Skeleton Coast source-sink coupling manuscript – Response to Anonymous Referees #1 and #2

Content

General changes made to the manuscript

General changes: Throughout the manuscript, the notation for "approximately" was changed (≈ instead of ~).

l. 5: Added "(hydro-) morphometric": "On the regional scale, this heterogeneity blurs (hydro-) morphometric source-sink relationships […]".

ll. 19: Sentence rephrased for clarification: "Three distinct clusters were identified for both alluvial landforms and catchments, with limited matching observed between alluvial landform and catchment clusters."

l. 311 / Tab. 2: Description changed for the variable "Drainage density" (typo corrected): $dd_c = a_c / s_{c,tot}$ → $dd_c = s_{c,tot} / a_c$

l. 311 / Tab. 2: Index changed for the variable "Average FLC frequency of occurrence, catchment": FLC_f → FLC_c

l. 479: Number of variables changed to the appropriate value: "[...] with n = 8 variables describing the mapped alluvial deposits, [...]"

l. 593: Section heading changed to: "Correlation and scaling relationships"

l. 741: Sentence rephrased to: "The normal distribution may also be deemed indicative for a limited influence of coastal basement surface gradient on fan gradient."

ll. 827: The entire paragraph fog input modelling and the environmental significance of precipitation from fog was shifted to chapter 5.1 (see AR1#1).

Response to Anonymous Referee #1

Dear Anonymous Referee #1, thank you very much reviewing our manuscript and for providing your very helpful comments. We address the points you raised below.

AR1 #1: It is unclear to me how the fog/low-cloud dataset over 2015–2017 is expected to imprint a climatic signal on morphometry of these fluvio-alluvial systems, which likely integrate much longer timescales. More broadly, the climate variables used here represent present-day climatologies, so I think the "limited climatic signal" result should be framed as "limited signal from modern climatologies," rather than evidence that climate was unimportant during formation. Is it possible to: 1) justify why modern gradients are expected to reflect the formative interval, [...]

<u>Reply AR1 #1: We agree and acknowledge that we should make the timescales issue clearer and justify the assumption of long-term stability of modern gradients. We add the following information and statements:</u>

<u>l. 26: Sentence rewritten to:</u> "No robust lithological or climatic (as inferred from modern climatological data) control [...]."

<u>l. 167: Paragraph added by shifting it from l. 831 (see response to AR2 #4):</u> "For example, Li et al. (2018) measured […], but can also promote sediment production as observed in the coastal Atacama Desert (Walk et al., 2022)."

<u>l. 656: Added new paragraph and shifted/rewrote paragraph from ll. 827 (see also AR2 #8):</u> "Despite model and downscaling-depended uncertainties, a glimpse in glacial climate conditions across our study area is provided by the CHELSA-TraCE21k dataset, which is based on the Community Climate System Model Version 3 and a reconstructed paleo-orography for that time, downscaled to a spatial resolution of 1 km (Karger et al., 2020, 2023). From here, dividing modern (Brun et al., 2022a) by LGM (Karger et al., 2023) precipitation model data ($P_{c,mean}$; LGM data prepared as described in section 3.3) yields relative catchment-wide change factors ranging from ≈0.6 (#55) to ≈1.2 (#2), with a mean value of 0.9 across the investigated drainage areas (Fig. C11). Values <1 therefore indicate higher (modelled) precipitation during the LGM, suggesting slightly less arid conditions in our study area, with a spatial focus to the near-coast catchment areas. More importantly, the LGM precipitation gradient towards the hinterland generally mimics the gradient presented by modern precipitation data.

Analogously, fog advection patterns may have followed broadly comparable gradients in the past. However, the modern climate dataset used in this study relies on gauge-corrected European Centre for Atmospheric Research (ECMWF) climatic reanalysis interim (ERA-Interim) data, which does not account for precipitation from fog (Träger-Chatterjee et al., 2010). Large-scaled climate models tend to provide contradictive data at Namibia's coastline (see Karger et al., 2017) and generally fail to capture low-intensity precipitation from fog in a sufficient manner (Hemp and Hemp, 2024). This is problematic in the Skeleton Coast setting, given that fog constitutes a major water input (e.g., Lancaster, 1984; Li et al., 2018) contributing to the preservation of alluvial surfaces by cementation (Sect. 2).

