Author responses to anonymous referee #1:

This manuscript presents new magnetic-parameter and median grain-size records from the Gansen section in the western Qaidam Basin and integrates them with previously published records to reconstruct hydroclimate variations during the Late Pliocene to Early Pleistocene. The study addresses an important question: whether the precession-dominated precipitation pattern previously identified during the mPWP was persistent throughout the Late Pliocene or restricted to a specific warm interval.

The manuscript is clearly structured, the scientific question is relevant, and the new data provide useful information for understanding orbital-scale hydroclimate variability in the Asian interior. The comparison between the 3.6–3.3 Ma interval and the previously published 3.25–2.95 Ma interval is particularly interesting. The finding that precipitation variability may have shifted from a 100-kyr-dominated pattern to a precession-dominated pattern under different background climate states is potentially significant.

Overall, I find the manuscript suitable for publication after minor revision. The main conclusions are generally reasonable, but several points require clarification, especially regarding the age model, spectral-analysis procedures, proxy interpretation, and the wording of the forcing mechanisms.

Reply: Thank you for the encouraging comments.

1. The chronology is based on the previously published paleomagnetic framework. Because the manuscript focuses on orbital-scale variability, the age model should be described in slightly more detail. I suggest that the authors add a short summary of the

main magnetostratigraphic tie points, interpolation approach, and sedimentation-rate changes. It would also be helpful to briefly mention how chronological uncertainty may affect the identification of 20-kyr, 40-kyr, and 100-kyr cycles. This does not require a new age model, but the current manuscript would benefit from a clearer statement of the chronological basis of the orbital interpretation.

Reply: Thanks for the suggestion and we have expanded the description of the GS age model in the materials and methods section (Lines 159-177).

Lines 159-177: 3.1 Chronology of the GS section

The chronology of the GS section is based on the previously published paleomagnetic framework of Luo et al. (2024). In that study, the observed polarity sequence of the sampled 0-453 m interval was well correlated with the geomagnetic polarity time scale (GPTS), and 10 paleomagnetic age control points were used to establish the age model for the section, indicating that the sampled interval spans ~3.6-~1.8 Ma (Luo et al., 2024). Ages for depths between adjacent paleomagnetic tie points were obtained by linear interpolation, and the resulting age-depth relationship indicates that sedimentation rates were not strictly uniform throughout the GS section. Because the age model is constrained by discrete paleomagnetic tie points, some uncertainty remains in the interpolated ages between adjacent control points, potentially affecting the identification of orbital cycles. Nevertheless, the paleomagnetic chronology is broadly consistent with the Plio-Quaternary age assignment of the GS strata on the regional geological map (Luo et al., 2024), providing an independent geological framework for the studied interval. Furthermore, the same paleomagnetic framework has successfully resolved significant orbital cycles in the previously published high-resolution GS record for 3.25-2.95 Ma (Luo et al., 2024), supporting the use of this chronology for orbital-scale analysis in the studied interval.

2. The spectral results are important for the main conclusion, but the methods are not described in sufficient detail. Please specify the spectral-analysis method used, the interpolation step, detrending method, red-noise background, confidence-level calculation, and filtering procedure. The figure captions should also include enough information for readers to understand how the spectral peaks and filtered curves were obtained. The authors may also consider adding a short statement on the robustness of the 100-kyr peak during 3.6–3.3 Ma, given that this interval contains only a limited number of eccentricity-scale cycles.

Reply: Thanks for the suggestion. We added introduction of spectral-analysis method (Lines 198-215). We also revised the figure 4 caption to include the key methodological information needed to interpret the spectral peaks and filtered curves (Lines 245-250). In addition, we added a short statement in the discussion section (Lines 382-387) to clarify the robustness of the 100-kyr peak during ~3.6-3.3 Ma.

Lines 198-215: 3.3 Spectral analysis

The average sampling resolution of the GS section is ~4 kyr for the ~3.6-3.3 Ma interval and ~19 kyr for the 2.95-~1.8 Ma interval, indicating that the ~3.6-3.3 Ma record has sufficient temporal resolution to resolve orbital-scale variability. For spectral analysis of the ~3.6-3.3 Ma interval, the χ_{fd}/HIRM and median grain-size records were first converted from depth to time based on the paleomagnetic age model of the GS section and then interpolated to evenly spaced 1-kyr time series. Power spectra were calculated using the REDFIT procedure implemented in PAST 3 software, which estimates the red-noise background and tests spectral peaks against an AR(1) red-noise null model. Spectral peaks exceeding the 90% red-noise confidence level were regarded as statistically significant. No additional detrending was applied prior to the Redfit analysis.

