Regarding: response to the reviews of our research article “**The effects of diachronous surface uplift of the European Alps on regional climate and the isotopic composition of precipitation**” by Boateng et al.

Dear Prof. Gabriele Messori,

We carefully considered and addressed all of the reviewer’s remaining concerns. We revised our manuscript accordingly. The most notable changes are summarized below:

1. We followed the reviewer’s suggestion to modify the abstract and conclusions to include a more nuanced discussion of our results, interpretations and associated uncertainties.

2. We agree with the reviewer that our “back of the envelope” calculation of adiabatic and non-adiabatic contributions to temperature changes is insufficient to say with any certainty that non-adiabatic processes play a role. We have followed the reviewer’s advice to drop the approach and adjusted our discussion accordingly.

3. We clarified the confusion around statistical uncertainties and added specific examples of significant and insignificant parts of our work to our manuscript and abstract. This will also prevent similar confusions among future readers.

4. We have followed the reviewer’s advice to calculate and include prediction intervals in our analysis. Fig. 6 and 7 were updated accordingly. However, we disagree with the reviewer that prediction intervals are more suitable and therefore still keep and emphasize confidence intervals. We explained our reasons in detail in our response.

We believe that the implemented changes will resolve all of the raised issues. We kindly ask the editor to carefully consider our detailed response and explanations, where we only partially agree with the reviewer (over point 4).

With kind regards and thanks for your contributions to the review process thus far,

Daniel Boateng and co-authors

Response to Reviewer 1 (J. E Saylor)

Reviewer's comments are repeated in black. Authors' replies are highlighted in blue font, and the revised texts in the manuscript are in quotation marks with blue italics font.

Summary

The authors have addressed the reviewer's concerns in part. However, there are still significant gaps in the data analysis and presentation as outlined below.

Recommendation

My primary reservations regarding the manuscript from the first round still stand. I do not recommend publication of this manuscript in its present form. I recommend that it undergo an additional round of major revisions before being reviewed a third time.

We thank the reviewer for their comments and suggestions regarding the parts of the manuscript that require improvement and clarification, and for their time for reviewing our manuscript the second time. We have addressed all of their comments and suggestions and have implemented the changes in the manuscript, which helped improve it further.

General comments

As in the first version, I do not think that the Abstract or Conclusions sufficiently lay out the results and associated caveats. For example, it is insufficient to indicate "changes" in the model output associated with changing topography without indicating whether those changes are within uncertainty. That the model would change with changing topography is a facile statement. Since most readers will read only the abstract, the abstract must convey both the results and some sense of whether the results are significant. For this study, I suspect that some of the results are significant but others (e.g., temperature, see comment on Lines 540, 543, and 552 below) are not.

We agree with the Reviewer. We have therefore modified the abstract (see lines 15-33) to highlight the key results of the study, the statistical uncertainties, as well as the finer nuances related to the isotopic lapse rates changes. We have also modified the conclusion (see lines 765-798) to present the magnitude of the changes associated with topographic alterations and their statistical significance in reference to the control experiment (see our replies to comments in lines 15-12 and 733).

The authors have provided uncertainties associated with their lapse rates in the form of 95% confidence intervals (presumably of the lapse rate linear fit). This is useful, but a more appropriate uncertainty would be the 95% prediction interval. Given that the lapse rate is empirically calculated, the most relevant question is whether an additional data point would be consistent with the calculated lapse rate (i.e., the prediction interval, not the confidence interval). In other words, if you want to know whether an observation is consistent with a model you want the prediction interval. As I stated previously, I still suspect that these lapse rates are indistinguishable in terms of their prediction intervals.

We have now further calculated the "prediction interval" on the linear regression best fit used for the lapse rate estimates, as suggested by the reviewer, and updated figures 6 and 7 to include these.

However, since the lapse rate estimates are based on simulated $\delta^{18}O_p$ values within the defined transect (fixed data points and additional data not necessary here) and are intended to be compared with similar estimates from different topographic scenarios but not as predictive models for constraining past elevation in this study. We therefore find the "confidence interval," which accounts for the mean response in the transect, more appropriate. The prediction interval of the fitted line as an additional statistical uncertainty metric does not change the reported "slope error" based on the confidence interval with the standard deviation of the slope as a point estimate. Therefore, we cannot conclude that the lapse rates are indistinguishable. We provide details in our replies to the comments lines 685 and 720.

