Response to Reviewer 2

In this study, Aguilar et al. present new data of subglacial sediments at Camp Century to evaluate climate conditions in northwestern Greenland during MIS11 and the early Pleistocene / Pliocene. Specifically, the authors use lipid biomarkers to reconstruct temperature and hydrogen isotopes in leaf wax to reconstruct precipitation variability. The authors additionally conduct a careful comparison between there results and existing records across Greenland in order to compare the differing interglacial periods.

The methods and results of the study are scientifically sound and provide remarkable evidence of past conditions in Greenland beyond the available paleo-records. This work is a valuable contribution alongside the growing suite of information coming from the Camp Century basal sediment community. In particular, this study improves our understanding of the sensitivity of the Greenland Ice Sheet to climate forcings beyond the Holocene and Last Interglacial. My congratulations to the authors on a well conducted study and exciting new data.

My major comments on the manuscript are focused on the sensitivity of results to the theoretical "modern" temperature and deuterium values at ice-free bedrock for Camp Century. The additional reliance on reanalysis data to provide modern baselines for other records is a challenge but is likely a necessity for this study.

My minor comments on the manuscript are primarily focused on clarity and the balance between the main text and supplement. I feel there is information within the supplement which should be included in the main text, particularly surrounding information about the core (age control, number of samples, etc). Additionally, there are a number of supplemental figures which are referenced before the main text figures and are not presented in the order they are referenced (ie, the first 3 figures are S4, Figure 1, S11). I recommend moving supplemental figures regarding the new data to the main body in order to highlight the exciting new results from this study.

We thank the Reviewer for the constructive evaluation of our manuscript. We appreciate the reviewer's positive assessment of the scientific quality of the study and are grateful for the recognition that our results provide an important contribution toward understanding Greenland Ice Sheet sensitivity during pre-Holocene warm periods. In response to the reviewer's comments, we will revise the manuscript to improve clarity, expand the description of the Camp Century core and its age constraints in the main text, reorganize the Supplementary Information so that the text and figures are presented in the order in which they are cited, and correct the supplementary figure numbering and references throughout the manuscript.

Major Comments

Line 130: Should this be increased seasonality of precipitation rather than periods of greater snowfall? If winters are increasing in accumulation and summers are decreasing, which is the dominant change in net accumulation?

Thank you for this comment. We agree that our original wording could be interpreted as implying greater net snowfall. We will revise the sentence to emphasize changes in precipitation seasonality, characterized by greater winter snowfall and potentially drier summers, rather than implying an overall increase in annual accumulation.

Line 140: For the “pre-Holocene warm periods”, do you mean other interglacials? As written, there are a number of other time periods (ie interstadials) that it can reference. If the pre-Holocene warm periods refers to either the LIG, MIS11, or the Plio-Pleistocene, define that on first use.

Thank you for this comment. We will revise the text to refer specifically to pre-Holocene interglacial periods, rather than the broader term "pre-Holocene warm periods," to clarify the intended meaning.

Methods: While the information is available in the supplement and later (Section 4.1), I would recommend adding a brief overview of the basal sediments themselves early within the methods section. Primary information such as the dating method, number of age points, total number of samples, total length of the section, etc, should be included. The rough age estimation for each unit should be included (ie, LIG, MIS11, pre-Holocene interglacials). This will provide context and motivation for the remainder of the methods.

Thank you for this suggestion. We will add an additional subsection (Section 2.1) with a concise overview of the Camp Century basal sediment sequence early in the Methods section to provide clearer context for the study design. This will now include the total sediment thickness, the five lithostratigraphic units, and a summary of the age control framework (luminescence and cosmogenic nuclide dating). We will also explicitly summarize the main age constraints, including the MIS 11 age of Units 3–5 and the older Plio–Pleistocene to Early Pleistocene constraints for Unit 1, while referring to the Supplementary Information for further details on core recovery and sampling procedures.

Line 197: Why is the first supplemental figure and supplemental text referenced Figure S4 and Text S3? They should be ordered as they are introduced in the main text. Additionally, why is the first figure referenced in the supplement? If it is important, it should be referenced in the main text.

We thank the reviewer for pointing this out. We will reorganize and renumber the Supplementary Information so that the supplementary text and figures appear in the order in which they are first cited in the manuscript.