As an attempt to overcome the missing information on fog input, we used the independent dataset provided by Andersen and Cermak (2018). Yet, its short observational record of approximately three years introduces substantial uncertainty when drawing conclusions from modern spatial patterns with respect to long-term topographic evolution, and it did not provide information of significant value for the catchment areas (Section 4.1, Table B6).

As valid for the other modern climate parameters applied in this study, timescale-related uncertainties are inevitably attached to the wind data we used. There are indications that wind regimes may have varied during the Quaternary (e.g., Stuut and Lamy, 2004; Gingele, 1996), providing arguments for a late Quaternary formation of the Skeleton Coast Erg (Miller et al., 2021; Krapf et al., 2005; Sect. 2). However, given the strong role of the erg in shaping fan morphology, wind must be considered a relevant driver for morphometric analysis, even on modern timescales."

<u>l. 1032: Figure added:</u>

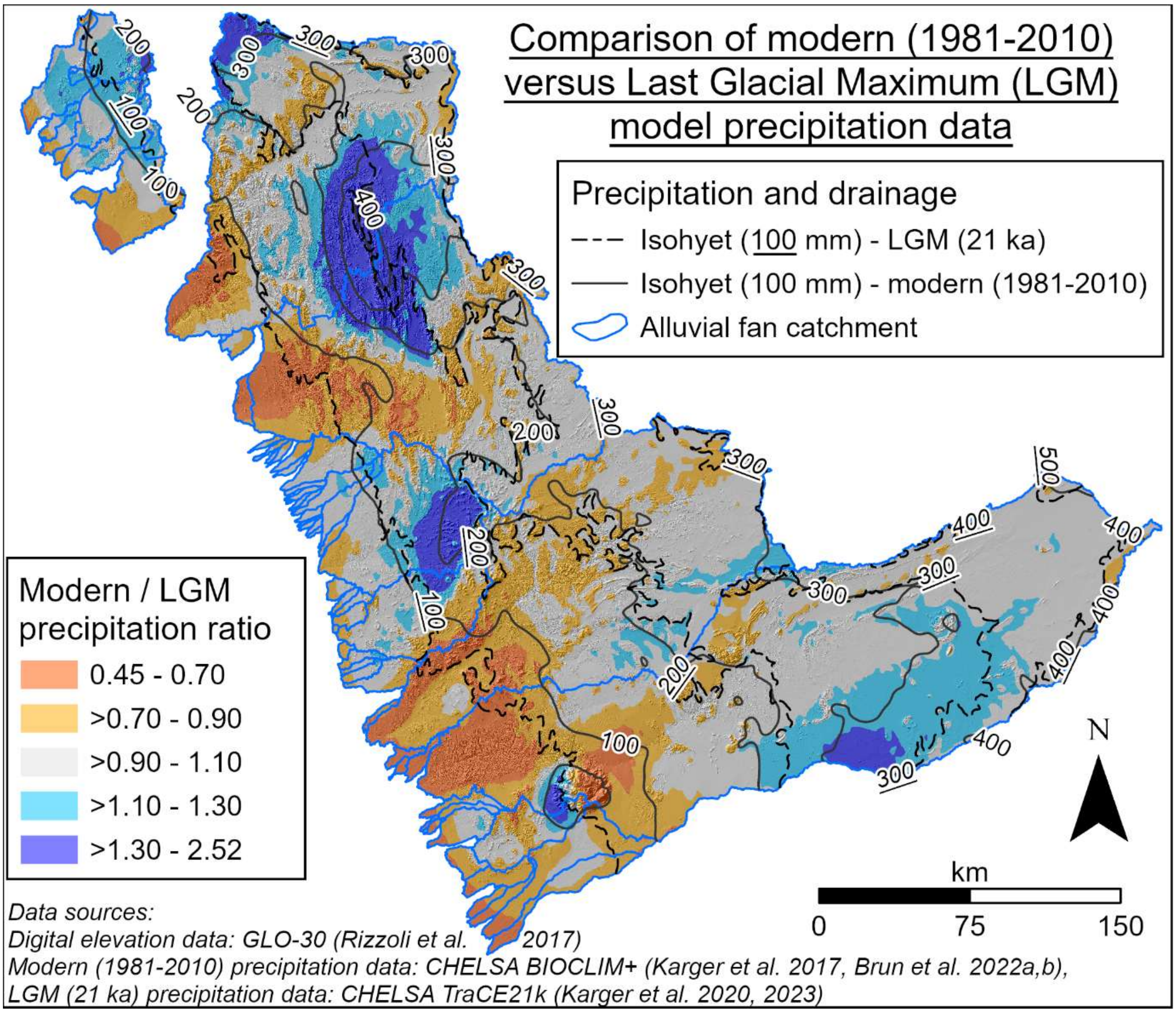

Figure C11. Comparison of modern (1981-2010) versus LGM model precipitation data (Brun et al., 2022b; Karger et al., 2017; Karger et al., 2023, 2020). Ratios calculated from the datasets indicate drier modern conditions close to the present-day coastline, while more humid present-day conditions are predominantly located in elevated and hinterland areas. The coast-parallel precipitation gradient appears in both model

datasets. The bundle of 21 ka 100 mm isohyet contours was thinned out by removing isolated and closed contours related to topographical noise.

l. 841: Added "modern": "[...] that we are unable to link modern fog precipitation [...]"

l. 842: Added: "Besides the general problem of temporal limitations inherent to the climate data (Sect. 5.1), a possible [...]"

l. 856: Added "modern": "Modern wind data [...]"

l. 915: Added "In present-day climate": "Under present-day climatic conditions, the fans in this cluster [...]"

AR1 #2: [...] and/or 2) discuss or test against available paleoclimatic proxies/chronologies for the region to evaluate whether past climatic changes may have left an imprint on these fans?

Reply AR1 #2: We provide more details on past climatological changes, based on sediment archive data:

l. 172: Sentence added: "Regarding the latter, grain size analyses of drill-core sediments collected offshore and slightly south of our study area (≈ 20° S) indicate that over the past ≈300 kyr, less arid conditions and stronger winds were associated with glacial stages along the Namibian coast, whereas interglacials were characterised by more arid conditions and weaker winds (Stuut et al., 2002)."