The treatment of temperature changes attributes very small changes in lapse rate to nonadiabatic processes. However, the small changes are within uncertainty of the adiabatic lapse rates. Therefore, although it is possible that these are non-adiabatic changes, it is at least equally likely that they are simply the result of the adiabatic lapse rate. It is impossible to distinguish these two scenarios as far as I can tell. I would favor a conservative approach in which all changes that are within uncertainty of the adiabatic lapse rate are attributed to the adiabatic lapse rate. Nevertheless, the manuscript needs to clearly state what the model results support, and what is interpretation. As it stands, these two are conflated as indicated by statements such as Line 552 in the manuscript (see also comment on Line 552 below).

We agree with the Reviewer that the temperature changes due to the non-adiabatic lapse rate are very small, and that there is a possibility that all the changes can be attributed to the adiabatic lapse rate. We have modified the text to highlight this in lines 550-561. However, due to the known influence of large-scale atmospheric circulation on the region and its potential changes due to alterations in topography, we only suggest that the small temperature changes over the adjacent areas of modified topography 'might be attributed to' a non-adiabatic process. More details are provided in our response to the comment in Line 552.

Detailed comments

Lines 15–21: This could be condensed into 1–2 lines. For example, most of the motivation is irrelevant to the Abstract. Save the space for communicating your results and interpretation.

We have shortened the introductory lines of the abstract, and modified it to clearly indicate the manuscript's main hypothesis and the summary of the results that support the answer to the hypothesis and its implication (see lines 15-32).

"This study presents the simulated response of regional climate and oxygen isotopic composition of precipitation ($\delta^{18}O_p$) to different along-strike topographic evolution scenarios. These simulations are conducted to determine if the previously hypothesized diachronous surface uplift in the Western and Eastern Alps would produce $\delta^{18}O_p$ signals in the geologic record that are sufficiently large and distinct for stable isotope paleoaltimetry. We present a series of topographic sensitivity experiments conducted with the water isotope tracking atmospheric General Circulation Model (GCM) ECHAM5-wiso. The topographic scenarios are created from the variation of two free parameters: (1) the elevation of the West-Central Alps and (2) the elevation of the Eastern Alps. The results indicate $\Delta\ \delta^{18}O_p$ values (i.e., the difference between $\delta^{18}O_p$ values at the low- and high-elevation sites) of up to -8 ‰ along the strike of the Alps for the diachronous

uplift scenarios, primarily due to changes in orographic precipitation and adiabatic lapse rate driven localized changes in near-surface variables. These simulated magnitudes of Δ $\delta^{18}O_p$ values suggest that the expected isotopic signal would be significant enough to be preserved and measured in geologic archives. Moreover, the simulated slight $\delta^{18}O_p$ differences of 1-2 ‰ across the low-elevation sites support the use of the δ-δ paleoaltimetry approach and highlight the importance of sampling far-field low-elevation sites to discern between the different surface uplift scenarios. The elevation-dependent rate of change in $\delta^{18}O_p$ ("isotopic lapse rate") varies depending on the topographic configuration and the extent of the surface uplift. Most of the changes are significant (e.g., -1.04 ‰/km change with slope error of ±0.09 ‰/km), while others were within the range of the statistical uncertainties (e.g., -0.15 ‰/km change with slope error of ±0.13 ‰/km). The results also highlight the plausible changes in atmospheric circulation patterns and associated changes in moisture transport pathways in response to changes in the Alps topography. These large-scale atmospheric dynamics changes can complicate the underlying assumption of stable isotope paleoaltimetry and therefore require integration with paleoclimate modeling to ensure accurate reconstruction of Alps paleoelevation."

Line 56: The theoretical Rayleigh distillation curve is non-linear (Rowley, 2007).

We agree with the Reviewer and made no statement about the Rayleigh distillation curve being linear in our manuscript. However, we acknowledge that the use of "non-linear" climatic responses in this particular sentence may confuse the readers as though we are suggesting something different for the Rayleigh distillation curve. We therefore removed "non-linear" from the sentence, which reads now as follows (see line 56):

"*However, numerous climatic processes, such as surface recycling, aridity, vapor mixing, variability in moisture source, and precipitation dynamics, can also influence the isotopic lapse rate and thus complicate stable isotope paleoaltimetry estimates (Ehlers and Poulsen, 2009; Insel et al., 2010; Feng et al., 2013; Lee and Fung, 2008; Risi et al., 2013; Botysun and Ehlers, 2021).*"

Line 540: The manuscript already states that it is reasonable to attribute 80% of the temperature change to the adiabatic lapse rate. Rephrase this sentence. I suspect it is a hold-over from the first version.