Section 2.2: I recommend explicitly stating the goal of generating an elevation corrected bedrock equivalent temperature early within this section. To check my understanding, after scaling the Pituffik climatology via the lapse rate for an increase in 810m, the result is temperature at the Camp Century basal elevation in the absence of an ice sheet under modern conditions. This is so that an exposed Camp Century basal environment can be compared against MIS11 and older data. Is this correct or am I misinterpreting this section?

Thank you for this helpful suggestion. Our objective was to generate a modern, ice-free bedrock-equivalent baseline for both temperature and precipitation isotope values at the Camp Century site. This allows the reconstructed MIS 11 climate to be compared with the climate that would be expected at the Camp Century land surface under modern boundary conditions in the absence of the Greenland Ice Sheet. We will revise the beginning of Section 2.3 to state this objective explicitly and to clarify that the elevation correction was applied to both temperature and precipitation isotope values.

Section 2.2: How realistic is the assumption that the only factor changing temperature under the loss of the ice sheet is elevation? Could another factor like local albedo or atmospheric circulation be playing a larger role?

We thank the reviewer for this insightful comment. We agree that changes in local albedo, atmospheric circulation, and moisture transport would likely accompany the loss or reduction of the Greenland Ice Sheet and could influence local climate beyond the effect of elevation alone. Our objective here, however, is not to reconstruct the complete climate of an ice-free Camp Century, but rather to establish an elevation-corrected, bedrock-equivalent reference baseline for comparison with the paleoclimate reconstructions. We will revise this section to clarify that the lapse-rate correction accounts only for the first-order effect of elevation.

Section 2.2: While the upper limit is 810m, how impactful is the difference between the current elevation (530m) and the upper limit (810)? In other words, what is the sensitivity of the results to the uncertainty in your elevation-corrected modern baseline beyond the +/- 60m?

We thank the reviewer for this comment. We agree that our original wording could be interpreted as implying that the present-day elevation (530 m) represents a plausible endmember for the exposed Camp Century land surface. This was not our intention. We will revise the text to clarify that once the Camp Century site became ice free, substantial isostatic rebound would already have occurred, making an elevation much closer to the fully compensated value (~810 m) more likely than the present-day bed elevation. We therefore retain 810 ± 60 m as our best estimate of the exposed land surface, with the uncertainty reflecting plausible deviations from full isostatic adjustment and transient crustal response during ice-sheet retreat. The sensitivity of our reconstructed temperature anomalies to the assumed elevation is modest. Even if a substantially larger elevation uncertainty of ±300 m were assumed, the resulting temperature uncertainty would be approximately ±1.37°C. Because this scenario represents a much larger uncertainty than our preferred estimate of ±60 m, and because it does not alter the interpretation that Camp Century experienced substantially warmer conditions than the modern baseline, we retain 810 ± 60 m as our best estimate of the exposed land-surface elevation.

Section 2.2: If you were to use the ERA5 reanalysis at the location of Camp Century and scale it down to 810m, how does that compare to scaling Pituffik up?

We thank the reviewer for this suggestion. We evaluated the potential use of ERA5 directly at the Camp Century location and scaling the climate variables to the reconstructed elevation of 810 m. However, we retained the Pituffik-based approach because Camp Century is located within the Greenland Ice Sheet interior, where reanalysis products have larger uncertainties due to limited observational constraints and challenges in representing high-elevation ice-sheet processes (Chen et al., 2026; Zhang et al., 2021). In contrast, Pituffik has a long-term meteorological record that provides stronger observational constraints for evaluating modern climatological conditions (Hersbach et al., 2020; Zhang et al., 2021).

To account for the elevation difference between Pituffik and Camp Century, we applied lapse-rate corrections derived from ice-free regions. Although modern lapse rates over the ice sheet could differ because of ice-surface processes, ice-free lapse rates are more representative of the conditions expected at Camp Century during past ice-free intervals investigated in this study. Therefore, we consider the Pituffik-based elevation correction to provide a more appropriate estimate of the local climate conditions at Camp Century during ice-free periods than applying modern ERA5 values directly over the present-day ice sheet. Given the uncertainties in ERA5 data above the ice sheet, and the greater relevance of ice-free Pituffik to our study samples, we decided it was not necessary to assess in detail the similarities/differences between using Camp Century vs Pituffik data to do this calculation

Line 257: How many records did you compile? While the text references the supplemental tables, providing a brief overview would be useful within the main text.