l. 874: Sentence added: "These morphometric patterns are indicative for significant environmental changes as captured by both on- (Walsh et al., 2023) and offshore (Stuut et al., 2002) sediment records, causing alluvial landform alterations during the Quaternary despite generally persisting hyperaridity.

l. 875: Added "dissected but": "The Horingbaai fan delta exemplifies this, with dissected but heavily encrusted sediments [...]"

AR1 #3: I think treating the sink mainly as an expression of area in this confined setting might not be accurate. If confinement exists, deposition will tend to stack rather than spread over a larger area. In that case, correlating catchment metrics with fan area will naturally give weak correlations even if the system is strongly connected. I suggest a sensitivity analysis using a simple volume/thickness proxy for the sink. [...]

Reply AR1 #3: We agree that focusing on fan area introduces a certain degree of inaccuracy in our confinement setting but note that is difficult to obtain estimations for fan thickness or volume for all our fans across our study area, given the different depositional settings (e.g. bajadas), often somewhat irregular fan shapes, and uncertainties on the bedrock surface morphology. However, we try to apply a rough workaround by assessing the 2D swath profile area framed by the minimum and maximum fan elevations:

l. 652: Paragraph added: "Nevertheless, we acknowledge that the varying degrees of alluvial landform confinement in our study area impose a limitation when using planar fan area a_f as a key morphometric variable to interpret source-to-sink coupling. A potentially more meaningful metric could, in principle, be derived from fan thickness and/or volume. Unlike a_f, such measures may capture the influence of confinement on fan progradation and aggradation more sufficiently, and thus relate fan sediment storage more adequately to their drainage systems. However, owing to the diversity of depositional settings, irregular fan geometries, and uncertainties in the morphology of the underlying bedrock surface, we are unable to provide such a proxy with a level of accuracy comparable to that of a_f. We note, however, that the two-dimensional area of the individual swath profiles – bounded by their minimum and maximum elevation curves – shows a strong linear relationship with a_f (r = 0.92 for n = 67 landforms; Fig. C10). It therefore seems likely that metrics incorporating fan thickness would also be strongly correlated with a_f, and thus fail the initial variable filter step described in Section 3.4. An implication would be that these metrics would not provide a significant gain in morphometric information for the approach we follow."