We thank the reviewer for catching and correctly identifying that. We removed the sentence.

Line 543: This approach absolutely needs to be dropped. If there is a potential range of temperature lapse rates, then you need to calculate the potential range of adiabatic temperature decreases based on that range in lapse rates. It is invalid to only use one value (the mean?) and then conclude that some small fraction of the total observed change must be due to non-adiabatic climate change. The best that could be argued is that the misfit _might_ be due to non-adiabatic temperature changes. But it might not be…

We agree. Confidently quantifying adiabatic and non-adiabatic contributions would require a more sophisticated approach than the "back of the envelope" calculation we had conducted. We have therefore discontinued our approach and acknowledge that all the localized simulated temperature changes can be attributed to the adiabatic lapse rate (see our response to the comment in Line 552).

Line 552: No. The results suggest nothing of the sort. They suggest that all of the change can be attributed to adiabatic temperature changes, but that a small fraction _might_ be attributable to non-adiabatic changes. The signal is within the range of the noise.

We agree. We have modified the text to emphasize that all the localized temperature changes are due to the adiabatic lapse rate (see lines 550-561). We attribute only the adjacent far-field temperature changes to non-adiabatic-related processes, such as changes in the atmospheric circulation process.

"The topography sensitivity experiments show significant localized changes in near-surface temperature. For all topographic configurations, the maximum changes were estimated in regions with modified topography, while changes in regions farther from the orogen are less pronounced. The less pronounced regional changes farther from the modified topography areas might be due to associated large-scale atmospheric changes and, therefore, caused by a non-adiabatic mechanism. However, these small and insignificant temperature differences may simply be due to modeling artifacts. On the other hand, the significant changes in regions of modified topography can mainly be attributed to the adiabatic temperature lapse rate, which defines how temperature changes with altitude. Although previous studies have indicated the possibility of non-adiabatic mechanisms (e.g., changes in tropospheric dynamics, local atmospheric humidity, and atmospheric circulation patterns) contributing to changes in addition to the adiabatic lapse rate changes (Ehlers and Poulsen, 2009; Feng and Poulsen, 2016; Kattel et al., 2015), an in-depth quantification of the relative contributions would be required to confidently attribute the changes to non-adiabatic processes."

Line 677: I wonder if it would be worth highlighting the fact that the only way to get d18O values more negative than ~-8 per mil is to have topography that is higher than modern.

We agree with the reviewer and added a sentence with this statement in line 690.

"We highlight that a magnitude of $\Delta\delta^{18}O_p$ value of -8 ‰, which is significant enough to be preserved in geologic archives, would only be achieved when the mean topography is higher than the modern Alps."

Line 685: I don't see the 1 per mil per km. 0.5 per mil per km might be possible based on average values, but, again, the uncertainties are important.

The 1 ‰ and 0.5 ‰ in the Reviewer's comment can be derived from subtracting the modeled lapse rates in Figures 7A and 7B. We refer the reviewer to Fig. 7A for the 0.46 ‰/km difference between CTL and W2E1 for the western transect (i.e., -2.78 minus -2.32 ‰/km) and Fig. 7B for the 1.19 ‰/km difference between CTL and W2E1 for the northern transect (i.e., -3.37 minus -2.18 ‰/km). To avoid confusion for the reader, we have modified the text (see lines 695-699) to include the exact difference and the range of statistical uncertainties for the specific cases we highlighted in this section:

"*For instance, the W2E1 topographic configuration, which best matches the paleoelevation reconstruction in the Middle Miocene by Krsnik et al., 2021 would correspond to an increase of 0.46 (±0.15-0.24) and 1.19 (±0.09-0.11) ‰/km across the western and northern flanks compared to present-day topography. However, the estimated difference between W2E1 and the CTL across the southern flank is 0.2 (±0.13-0.16) ‰/km. This indicates that the impact on the isotopic lapse rate changes depends on the topographic rise and configuration, and the transect considered.*"

Line 692: Without specifying what the effect of the model shortcomings are it is virtually impossible for most readers to consider these limitations in any meaningful way. I am not sure what to advise here, because I assume the effects of the model limitations are unquantified (and perhaps unquantifiable until better models are built). Nevertheless, this section reads very much like a disclaimer.