Thank you for this helpful suggestion. We will revise the Methods section to include a brief overview of the compiled paleoclimate dataset used for comparison with the Camp Century record. We now explicitly state the number and types of records included for both temperature and precipitation isotope reconstructions, including eight brGDGT records, seven ice-core records, five chironomid records, and six macrofossil records for temperature, and six lake records, one marine record, and seven ice-core records for precipitation isotopes. This summary will be provided in the main text, while full details of each record are retained in the Supplementary Tables.

Line 274-276: Do the biomarkers represent mean climate, ie annual mean, or mean of summer climate, or the mean of various summer conditions? Please specify. Does each sample integrate climate over a few centuries / millennia, or does each unit?

Thank you for this helpful comment. We discuss the proxy seasonality in detail in section 3, and this varies slightly by proxy, so we chose to not discuss the details here as well. We will clarify in the text that the exact temporal integration of individual samples is not well constrained by the available chronology. Instead, we state that the biomarker records likely represent long-term average environmental conditions over extended timescales, rather than short-term climate variability.

Line 291-294: Is there station data from Pituffik to compare against rather than ERA5? It would be useful to establish the relationship between the ERA5 reanalysis and actual observations from your sites (at least Pituffik), as there are biases in reanalysis products outside of heavily observed regions.

We thank the reviewer for this suggestion. We agree that comparison between reanalysis products and local observations provides an important assessment of potential biases. Although a direct station-based comparison was not performed here, ERA5 assimilates available meteorological observations through its data assimilation system and provides a spatially and temporally continuous estimate of modern climatology (Hersbach et al., 2020). Because our study requires a continuous climatology that is also applied consistently across comparison datasets, we retained ERA5 for this analysis.

We acknowledge that reanalysis products may contain biases, particularly in data-sparse regions such as the Greenland Ice Sheet interior, where observational constraints are limited (Chen et al., 2026; Zhang et al., 2021). However, Pituffik is supported by a long-term meteorological record and therefore provides a better-constrained location for comparison than the high-elevation ice-sheet interior.

Line 593-594: What unit/units are you referring to for MIS11?

Thank you for pointing this out. We will revise the text to and state that the MIS 11 sediments are the from Units 3-5.

Line 632: There has been a range of recent work on MIS11 and LIG Greenland extent, in references such as Creel et al. (2026) and Holschuh et al. (2026), which should be included here.

Thank you for this suggestion. We will incorporate the recommended references (Creel et al., 2026; Holschuh et al., 2026) and will revise the text to acknowledge recent observational and synthesis studies that further constrain Greenland Ice Sheet extent during the Last Interglacial and MIS 11.

Line 702: Is the increased contribution of local moisture / increased evapotranspiration the cause of the enrichment in d2H as you proposed in the previous paragraph? If so, I would update the text to reflect that.

Thank you for this helpful suggestion. We will revise the text to state that we interpret the enriched summer water vapor δ^2H values as reflecting an increased contribution of locally recycled moisture driven by enhanced terrestrial evapotranspiration over a more extensive ice-free and vegetated landscape.

Line 713-717: Please clarify this statement. The ice core records will be similarly influenced by seasonal biases in precipitation (for instance, He et al. (2021)) which influence d18Oice records.

We thank the reviewer for this helpful comment. We agree that our original wording oversimplified the interpretation of Greenland ice-core isotope records. We will revise the text to clarify that ice-core $\delta^{118}O$ reflects precipitation-weighted snowfall, with the seasonal weighting varying through time (He et al., 2021), whereas the Camp Century leaf-wax and lake-based isotope records primarily record summer moisture conditions.

Figures

Figure 3: Are the data arranged north to south (in the caption), or north to south within each proxy type? I would recommend plotting north to south, starting with sediments and ending with ice cores, such that there can be a more direct comparison between similar proxies at similar latitudes.

We thank the reviewer for this suggestion. We explored several alternative figure layouts, including a north-to-south arrangement. However, because Figure 3 synthesizes multiple proxy types with different climatic sensitivities, we found that the current organization provides the clearest comparison among records while avoiding a less intuitive mixing of proxies or archives.

Figure 4: Add acronym for Camp Century (CC), as both Camp Century and CC are used in the figure.

Thank you for this suggestion. We will add the acronym of Camp Century in the figure.

