocene isotopic data in the Figure 2b.

Q16: Regarding PSA fields, it would be good in the caption to clarify where in Antarctica your Sr-Nd isotope compositions are representing (i.e., McMurdo Dry Valleys). It makes sense to me to have a PSA that represents just the Dry Valleys to match where the REE concentration data are coming from spatially. But it should be clear to the reader that, as drawn, the ANT PSA does not represent all ice-free areas of Antarctica, which can be quite diverse. For example, the McMurdo area is complicated because it contains material from the West Antarctic Rift System (WARS), which is reflected in the glacial drift samples from McMurdo Sound within Blakowski et al. (2014). These WARS data are less radiogenic in 87Sr/86Sr (<0.710) and contain almost exclusively positive εNd values, which are isotopically distinct from the Dry Valleys.

A16: We thank the reviewer for highlighting this potential ambiguity and we clarified the caption with: "*Figure 2: (a) Measured $^{87}Sr/^{86}Sr$ and $\varepsilon_{Nd(0)}$ isotopic compositions of dust in EDC, Taylor Dome, Taylor Glacier, Komsomolskaya, Dome B, Old Dome C ice cores during the LGM (Table S5, open symbols) are compared with expected isotopic values calculated using the REE mixing model applied to EDC samples (solid dots; see section 4.1). (b) Measured isotopic compositions of modern dust collected* *on Berkner Island and Holocene dust from Taylor Glacier, Taylor Dome, Talos Dome (Table S5, open symbols), representative of Holocene dust depositions, are compared with expected isotopic values calculated for the Holocene using the REE mixing model applied to EDC samples (solid dots). Colored frames indicate the isotopic fields of the main dust potential source areas (PSAs) (data from Grousset et al., 1992; Delmonte et al., 2004; Gingele and De Deckker, 2005; De Deckker et al., 2014; Revel-Rolland et al., 2006; Gaiero, 2007; Gili et al., 2017; Gili et al., 2022; Li et al., 2020; Koffman et al., 2021; Blakowski et al., 2014). Note that the SAF domain is more extensive than shown in the figure and that the ANT is represented by the McMudro Dry Valley. For details on calculation see Table S4.*"

Q17: The ANT isotopic data in the manuscript (Table S4) is listed as being sourced from Blakowski et al. (2014), Delmonte et al. (2004)b, and Diaz et al. (2020). To my knowledge, Diaz et al. (2020) does not present data on Sr-Nd isotope compositions. Please confirm the data sources.

A17: We agree that Blakowski *et al.,* (2014) did not report any isotopic signatures for Nd and Sr. However, they provided concentration values ($[Sr]_{PSA}$, $[Nd]_{PSA}$) which are useful to us when calculating isotopic values based on our REE-based provenance results. This is why we have removed this reference from the captions of Figures 2 and S5 but left it in Table S4, which justifies our calculation of the ANT end-members used in our calculation (Eq. 3).

Q18: The legend in panel (b) appears slightly offset, but this is very minor. Also, for consistency with the rest of the manuscript, please use decimals instead of commas for the x-axis. Please also capitalize Old Dome C and Taylor Glacier in the caption.

A18: We followed your suggestion and corrected the caption and the rest of the manuscript.

Figure 3:

Q19: The median lines appear to be missing for NZ and PAP on the Holocene plot. Is the median 0%? When looking at Figure 1, this would imply more than half of the contributions for the Holocene are 0% for both NZ and PAP, but that doesn't appear to be the case. Similarly, ANT appears to have appreciable contributions during the Holocene, yet on the box and whiskers plot, this seems reduced. Perhaps I'm missing something here.

A19: The median lines are not missing, they are at 0% for PAP, NZ and ANT when calculated the full Holocene period.

Holocene Median			Holocene Mean		
PAP	NZ	ANT	PAP	NZ	ANT
0.0	0.0	0.0	10.8	3.3	4.1

This does not imply that these PSAs never contribute during the Holocene. Rather, their contributions are intermittent: many Holocene time steps yield 0% contribution, while other time steps show non-zero and occasionally substantial contributions, as visible in Figure 1. This zero-inflated distribution explains why the median is 0%, whereas the mean values remain positive: 10.8% for PAP, 3.3% for NZ, and 4.1% for ANT. We have clarified this point in the figure caption as follows: "*Figure 3: Box plots of provenance contributions (%) to dust deposited in the EDC ice core during the Holocene and Last Glacial Maximum (LGM). Horizontal lines within the boxes indicate the median contribution for each source, crosses denote the mean, box boundaries represent the first and third quartiles, and whiskers indicate the minimum and maximum values. For PAP, NZ, and ANT during the Holocene, median contributions are 0%, reflecting the large number of time steps with no contribution from these sources, despite episodic non-zero* *contributions that result in positive mean values. Box plots for HS1, ACR, and YD* are shown in Figure S6."*

Figure 4:

Q20: Please reverse the direction of the y-axis for panel D so that wind intensity is consistent with panel C. In the caption, it would be good to add "(this study)" in the description of panel A.