l. 1032: Figure added:

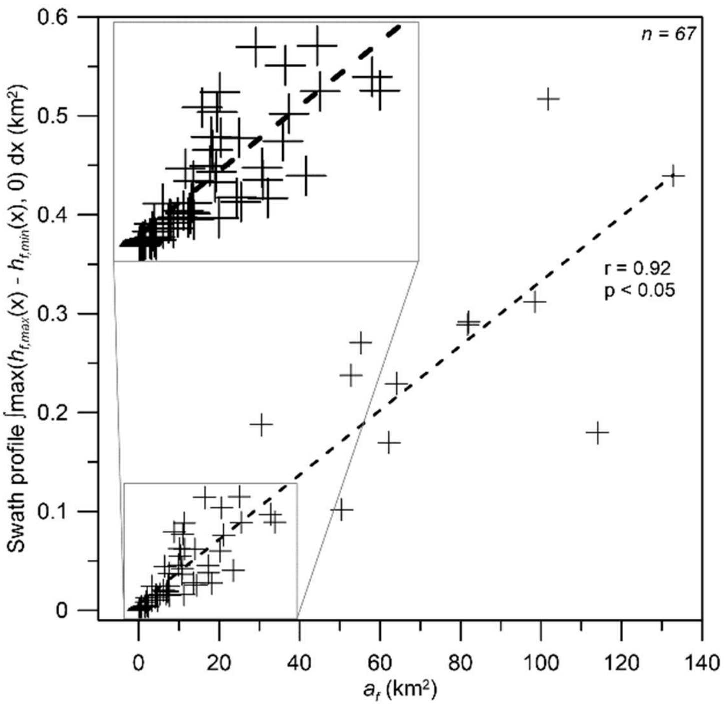

Figure C10. Relationship between fan area a_f and the area between the minimum and maximum (90th percentile) swath profile line. The area represents the integral of the positive part of the elevation difference (calculated in Matlab ver. R2024a using the *trapz* function on densely gridded, interpolated data points). A similar linear relationship is obtained for the fan dataset (n = 52, r = 0.91).

AR1 #4: [...] If this is difficult, I would at least state this explicitly as a limitation and explain that weak correlations may reflect the choice of sink metric (area) under confinement, rather than weak source-to-sink coupling.

Reply AR1 #4: See reply to AR1 #3.

AR1 #5: The overall manuscript leans heavily on confinement by ocean/coalescence/erg as the reason relationships blur. But I would also mention alternative explanations, or at least clarify the mechanisms. For example, confinement can blur the measurements because it reduces avulsion freedom and leads to thicker stacking (not measured) and different distributary behavior, rather than simply reducing fan area. So, I would explicitly mention this as a limitation: that the morphometric measurements (especially area-based metrics) could be impacted by confinement in a way that weakens correlations, even if the source-to-sink system is strongly connected.

Reply AR1 #5: See reply to AR1 #3 and further changes to the main text:

l. 792: Sentence rephrased to: "While this finding highlights the considerable potential of accurately estimating fan thickness and/or volume to further refine source-to-sink coupling analyses in our study area, it may nevertheless appear counterintuitive, given that strong source-sink relationships using catchment metrics as predictor variables do exist at the Skeleton Coast."

l. 924: Sentence rephrased for clarification: "Among the morphometric variables we applied, fan gradient emerges [...]"

Response to Anonymous Referee #2

Dear Anonymous Referee #2, thank you very much reviewing our manuscript and for providing your very helpful comments. We address the points you raised below. We kindly note that we received the comments from Referee #1 earlier in time and completed our response before we received your comments. Since some of the Referee #1's comments are similar to yours, in some instances we refer to our replies to this reviewer where we deem it appropriate.