Band-pass filtering was further applied to extract the 20-kyr, 40-kyr, and 100-kyr components. The central frequencies and bandwidths used for filtering were 0.05 kyr^{-1} and 0.012 kyr^{-1} for the 20-kyr band, 0.024 kyr^{-1} and 0.004 kyr^{-1} for the 40-kyr band, and 0.01 kyr^{-1} and 0.002 kyr^{-1} for the 100-kyr band, respectively. The filtered GS records were then compared with the corresponding filtered insolation, eccentricity, and benthic $\delta^{18}O$ stack.

Lines 382-387: Although the ~3.6-3.3 Ma interval spans only ~0.3 Myr and therefore contains only a limited number of 100-kyr cycles (Fig. 5), both χ_{fd}/HIRM and median grain-size records consistently exhibit a prominent 100-kyr signal (Fig. 4). This interpretation is further supported by the similar long-term variations in the two precipitation records and by the similar patterns of their filtered 100-kyr components (Fig. 3 and 6).

3. The interpretation that the 100-kyr cyclicity reflects a nonlinear response to insolation forcing is interesting and reasonable. However, eccentricity itself has a weak direct effect on insolation, so the mechanism should be described more cautiously. I

suggest using wording such as “may reflect” or “is consistent with” rather than stronger statements implying a direct causal relationship. The possible roles of Antarctic ice-sheet variability and annual insolation are worth discussing, but they should be presented as plausible hypotheses rather than fully demonstrated mechanisms

Reply: Thank you for this helpful comment. We agree that the proposed mechanism should be described more cautiously. Accordingly, we have revised the relevant text throughout the manuscript by replacing stronger causal wording with more cautious expressions such as “may reflect” We have also revised the discussions of Antarctic ice-sheet variability and annual insolation as possible explanations rather than demonstrated mechanisms, emphasizing that they represent plausible hypotheses requiring further investigation (Lines 415-433).

Lines 415-433: One possible explanation is that eccentricity-scale forcing may have modulated high-latitude ice-volume variability, including Antarctic ice-sheet variability, in a nonlinear way, and that these changes may in turn have influenced EASM intensity through changes in the thermal contrast between Eurasia and the surrounding oceans and/or through changes in Pacific and Atlantic meridional overturning circulation (Zhang et al., 2022; Wang et al., 2023). Because the Arctic ice sheets did not develop on a large scale before ~2.7 Ma (Brigham-Grette et al., 2013; Rahaman et al., 2020; Bridges et al., 2023), Antarctic ice-sheet variability was likely an important component of high-latitude ice-volume changes during the Late Pliocene. Thus, at the 100-kyr band, the broadly similar variations between the two GS precipitation records, eccentricity, and the benthic δ18O stack are consistent with the hypothesis that eccentricity-paced high-latitude ice-volume variability, potentially involving Antarctic ice-sheet changes, contributed to the observed 100-kyr signal in the GS section (Fig. 8). Another possibility is that the dominant 100-kyr cycles in the precipitation records could have been controlled by annual insolation instead of summer insolation. Because the annual insolation integrates seasonal insolation variations caused by precession, it has more power in eccentricity bands and weak power in precession bands (Laskar et al., 2004). However, more investigations are needed to validate this hypothesis.

4. The use of χ_{fd}/HIRM as a precipitation-sensitive proxy is appropriate and is supported by previous work in the Qaidam Basin. However, it would be helpful to briefly summarize why this ratio can be used in the GS section. In particular, the authors should clarify whether post-depositional dissolution, evaporite dilution, or changes in sediment source are unlikely to dominate the magnetic signal.

Reply: Thanks for your careful review. We have revised the manuscript accordingly. In the revised text, we further clarified the applicability of χ_{fd}/HIRM as a precipitation-sensitive proxy in the GS section by adding a brief discussion of potential non-climatic influences. In particular, we now explain why post-depositional dissolution, evaporite dilution, and sediment-source changes are unlikely to have dominated the observed χ_{fd}/HIRM variations in the studied intervals (Lines 304-322).

Lines 304-322: However, to interpret χ_{fd}/HIRM as a precipitation proxy in the GS section, potential non-climatic influences, including post-depositional dissolution, evaporite dilution, and changes in sediment source, need to be considered. First, thermal demagnetization results reported by Luo et al. (2024) for the GS section indicate the preservation of magnetite-bearing remanence carriers, suggesting that pervasive post-depositional reductive dissolution was unlikely to have dominated the magnetic signal. Previous studies from Qaidam fluvial-lacustrine sediments further support the applicability of χ_{fd}/HIRM as a precipitation proxy in settings where magnetic minerals were not significantly dissolved after deposition (Nie et al., 2017; Su et al., 2019; Ren et al., 2020). Second, although evaporite-bearing lithologies occur in the section, the χ_{fd}/HIRM variations are difficult to explain by simple evaporite dilution alone, given their broad consistency with the median grain-size record (Fig. 5). Third, the GS section is dominated mainly by fine-grained lacustrine deposits with relatively uniform lithology, suggesting that major changes in sediment provenance were unlikely to be the primary driver of the observed χ_{fd}/HIRM variations. These considerations support the interpretation that χ_{fd}/HIRM in the GS section primarily reflects precipitation variations rather than being dominated by post-depositional dissolution, evaporite dilution, or sediment-source changes.