A20: We followed your recommendation.

Additional miscellaneous corrections:

Q21: L21: please change "Marine isotope 3" to "Marine Isotope Stage 3"

A21: Done.

Q22: L80: "as well as and" please omit "and"

A22: Done.

Q23: L198: Figure S3 should be Figure S2

A23: Totally true, this is corrected.

Q24: L252-255: Commas are probably best here instead of semicolons.

A24: Done.

Q25: L310: Consider revising "Based on Sr-Nd isotopes" to "Using the Sr-Nd isotope composition of dust,"

A25: Done.

Q26: L314: ~10,8% should be ~10.8%

A26: Done.

Q27: L338: Nd should be subscript

A27: Done.

Q28: L389 + L459: Please capitalize Dry Valleys

A28: Done.

Q29: L404: "Westly" should be "Westerly"

A29: Done.

Q30: L415: Please add the word "the" so that this line reads "during the Holocene" and also perhaps add references to Fig. 1 and 3 for the reader to refer to.

A30: Done.

Q31: L457: "Est" should be "East"

A31: Done.

Q32: In general, the use of dashes and e

n dashes are both used for ranges (e.g., L22-23). I recommend picking one or the other and being consistent.

A32: We change everyone in short dashes.

Q33: Author Contributions: N.M. and A.B. contributions are missing.

A33: There is no shortage of contributions; they are included under the heading "all authors".

Q34: Fig. S1: change DEPOT to DEEPOT and change Localization to Location

A34: Done.

Q35: Fig. S5: The caption should be revised. As written, it appears that much more data from many sites are plotted than actually are. Only Taylor Dome, Taylor Glacier, and Old Dome C are being plotted as reported in Table S5. I would recommend being explicit about what's being shown for each site and period.

A35: We adjusted the caption like you suggested: "*Figure S5: (a) Comparison between REE-based modelled $^{87}Sr/^{86}Sr$ and ε_{Nd} values and measured dust isotopic compositions from East Antarctica during the MIS3, HS1, ACR, and YD*, shown together with the isotopic domains of the PSA in the Southern Hemisphere. Measured data (open symbols; references, values, and locations in Table S5; see Figure 2 for other time periods) were obtained from ice cores Taylor Dome (MIS3, HS1, ACR), Old Dome C (HS1), and Taylor Glacier (HS1, ACR, YD*). Modelled expected isotopic compositions (solid symbols; see Section 4.1) were calculated using (i) the contributions of PSA (Table S2) and (ii) the isotopic fingerprints and elemental concentrations of PSA end-members (Table S4). Colored frames delineate the isotopic ranges of the respective PSA sources contributing to the dust assemblage (data from Grousset et al., 1992; Delmonte et al., 2004; Gingele and De Deckker, 2005; De Deckker et al., 2014; Revel-Rolland et al., 2006; Gaiero, 2007; Gili et al., 2017, 2022; Li et al., 2020; Koffman et al., 2021; Blakowski et al., 2014—Table S4). Note that the SAF domain extends beyond the range shown in the figure. (b) Sr-Nd isotope composition data used to construct the isotopic fields for each PSA.*"

It appears that the authors addressed the comments from the other reviewer nicely as well. Perhaps a few lingering points include:

Q36: The other reviewer was interested in a supplemental figure that shows the Sr-Nd isotope composition data used to construct the isotopic fields for each PSA. I think this would be a good addition. The authors should consider including this supplemental plot of just the PSA data for the curious reader.

A36: We added this figure in the Figure S5 (see caption corrected in A35).

Q37: The other reviewer requested the use of decimals instead of commas on figures, which author response A48 suggests this was completed, although Fig. 2 and Fig. S5 remain as commas.

A37: This was an unfortunate oversight of mine. This has now been corrected in Figures 2 and S5.