AR2 #1: It gets quite confusing on reading the paper how many landforms have actually been analysed in the cluster analysis. Somewhere it says 52 landforms that could be delineated confidently, and then when the reader looks at Figure 4, they see n=60 for catchments and n=47 for alluvial landforms. But in the text is says n=38 for the fan dataset after removing outliers. And later again (page 27) the reader is told n=41 drainage system pairs could be matched between catchment and fan clusters. The main message about the number of these fan-catchment systems that are analysed in the paper needs to be consistent throughout the paper. Is it 41 or 38? (it isn't the headline of 67).

Reply AR2 #1: We agree that we should clarify how many landforms and systems are studied:

l 18: Clarification on the number of clustered landforms: "An exploratory data analysis framework combining cluster and partial correlation analyses was applied to these datasets after quality filtering and outlier removal, retaining 47 alluvial landforms."

l. 432: Sentence added: "An overview of the number of landforms retained after the different workflow steps we applied, and the counts used for display in our figures, is provided in Table B2 in addition to the information given in the main text and figure captions."

l. 471: Figure 3 caption rephrased: "Data in (a) and (b) is shown for n = 62 catchments, with nested subcatchments not being shown for clarity."

l. 505: "such" and number of clustered fans added: "To avoid such excessive data loss, we removed only the most distant cases, defined as being separated by more than ≈33 % of the total cophenetic distance across the single linkage dendrogram: #11.1, #11.2, #17.1, #17.2, and #62.2 (n = 47)."

l. 960: Table added (Table B2, table numbering updated accordingly):

Content element	Section	Alluvial landforms (n)	Catchments (n)	Source to sink (n)	Comments
Workflow step					
Fan mapping and catchment delineation	3.2	67	67	-	Initial work step
Fan mapping quality assessment	3.2	52	-	-	See Tab. A1
Fan classification	3.2	52	-	-	See Tab. 1
Morpho-parametrical data generation	3.3	52, 67	67	-	Statistical analyses provided for full and quality-filtered dataset

					("catchment" and "fan" datasets; see Sect. 4.1).
Cluster analyses	3.5	47	60		Outlier removal
Cross-dataset cluster matching	4.3.3			41	Pairs of fans and catchments after outlier removal (see Sect. 3.5)
Figure					
Fig. 2 (study area overview map)	2	67	67		All landforms shown
Fig. 3a,b (catchment morphology)	4.1	-	62		Nested catchments not shown for clarity
Fig. 3c (alluvial landform swath profiles)	4.1	52	-	-	Based on mapping quality assessment (see Sect. 3.2)
Fig. 3d (power correlations)	4.1			52 (coloured), 67 (grey)	Power correlations calculated using n = 52 alluvial landforms (based on mapping quality assessment; see Sect. 3.2)
Fig. 4 (catchment cluster assignments)	4.1		60		Outliers removed (see Sect. 3.5)
Fig. 5 (fan cluster assignments)	4.2.2	47			Outliers removed (see Sect. 3.5)
Fig. 6 (clusters locations)	4.3.1	47	60		Outliers removed (see Sect. 3.5)
Fig. 7a,b (boxplots of alluvial landform cluster variables)	4.3.2	47	60		Outliers removed (see Sect. 3.5)
Fig. 8 (boxplot of catchment cluster variables)	4.3.2	-	60		Outliers removed (see Sect. 3.5)
Fig. 9 (combination diagram of catchment and fan clusters)	4.3.3			41	Pairs of fans and catchments after outlier removal (see Sect. 3.5)
Fig. 10 (power-law relationships)	4.3.4			47 (coloured), 52 (grey)	Outliers-removed dataset (see Sect. 3.5) used for cluster population display

AR2 #2: Another aim is expressed at the end of the section 2 about investigating source-sink coupling and identifying driers of fan evolution. I think the aim(s) should all be in one place in the paper, and towards the end of the introduction. The leading aim is the exploration of heterogeneity, and this leads to being able to explore any patterns in the way the source (catchment) and sink (alluvial fan) might be connected/coupled.

