Reply to the reviewers' comments: Investigating oxygen and carbon isotopic relationships in speleothem records over the last millennium using multiple isotope-enabled climate models (cp-2021-152)

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Summary of changes

We thank the reviewer for their constructive comments and detailed reading. In response to the suggestions by the reviewer we plan to

- change the title to **"Investigating stable oxygen and carbon isotopic variability in speleothem records over the last millennium using multiple isotope-enabled climate models"**
- carefully restructure and rewrite the introduction to better motivate our research and change the conclusion alongside
- change Fig. 5 to include Fig. 5c, which will strengthen our discussion on major climatic drivers,
- revise the discussion to include fundamental isotopic effects, different climatic backgrounds,
- revise the text throughout the manuscript to clarify statements,
- fix formatting where necessary.

A detailed response to the helpful remarks of the referee is given below.

Reply to the second reviewer

(Original report cited in italics)

Dear editor and authors, the manuscript "Investigating oxygen and carbon isotopic relationships in speleothem records over the last millennium using multiple isotope-enabled climate models" is an interesting work. This study compared the speleothem oxygen isotopic records from SISAL v2 with four water-isotope-enabled GCMs over the last millennium, and found regional differences in the oxygen isotope signatures between models are partly attributed to modelled temperature, the lower temporal resolution makes speleothem records is unsuitable to analysis the response to volcanic and solar forcing, and all models underestimate decadal and longer variability compared to speleothem records. However, some analyses may not be sufficient enough and there are several inaccuracies in details. Thus, I recommend publishing it after a revision.

We thank the reviewer for this positive assessment.

Major comments:

1) The subject of this manuscript is unclear. The current models cannot simulate the carbon isotope, how to investigate the carbon isotope using models? Thus, the title is inappropriate. This work cannot explain the relationship between the oxygen and carbon isotopes. Another option focus on the ensemble mean of the multiple GCMs. The highlights is likely derived from the differences and commonalities between the ensemble mean and each member.

We thank the reviewer for this comment, which can help us clarify the manuscript. Indeed, simulated carbon isotopes are not implemented in the models. However, we can compare simulated climatic variables, such as temperature, precipitation and evaporation, to the speleothem data, as these variables have shown to partially control speleothem δ^{13}C (Fohlmeister et al., 2020; Novello et al., 2021). Thus, our aim is not to investigate the direct relationship between speleothem δ^{18}O and δ^{13}C, but rather their climatic controls and their response to forced events, such as volcanic eruptions and changes in solar forcing. Following the comment raised by the reviewer we will modify the title to **"Investigating stable oxygen and carbon isotopic variability in speleothem records over the last millennium using multiple isotope-enabled climate models"**. We intend to make sure that the introduction clearly states what relationships we are investigating and how this is performed in regard to the model simulations.

2) The mechanism and the reason need to be further explored. The advantage of climate model is to explore the mechanism. How does the temperature affect the oxygen isotope signature? What's the feedback? How does precipitation amount impact the water isotope at low latitudes?

We agree with the reviewer that model simulations are a great tool for exploring and understanding mechanisms in the climate system. From the implementations of stable water isotopes in each of the individual models, their individual performance and potential biases in $\delta^{18}O_{sim}$ compared to observations and/or proxy data is already established (e.g. Bühler et al., 2021; Comas-Bru et al., 2019; Midhun et al., 2021). Following the comment raised by the reviewer, we intend to be more explicit in our explanations of the isotopic signatures and the mechanisms behind them theoretically, based on our findings. The fundamental processes causing isotopic fractionation effects by changes in temperature, precipitation amount, geographical location, circulation patterns and seasonal effects are well-established in previous literature (Dansgaard, 1964; Rozanski et al., 1992). Here, we do not aim to explain the mechanics and dynamics in all five simulations in relation to the speleothems. We rather find and investigate where simulations and proxy data match – or don't, and whether simulations yield consistent patterns themselves.

However, also following the suggestions of reviewer 1, we will include more discussion throughout the manuscript on these fundamental isotopic effects as described by Dansgaard (1964) and Rozanski et al. (1992), and elaborate more on where we see the effects (like amount and continental effect) in proxy and model.

3) The details are needed be carefully checked and the logic and legibility should be further improved.g. It is too arbitrary to obtain the conclusion of the "major driver" from a correlation map in the climate model study. If the differences between the models is so large, how to definite that the ensemble mean is climate signal or noise.