We added the model limitations in section 5.6 (lines 703-711) to highlight a certain degree of (unquantifiable) uncertainty associated with our simulation, as presented in previous studies (e.g., Langebroek et al., 2011; Werner et al., 2011). Quantifying the exact implications of these individual model limitations would likely require years (or decades) of model development and testing, expansion of $\delta^{18}O_p$ observations, and numerous sensitivity experiments that are not feasible to address in this manuscript (or within a single project or workgroup). We believe it is important to mention the possible sources of uncertainty for future studies. However, we emphasize that estimating the difference between the same specific iso-GCM outputs (and not observations) does not amplify any systematic biases or misrepresentations of the physics of the system; therefore, the presented signals should be robust.

Line 720: The limitations of this section come back to the uncertainties, which in this case should certainly be the prediction intervals. The primary question is whether, given a new data point or data set, you could distinguish between the proposed models. I suspect that given the spread in the data used to calculate lapse rates, the answer is no. However, the authors need to demonstrate that that is not the case.

We disagree. The primary focus of the linear approximation slope estimate between elevation and $\delta^{18}O_p$ values ("isotopic lapse rate") in this manuscript is to determine their potential changes compared to the estimates from the unmodified topographic configuration experiment. We do not intend to use these lapse rate models from our topographic sensitivity experiments as realistic predictive models for estimating paleoelevation. Instead, our goal is to compare these linear relationship estimates among the different experiments. Moreover, these estimates are based on simulated $\delta^{18}O_p$ values within a defined transect with fixed data points. Therefore, their estimated slope and ranges can only be applied to these specific simulation data points. The question raised by the reviewer about whether a new point or dataset would make a difference in the regression estimates is not relevant here, as the estimates are only related to fixed data points. Therefore, the uncertainty of the mean response for the fixed data points within the transect is what is important in this context. We acknowledge that the prediction interval (upper and lower limits) is larger, but its interpretation is limited to that specific regression line and cannot be transferred for comparison with others due to the different distribution of the fixed data points in the transect for a specific topographic scenario. We have added the prediction interval around each of the regression lines, but its interpretation has less significance in this study. We have also modified the text in the methods section (lines 249-261) to clarify these points. If our explanation does not seem satisfactory to the reviewer, we respectfully ask them to clarify the mathematical basis and the reasons for suggestions so that we can efficiently resolve any concerns.

"The elevation-$\delta^{18}O_p$ relationships, referred to here as the isotopic lapse rates (ILRs), were estimated for different geographic areas around the Alps (Fig. 1 A) by performing Ordinary Least Squares (OLS) linear regressions on the grid point values within each region. We use the notation -1‰/km (instead of 1‰/km) to report a decrease of 1‰ for an elevation increase of 1km. We highlight that the aim of the analysis is to determine if the elevation-$\delta^{18}O_p$ relationship over a specific transect would change in response to the different topographic configurations. The estimated lapse rates are not intended to serve as a predictive model for calculating paleoelevation but as a comparison among the topographic configurations to highlight the need to consider the potential changes in lapse rate through space and time. The statistical uncertainties of the calculated lapse rate are determined using the 95% confidence interval around the calculated OLS slope using t-distribution with n-2 degrees of freedom where the standard deviation of the slope is the point estimate for n data points. Additionally, the coefficient of determination (R^2), a measure for the fraction of the variability of the $\delta^{18}O_p$ values that can be explained by the best-fitted OLS estimates, is also reported. We further show the 95% confidence and prediction interval around the regression fitted model to highlight the uncertainties around the individual topographic configuration if it was meant to be used to calculate the paleoelevation for a reconstructed $\delta^{18}O_p$ values. In such a case, however, it would not be appropriate to compare the error limits around the regression line for the different scenarios, since their estimates are based on samples from different distributions. We refer the reader to Montgomery and Runger (2010) for more details about the mathematical derivation of the reported metrics."