Reply AR2 #2: We agree and merge the last paragraph of Sect. 2 with the end of the introduction and rephrase.

l 136: Paragraph added by shifting it from l. 223 plus rephrasing: "In this regard, the environmental conditions encountered along the Skeleton Coast pose an analogue to the setting of coastal alluvial fans found at the Atacama Desert in northern Chile (see Walk et al., 2020). However, the Skeleton Coast fans are much larger in size and of greater antiquity, thus categorised as large-scale type III' fans in the recent global comparison of alluvial fan systems provided by Lehmkuhl and Owen (2024). The classification assigns the cratonic environment at the Skeleton Coast to provide conditions for alluvial deposition characterised by comparably low sediment production and flux, while alluvial landforms range at the upper end of global fan size (>10^3 km radius) and time (on million-years timescales). As such, the alluvial deposits may represent valuable climate archives for the Quaternary.

However, available information on paleoenvironmental conditions along the Skeleton Coast has either temporal (see e.g. Stuut et al., 2002; Walsh et al., 2023) or spatial (see e.g. Stollhofen et al., 2014) limitations, which justifies a focus on a comprehensive analysis on alluvial landforms along the Skeleton Coast. A comprehensive regional interpretation of such archives would strongly benefit from knowledge on the characteristics of fluvio-alluvial source sink-relationships, allowing for a regional comparison of fan systems to identify drivers in transient fan evolution. Thus, we here take […]"

AR2 #3: I think the exploration of the heterogeneous fans and associated upstream catchments is the focus of the paper, and that a revised title would be more clearly accessible to the reader. I think that many readers will come to a "source-sink" relationship term in the current title with the idea that sediment is being traced/tracked through a system, instead of what I think this paper is designed to do, which is explore controls on why different fans/groups of fans look different to each other, and furthermore see how this yields an insight into a connection between fan source regions (the catchment) and the fan as a sink. So, would something like: "The nature, and potential controls over, alluvial fan and fluvial catchment heterogeneity in the Skeleton Coast of northern Namibia."

Reply AR2 #3: Thank you very much for suggesting the title. We do agree that the present title could be misleading. The version you provided is a suitable alternative, but our feeling is that there is too much emphasis on heterogeneity, which is – without doubt – a key characteristic of fluvio-alluvial (hydro-) morphometrics but does not include our findings that there are some homogeneities (clusters) present. To meet you critics, we therefore suggest an alternative.

l. 1: Title changed to: "Fluvio-alluvial source-sink relationships at the Skeleton Coast of northern Namibia: a parametric analysis"

AR2 #4: Whilst the methods are clearly outlined, the climate variables are a bit problematic. Within the climatic variables, one appears as a surprise – low cloud cover frequency. What is the proposed connection with landscape-forming processes here? Some explanation for the reader would help them to follow.

Reply AR2 #4: We refer to our response AR1 #1. To introduce the significance of fog earlier in the manuscript, we have shifted some text from l. 831 to l. 167.

AR2 #5: A larger-scale conundrum is the limitation/caveat of using modern-day climatological variables, given the time over which these landforms have formed/developed. Different climatic conditions in the past may have left an imprint on the fans. Indeed, elsewhere in the paper the authors suggest that alluvial fan deposits may represent valuable archives for the Quaternary (lines 229), so they are indeed assuming that climatic variables will have changed though the time these features accumulate. Given all of this, should the modern-day climatological variables be included at all? The authors start to interrogate this in section 5.1 "Cluster analysis performance" with "whereas climate variables may reflect shorter-term conditions". Perhaps what would be most interesting is to apply the same methodology without the modern-day climate variables and see what emerges.

Reply AR2 #5: We generally agree on the points you raised here, which heavily touch the comments of AR1. Therefore, we refer to our response AR1 #1 and AR1 #2. We believe that the overall annual synoptic patterns were fairly similar throughout the Quaternary, meaning that the overall climatic gradients – coast vs. hinterland and north vs. south – have been similar in relative terms. However, our findings support the plausible assumption that the present suite of alluvial landforms at the Skeleton Coast is not a product of the exact present-day climate conditions, which is a relevant finding for its own. Nevertheless, we note that even under present-day conditions, significant fluvial activity and fluvio-alluvial deposition has been recorded, although most deposits are temporary due to coastal and wind erosion. Therefore, we consider it reasonable to investigate to which extent present-day climate is relatable to fan and catchment (hydro-) morphometry. We also note that the only considered climate variable in our catchment clustering, i.e. rainfall, is strongly linked to geographical position, which would be chosen as input parameter as substitute of Ppk_c for a revised cluster analysis (Table B6). For the fan dataset, FLC_f has been found to have little impact on cluster formation (Table 3), while we believe that wind erosion (represented by $W_{f,mean}$) is an agent which affects alluvial deposits at present-day and should thus be considered in any case.