Figure S4: "…Greenland using Raberg et al., (2021) (red), and Otiniano et al., (2024) (blue)." Specify the use of calibrations within the caption.

Thank you for this comment. We will revise the figure caption.

Minor / Stylistic Comments:

Line 35: Add a comma following "Greenland" (… Camp Century, northwestern Greenland, to reconstruct…)

Thank you for this. We will review this in the manuscript.

Line 38: Use a sentence break rather than a colon.

Thank you for this. We will review this in the manuscript.

Line 73-75: Phrasing is complex – a possible alternative is “While melt due to increased atmospheric warming may be offset by increased winter accumulation, the elevation-albedo feedback…”

Thank you for this suggestion. We will revise the sentence to improve clarity by simplifying its structure while retaining the original meaning.

Line 91-94: Separate into two sentences following “… carbon cycle”, so that the high latitude and mid-to-high latitude connections can be clarified.

Thank you for this suggestion. We will separate the sentence into two sentences to improve readability and clarity.

Line 95-96: Phrasing is unclear and contradicts following sentence. A recommendation is: “… glacial periods became increasingly cold, whereas interglacial conditions remained broadly stable for both the tropics and high-latitudes”.

We thank the reviewer for this comment. We will revise the sentence to clarify that interglacial temperatures were not identical between the tropics and high latitudes, but rather exhibited broadly synchronous, orbitally paced variability with differing amplitudes between regions.

Line 98: MIS acronym is already introduced at line 86.

Thank you for pointing this out. We will remove the redundant definition of the MIS acronym.

Line 97-103: For the comparison between North Atlantic and Eastern Arctic, it would be useful to state which archives these data come from (ie, North Atlantic marine sediments/terrestrial Greenland biomarkers/lake sediments in Eastern Arctic).

We thank the reviewer for this suggestion. We will revise the text to identify the archive types underlying these paleoclimate reconstructions.

Line 125: Swap “Time series of…” for “Reconstructions of…”

Thank you for this. We will review this in the manuscript.

Line 129: Swap “There is therefore…” to “Therefore, there is…”

Thank you for this. We will review this in the manuscript.

Line 441-442: Remove the colon as the list only contains two regions.

Thank you for this. We will review this in the manuscript.

Line 577-580: Clarify this statement or break into multiple sentences.

Thank you for this suggestion. We will revise the text by separating it into multiple sentences to clarify the reasoning linking the biomarker evidence, then constrained depositional age, and the inference that the Camp Century site was ice-free during MIS 11.

Line 753-757: Separate into multiple sentences.

Thank you for this suggestion. We will the original sentence into two sentences to improve clarity while preserving the intended interpretation and supporting evidence.

References

Chen, Z.-M., Zeng, Z.-L., Ding, M.-H., and Wang, Y.-Q.: Comprehensive evaluation of multi-source reanalysis datasets for surface atmospheric parameters over the Greenland Ice Sheet, Advances in Climate Change Research, 17, 48-64, https://doi.org/10.1016/j.accre.2025.10.007, 2026.

Creel, R. C., Kopp, R. E., Dutton, A., Zhou, Y., Raymo, M. E., Britt, C. J., and DeConto, R. M.: North American ice sheet persistence into past interglacials should inform future projections, Nature Communications, 17, 2280, 10.1038/s41467-026-70032-y, 2026.

He, C., Liu, Z., Otto-Bliesner, B. L., Brady, E. C., Zhu, C., Tomas, R., Buizert, C., and Severinghaus, J. P.: Abrupt Heinrich Stadial 1 cooling missing in Greenland oxygen isotopes, Science Advances, 7, eabh1007, doi:10.1126/sciadv.abh1007, 2021.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999-2049, https://doi.org/10.1002/qj.3803, 2020.

Holschuh, N., Christianson, K., Dienstfrey, W., Hills, B., Hoffman, A. O., Paden, J., Winter, K., and Zuraw, R.: Entrained debris records regrowth of the Greenland Ice Sheet after the last interglacial, Nature Geoscience, 19, 573-580, 10.1038/s41561-026-01950-1, 2026.

Zhang, W., Wang, Y., Smeets, P. C. J. P., Reijmer, C. H., Huai, B., Wang, J., and Sun, W.: Estimating near-surface climatology of multi-reanalyses over the Greenland Ice Sheet, Atmospheric Research, 259, 105676, https://doi.org/10.1016/j.atmosres.2021.105676, 2021.