We agree with the reviewer, that more model diagnostics need to be checked in order to obtain a coherent picture of which variables drive $\delta^{18}O$ in the model world. However as for this analysis, only few variables were available for all models and even for evaporation, latent heat had to be used as a surrogate for some models. We will clarify in the discussion, that more variables need to be tested.

We also agree, that Fig. 5 is not sufficient to conclude on the major drivers. We revised Fig. 5 and added a Fig. 5c as in Fig. A3, from which conclusions can be drawn more easily. Before we were relying on the supplement SFig. 5, which show dominant regions for the variables temperature and precipitation. Additionally, we emphasise that Fig. 5 does not result from the correlation of the ensemble mean fields, but instead shows the mean of the correlation fields for each simulation. From SFig.5 as well as our agreement markers in Fig. 5 we show, that we do see a modelled climate signal.

We will carefully revise the sections, where we explain the correlation maps and better discuss our conclusions. Additionally we will highlight the need to analyse more variables in the discussion more clearly. A revised Fig. 5 is provided and explained in the Detailed Comments.

Detailed Comments:

The introduction is not focused. If possible, please highlight the importance of comparing simulated water isotopes with measured speleothem isotopes, illustrating the reasons for analysis from spatial, temporal and extreme events aspects.

We will revise the whole introduction and highlight the innovation of our study more clearly. We will especially follow the advise from the reviewer to highlight (1) the importance of comparing simulated water isotopes with measured speleothem isotopes, (2) illustrating the reasons for analysis from spatial, temporal and extreme events aspects. Besides restructuring, we will include the following thoughts into the introduction:

1. Following the recommendations of PAGESHydro2k-Consortium (2017), proxy and model comparison should take place on equal ground. If we want to analyze the representation of the modelled hydrological cycle, archives of δ^{18}O are the most common. Comparisons need to take place on the δ^{18}O level, to avoid uncertainty through proxy calibration to specific desired variables and subjective interpretation.

2. Spatial and temporal consistency between modelled and archived data is to be critically evaluated (PAGESHydro2k-Consortium, 2017) unless externally forced e.g. through volcanic eruptions. Spatial and temporal inconsistencies can arise from model-topography or internal variability. Nonetheless, modelled temporal variability in the frequency domain can be evaluated using proxy data. Also global spatial patterns in models can be evaluated.

Page 1, Lines 13-14. How to distinguish climate drivers of variability for both modelled and measured isotopes?

Thank you for pointing this out. Of course, we don't search for common drivers in both modelled and real world. We will rewrite the sentence as follows:
"... We systematically evaluate differences and commonalities between the standardized model simulation outputs. The goal is to distinguish climatic drivers of variability **for** modelled **isotopes and compare them to those of** measured isotopes. ..."

Page 2, Lines 20-21. Is it possible to show the formula of carbon isotope like oxygen isotope (line 19)? We will add a definition in line 24, where we introduce the carbon isotopes. It will read as follows:

"...Oxygen and carbon isotopes (δ^{13}C) are incorporated in calcite or aragonite matrices in accumulated growth layers and have long been used as proxies of terrestrial climate (Hendy, 1971). **For carbon isotopes, the δ notation is given as** $\boldsymbol{\delta^{13}\mathrm{C} = \left(\frac{\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}_{\mathrm{sample}}}{\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}_{\mathrm{standard}}} - 1\right) \cdot 1000}$ **‰ against V-PDB.**...."

Page 2, Line 35. Please add the cave monitor work (Duan et al., 2016).

Thank you for the suggestion. We will add the work to the section.

Page 2, Line 38. How to understand the "speleothem carbon isotopes can be easier to interpret than oxygen isotopes"? What's the easy explanation of the speleothem carbon isotopes?

Thank you for pointing our this misleading sentence. We wanted to emphasis, that for specific caves, some proxies may be easier to interpret than others. Our statement is also meant the other way around, that oxygen may be easier to interpret than carbon isotopes in other caves. We will rewrite the statement as follows:

"... Depending on the specific site, **some proxies may be easier to interpret than others. As such,** speleothem carbon isotopes can **carry a more straightforward signal** than oxygen isotopes **where overlapping processes in specific regions can complicate interpretation** (Scholz et al., 2012; Ridley et al., 2015), especially during large climate changes such as the deglaciation (Genty et al., 2006). **Vise versa, carbon isotope sometimes need to be pre-constrained through the help of other proxies, e.g. δ^{18}O to determine dominant processes (Fohlmeister et al., 2017).** Studies considering both isotopes profited from the isotopes' mutual information on fractionation processes and were able to disentangle the encoded climatic signal (Fohlmeister et al., 2017; Baker et al., 2017; Novello et al., 2019)...."