AR2 #6: Looking at Appendix B2, it becomes clear that those catchments with >50% of the catchment in volcanic bedrock all fall in cluster 2. And of those catchments with >50% in sedimentary bedrock, 66.6% fall in cluster 2 (then 5/24 in cluster 2, 4/24 in cluster 4). It is therefore surprising that geology (and particularly G1c, G4c) do not appear in Table 4 in the main manuscript. Why is that the case? I cannot follow this in the paper.

Reply AR2 #6: We are very grateful that you took your time for an in-depth examination of the tables. It turned out that at some point after the calculation of the isometric log ratios, we mixed up the bedrock variables. It is our luck that the isometric log ratios were used for clustering, so the results are still valid. With the corrected version, cluster 2 is characterised as follows: $G1_c$

(>50%): 4/13; $G2_c$ (>50%): 1/6; $G3_c$ (>50%): 4/22; $G4_c$ (>50%): 8/11. This distribution is reflected by the t- and F-Values provided in Table 4. We note that the necessary transformation of the data and the way we labelled the three variables created from this transformation represent a compromise of statistical necessities and readability, which is why $G4_c$ is not separately shown but incorporated in the three variables $G1_{c,ILR}$, $G2_{c,ILR}$, and $G3_{c,ILR}$.

Due to the mistake in mixing up data columns, we had to change following tables:

l. 961: Table B3 (B2 in preprint version): Geological variables $G1_c$, $G2_c$, $G3_c$, $G4_c$ → data shifted to the correct columns

l. 970: Table B5 (B4 in preprint version): Statistics updated for variables $G1_c$, $G2_c$, $G3_c$, $G4_c$

AR2 #7: Outside of the questions about how to best apply the methodology to this interesting research problem, there are some observations about references/citations, where there is a more appropriate choice of citation to be made for modern climate and for potential patterns of change in the Quaternary. For example:

(1) where discussing tropical-temperate troughs (line 169). Heine (2004) is not an appropriate reference here. These are: Harrison, 1984; Todd and Washington, 1998; Hart et al., 2010; Macron et al., 2014

Harrison, M.S.J., 1984. A Generalized Classification of South African Summer Rain-Bearing Synoptic Systems. J. Climatol. 4, 547–560. https://doi.org/10.1002/joc.3370040510

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Reply AR2 #7: Thank you for providing these references which we added as you suggested (Heine, 2004 removed).

AR2 #8: Where discussing possible shifts in wind regime (around lines 657-659). Krapf et al. (2005) is not appropriate fit here. There is no age control in this paper and no mention of wind direction. I think the idea of a "fundamental" shift of wind regime since the LGM is entirely speculative and not linked to any supporting data. I'd strongly advise the authors to revise this claim.

Reply AR2 #8: We agree that the knowledge of the timing of Skeleton Coast erg formation, which we tie to a present-day wind regime, is not backed up by solid data. Miller et al. (2021) suggested the expansion of the erg to have occurred at or after 4 ka when the present balance between offshore fluvial and aeolian deposition was reached. Their statement is based on data from an off-shore drill core published by Gingele (1996). We have changed the sentence.

l. 657: Text rephrased to: "There are indications that wind regimes may have varied during the Quaternary (e.g., Stuut and Lamy, 2004; Gingele, 1996), providing arguments for a late Quaternary formation of the Skeleton Coast Erg (Miller et al., 2021; Krapf et al., 2005; Sect. 2). However, given the strong role of the erg in shaping fan morphology, wind must be considered a relevant driver for morphometric analysis, even on modern timescales."

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