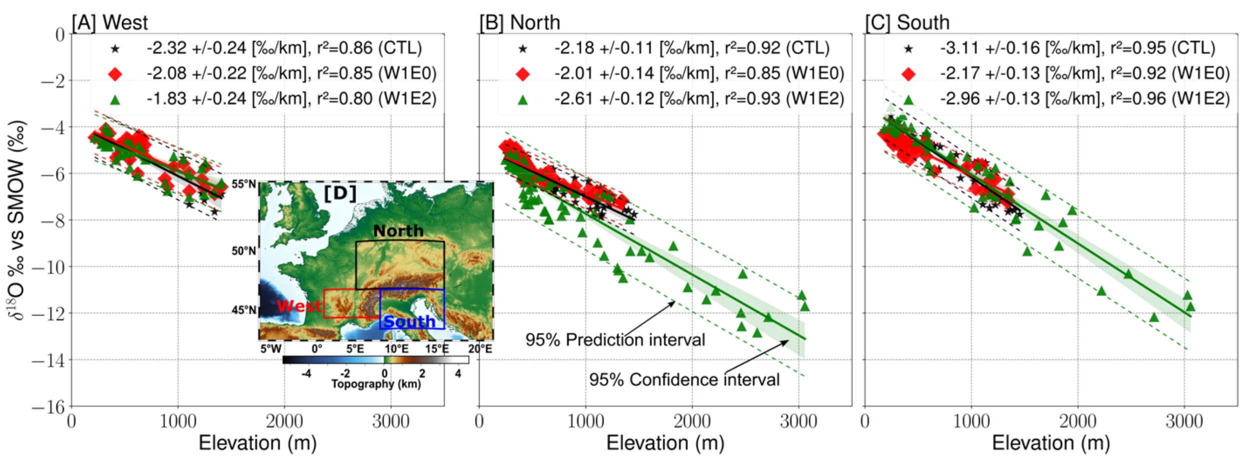

Figure 6: Summer isotopic lapse rates (ILRs) estimates for the W1 topography scenarios (i.e., W1E0 (red), W1E2 (green)), and CTL (black) experiments for the different transects around the Alps as shown in E (West: 44-47 °N, 1-8 °E, south: 43-47 °N, 8-15 °E, and north: 47-50 °N, 5-16 °E). The ILRs are estimated as the $\delta^{18}O_p$-elevation gradients using linear regression. The lapse rate uncertainties are determined using the 95% confidence interval around the calculated OLS slope using t-distribution with n-2 degrees of freedom where the standard deviation of the slope is

the point estimate, coefficient of determination (r^2) is the measure for the fraction of the variability of the $\delta^{18}O_p$ values that can be explained by the best-fitted OLS estimates and the 95% confidence and prediction interval around the regression fitted model to highlight the uncertainties around the individual topographic configuration if it was meant to be used to calculate the paleoelevation for a reconstructed $\delta^{18}O_p$ values.

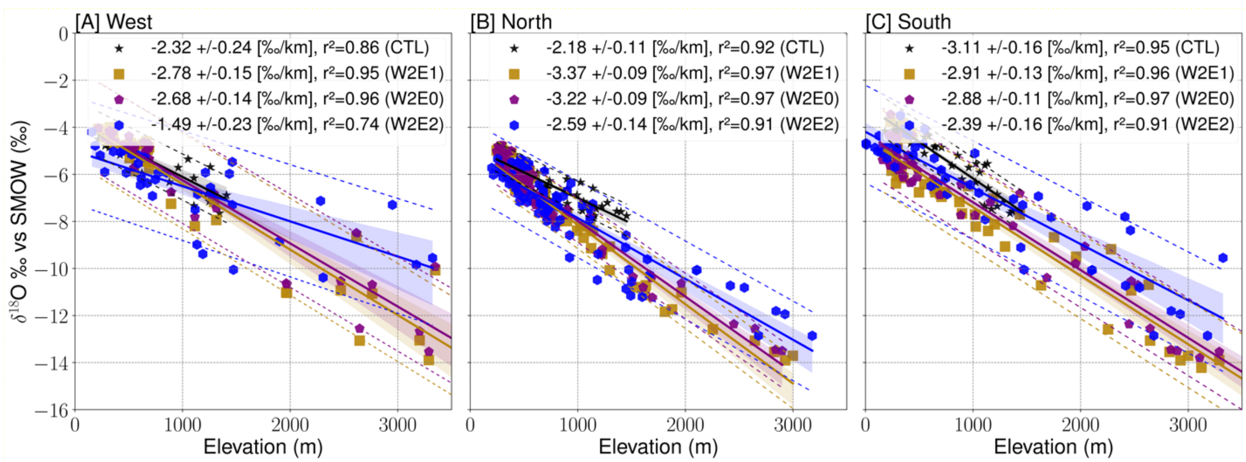

Figure 7: Summer isotopic lapse rates (ILR) estimates for the W2 topography scenarios (i.e., W2E0 (purple), W2E1 (gold)), CTL (black), and W2E2 (blue) experiments for the different transects around the Alps as shown in Fig. 6 E ((West: 44-47 °N, 1-8 °E, south: 43-47 °N, 8-15 °E, and north: 47-50 °N, 5-16 °E). The ILRs are estimated as the $\delta^{18}O_p$-elevation gradients using linear regression. The lapse rate uncertainties are determined using the 95% confidence interval around the calculated OLS slope using t-distribution with n-2 degrees of freedom where the standard deviation of the slope is the point estimate, coefficient of determination (r^2) is the measure for the fraction of the variability of the $\delta^{18}O_p$ values that can be explained by the best-fitted OLS estimates and the 95% confidence and prediction interval around the regression fitted model to highlight the uncertainties around the individual topographic configuration if it was meant to be used to calculate the paleoelevation for a reconstructed $\delta^{18}O_p$ values.