Page 3, Lines 10-15. What's the main conclusion from the previous model-data comparison? A detailed explanation is necessary to emphasize the motivation and innovation of this work.

Previous model-data comparisons using the SISALv2 database do support the usage of the database to evaluate modelled δ^{18}O in different time periods and to investigate different climatic features. Comas-Bru et al. (2019) found a consistency between observed and simulated changes in δ^{18}O between ECHAM5-wiso and SISALv2. However, the simulation could underestimate some of these changes between the researched time periods (Mid-Holocene and Last Glacial Maximum). The study suggests that speleothems are under a large effect of site specific parameters which can contribute significantly to regional signals. Thus, they conclude that both mismatches between models and speleothems, and speleothem chronological and proxy uncertainties, are reasons to mainly focus on large-scale spatial patterns. In studies on isotopic fingerprints of major climate modes (such as monsoons, ENSO and PDO), Midhun et al. (2021) found that pseudo-stalagmites spatially correlated with signatures of ENSO and PDO using iCESM, and Parker et al. (2021) found that using ECHAM5-wiso and GISS-E1-R, relationships between speleothem δ^{18}O and changes in circulation and precipitation were captured by speleothems in monsoon regions in Mid-Holocene, Last Interglacial and Last Glacial Maximum. Using iHadCM3, Bühler et al. (2021) found a fairly small time-mean spatial offset during last millennium, but lower speleothem δ^{18}O variability than the simulated δ^{18}O on interannual to decadal timescales. A lower temporal resolution of speleothem records and karst effects that smooth the δ^{18}O signal suggests that data-model comparisons perform better on (multi-)decadal and longer timescales (Comas-Bru et al., 2019; Bühler et al., 2021; Midhun et al., 2021).

Following the suggestion raised, we have summarized the main conclusions from previous comparisons and connected the remaining knowledge gaps to our aim and motivation of our study more clearly. This paragraph now reads as follows:

"The Speleothem Isotope Synthesis and Analyses (SISAL) working group has collected a large number of speleothem records globally and compiled the database SISALv2. It has been employed for model-data comparisons of the last glacial maximum, the Mid-Holocene, the last millennium, and the historical period using different models (iCESM: Midhun et al. (2021), iHadCM3: Bühler et al. (2021), ECHAM5-wiso: Comas-Bru et al. (2019); Parker et al. (2021) and GISS-E1-R: Parker et al. (2021)).~~, supporting the usage of the database to evaluate modelled δ^{18}O across different time periods, as the method reproduces first-order spatial patterns of isotopic variability (Comas-Bru et al., 2019)~~. **The previous model-data comparisons supports the use of the database to evaluate modelled δ^{18}O across different time periods, although speleothems have a lower δ^{18}O variability than simulated δ^{18}O on interannual to decadal timescales globally. However, a benchmarking study on model performance in simulating d18O, including multi-model comparison and model-data comparison with SISALv2 has not yet been performed.**"

Page 3, Lines 34-37. What's the main conclusion from the multi-model comparison? A detailed explanation is also necessary to emphasize the motivation and innovation of this work.

We agree with the reviewer, that we can more strongly draw attention to the innovative aspects of our work. Along with the previous section, which summarizes conclusions of these multi-model studies, we will change the section as follows:

"... The second evaluation in the SWING2-intercomparison of isotope-enabled AGCMs in 2012 showed that model differences most likely arise from differences in processes that control atmospheric humidity (Risi et al., 2012). Conroy et al. (2013) found that models which realistically capture precipitation patterns in the tropics are not necessarily successful in simulating the isotopic composition of precipitation compared to measured data and vice versa, cautioning on always using multiple models when comparing to paleoclimate proxy records. All models that are used in this study have been part of the SWING2 assessment for the historical period in their current, previous, or atmosphere-only version. **The historical period multi-model comparison is, however, too short to analyse and compare multi-decadal to centennial isotopic variability.** Therefore, this multi-model comparison complements previous work (Jungclaus et al., 2017; Midhun and Ramesh, 2016; Conroy et al., 2013), through its focus on **how different models represent** SWI **and its variability on different timescales** over the entire last millennium. We aim to identify common model biases (Kageyama et al., 2018) globally and in different regions, as well as distinguish specific climate drivers for modelled isotope variability on decadal and longer timescales. ... "