5. The interpretation of coarser median grain-size as reflecting stronger precipitation is plausible in a closed shallow-lake setting. However, hydrodynamic conditions should be considered. The grain size of fluvial, delta or nearshore lacustrine sediment is correlated with hydrodynamic conditions, which, in turn, are closely linked to precipitation variability. Therefore, it can indirectly indicate changes in precipitation patterns.

Reply: We agree with the reviewer that hydrodynamic conditions should be considered. Accordingly, the relevant text in the revised manuscript (Lines 322-328).

Lines 322-328: The median grain size can also serve as an indirect precipitation proxy because the grain size of fluvial, deltaic or nearshore lacustrine sediments is closely related to hydrodynamic conditions, which, in turn, are strongly influenced by runoff and precipitation. In the Qaidam Basin, coarser particles in closed and shallow lacustrine settings generally reflect stronger hydrodynamic conditions associated with increased runoff and precipitation (Su et al., 2019; Yang et al., 2020; Luo et al., 2024).

6. The phase relationship between the GS records and the benthic oxygen isotope stack at the 40-kyr band is interesting. However, the benthic δ18O stack reflects both global ice volume and deep-water temperature, and it should not be treated as a pure Antarctic ice-sheet record. I suggest revising the relevant sentences to "high-latitude ice-volume and/or deep-ocean temperature changes" or "Antarctic ice-sheet variability may have contributed to the observed 40-kyr signal." This would make the interpretation more cautious and scientifically precise.

Reply: We agree that the benthic $\delta^{18}O$ stack reflects both global ice volume and deep-water temperature and therefore should not be treated as a pure Antarctic ice-sheet record. Following this suggestion, we have revised the relevant sentences to make the interpretation of the 40-kyr signal more cautious and precise. In the revised manuscript, we now state more cautiously that high-latitude ice-volume variability, potentially including Antarctic ice-sheet variability, may also have modulated precipitation variations in the basin.

7. The title says "Late Pliocene," but the record extends to 1.8 Ma. Please consider using "Late Pliocene to Early Pleistocene" where appropriate.

Reply: We appreciate the reviewer's suggestion. Although the GS record extends to ~1.8 Ma, the orbital-scale analyses and the main conclusions of this study focus primarily on the Late Pliocene, because the sampling resolution in the Early Pleistocene interval is insufficient for robust orbital-scale analysis. We have therefore retained "Late Pliocene" in the title to reflect the primary focus of the study. At the same time, we have revised the title by replacing "hydroclimatic variations" with "precipitation variations" to better match the proxy interpretation and the main objective of the manuscript.

8. Please distinguish clearly between the formal mPWP interval, 3.264–3.025 Ma, and the broader 3.25–2.95 Ma interval used in the analysis.

Reply: We agree that the distinction between the formal mPWP interval (3.264-3.025 Ma) and the broader 3.25-2.95 Ma interval should be stated more clearly. To avoid possible ambiguity, we have checked the manuscript throughout and revised the relevant text where necessary to make this distinction clearer.

9. Line 38, "Precipitation variations during 3.6–3.3 Ma was characterized" should be revised to "precipitation variations during 3.6–3.3 Ma were characterized."

Reply: We have revised this sentence carefully.

10. Lines 135-136 "major moisture source" should be "major moisture sources."

Reply: Thank you for pointing this out. We have revised "major moisture source" to "major moisture sources".

11. Line 211, "high-frequent fluctuations" should be changed to "high-frequency fluctuations."

Reply: We have revised "high-frequent fluctuations" to "high-frequency fluctuations".

12. Lines 382-383, "seasonable insolation variations" should be "seasonal insolation variations."

Reply: We have revised "seasonable insolation variations" to "seasonal insolation variations".

13. Line 384 "Lasker et al." should be corrected to "Laskar et al."

Reply: We have revised "Lasker et al." to "Laskar et al.".

14. The sample numbers should be clarified. The manuscript states that 149 samples were measured, but the numbers given for different intervals should be made consistent.

Reply: We agree that the sample numbers should be clarified. The total number of samples used in this study is 149, whereas the sentence in question was intended only to describe the average sampling resolutions of the two main analyzed intervals. To avoid confusion, we have revised the relevant text by removing the interval-specific sample numbers from that sentence and clarifying the total number of samples in the manuscript.

15. Figure 4 should include more methodological information in the caption, including the spectral method and confidence level.

Reply: We have revised the caption of Figure 4 accordingly by adding the spectral-analysis method and the confidence level used in the spectral analysis (Lines 245-250).