Line 753: As I indicated in my first review, the conclusions and abstract need more detail and caveats associated with the conclusions, given the fact that these are the sections that most people will read. Stating that the changes are “distinctly different” does not communicate any of the nuances of potentially overlapping lapse rates in d8O or temperature.

We agree. We have modified the abstract to include a more nuanced presentation and discussion of the results, as suggested by the reviewer. We also expanded the conclusion to comment on the changes in $\delta^{18}O_p$ values. We now also mention the changes in temperature, precipitation, isotopic lapse rate, atmospheric circulation, and moisture transport that resulted in spatial changes of the $\delta^{18}O_p$ in response to the elevation changes (see lines 764-798).

"The European Alps are hypothesized to have experienced diachronous surface uplift in response to post-collitional process such as slab break-off. Understanding the geodynamic and geomorphic evolution of the Alps requires knowledge of its surface uplift history. This study employs a model-based sensitivity analysis to investigate the regional climatic and $\delta^{18}O_p$ values response to diachronous surface uplift across the Alps. Overall, our results let us accept the hypotheses that the diachronous surface uplift of the West-Central and Eastern Alps would result in distinct regional climates and meteoric $\delta^{18}O_p$ patterns that differ from (1) present-day conditions and (2) conditions produced when the whole Alps are uplifted. If this signal is not lost during the formation of geological proxy material like paleosol carbonates, these records can be used in a stable isotope paleoaltimetry approach to test the hypothesis of eastward propagation of surface uplift in the Alps. We summarize the results as follows:

1. *The diachronous surface uplift across the Alps significantly decreases $\delta^{18}O_p$ values up to ~8 ‰ over the modified areas, mainly due to an increase in orographic precipitation and adiabatic temperature lapse rate. The topographic scenarios with higher elevations in the West-Central Alps produce a greater decrease in $\delta^{18}O_p$ values and an expansion of the affected geographical domain surrounding the Alps when compared to present-day topography. The different topographic scenarios resulted in a less significant change in $\delta^{18}O_p$ values of 1-2 ‰ over the adjacent low-elevation areas around the Alps.*
2. *The $\delta^{18}O_p$ values changes were predominantly driven by the significant increase in precipitation amount of up to ~125 mm/month in response to surface uplift due to orographic airlifting and changes in precipitation dynamics. The surface uplift scenarios with higher West-Central Alps topography resulted in significantly drier conditions (rainshadow) over Northern Europe and towards the eastern flanks.*
3. *Surface uplift resulted in a localized decrease in near-surface temperature that also contributed to the decrease of $\delta^{18}O_p$ values. The temperature changes were only significant over the modified topographic areas, where they can be explained primarily by adiabatic temperature lapse rates. Smaller changes of up to -2 °C over regions farther from the Alps may be attributed to non-adiabatic processes, such as changes in atmospheric circulation.*
4. *The changes in elevation-$\delta^{18}O_p$ relationship (i.e., isotopic lapse rate) among the different topographic scenarios depend on the transect around the Alps and the magnitude of elevation changes. Some changes were small and within the statistical uncertainties' range. The differences in isotopic lapse rates are in the ranges of -0.24 to -0.83 (with the highest uncertainty of ±0.24), -0.17 to -1.19 (±0.14), and -0.15 to -0.94 (±0.16) ‰/km for the western, northern and southern transect, respectively. The differences in these estimates might be attributed to a different redistribution of precipitation and changes in moisture transport distance and pathways along specific transects.*

Note that this study only quantifies the topographic signal while keeping paleoenvironmental conditions constant. Further experiments are needed to investigate the synergistic effects of combined topographic and paleoenvironmental changes and move towards plausible reconstructions of Alps topography and paleoclimate of specific times in the past. Furthermore, the next logical step to close the gap between the predicted meteoric $\delta^{18}O$ response and isotopic ratios extracted from archives is to employ proxy system models to investigate the signal transformation that takes place between these steps. This would allow *for a more accurate back-transformation that can ultimately refine paleoelevation estimates for the Alps."*

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