Also, we will change the outline in the introduction to:
"...Here we will present a multi-model comparison of five isotope-enabled last millennium simulations: ECHAM5/MPI-OM (Sjolte et al., 2018), GISS ModelE2-R (Lewis and Legrande, 2015; Colose et al., 2016a,b), the iGCM version of the Community Earth System Model (CESM) (Stevenson et al., 2019; Brady et al., 2019), the iGCM version 3 of the Hadley Model (HadCM) (Bühler et al., 2021), and the water isotope-incorporated Scripps Experimental Climate Prediction Center's GSM (Yoshimura et al., 2008), with climate characteristics and forcings as depicted in Fig. 1 and listed in Tab. 1. **This allows, for the first time, for the joint intercomparison of stable water isotopologue variability in climate models and proxy archives in a time period dominated by natural forcing.**"

Also, we will emphasize this more in the conclusion:
"...**This joint intercomparison of stable water isotopologue variability in both models and speleothem data is the first dataset in a time period of natural forcing and allows for more future analysis by the scientific community.** Our analysis encourages the use of multi-model means whenever possible as already suggested by other studies (Colose et al., 2016a). From the point of model evaluation, the incorporation of different archives with higher resolution (e.g. corals, trees, ice cores as in the iso2k database (Konecky et al., 2020)) and with the help of improved proxy system models may provide further insight into why offsets between models can be so large regionally. From a speleothem perspective, within-cave and between-cave variability comparisons using both ...."

It is recommended to illustrate the ability of each model to simulate oxygen isotope in the introduction or Data section, which would help the readers to explain the differences among the models.

We follow the reviewer's suggestion, and will add figure A2 and Fig. A1, which was also suggested by reviewer 1, to the supplement file in the revised version of the manuscript. This figure will clearly show each model's individual representation at the speleothem location. We will also refer to these shortly in data section 2.1, the results section 4.1, and the discussion section 5.1 in the updated manuscript. For differences between the models, we will also add the vertical resolution of each model to Table 1 for reference.

The past millennium includes different climatic backgrounds (Medieval Warm Period, Little Ice Age, and Modern Warm Period), and the spatial distributions and main driving factors of simulated water isotopes and measured speleothem isotopes may be different under warm and cold backgrounds. Comparison analyses in different climatic backgrounds are suggested.

We agree with the reviewer, that both simulated and measured SWI will be different under different background states. While signatures of LIA-cooling or MCA-warming

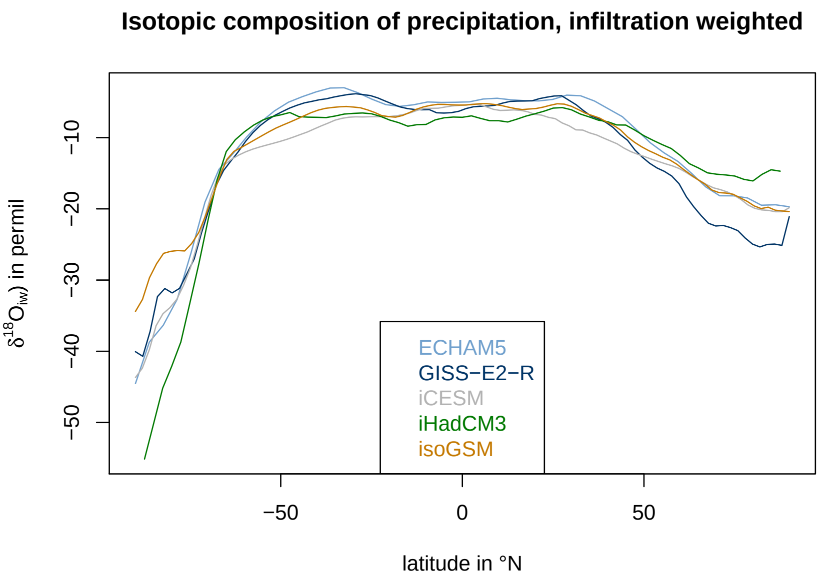

Figure A1: Mean simulated $\delta^{18}\mathrm{O}_{iw}$ across all latitudes for all simulations.

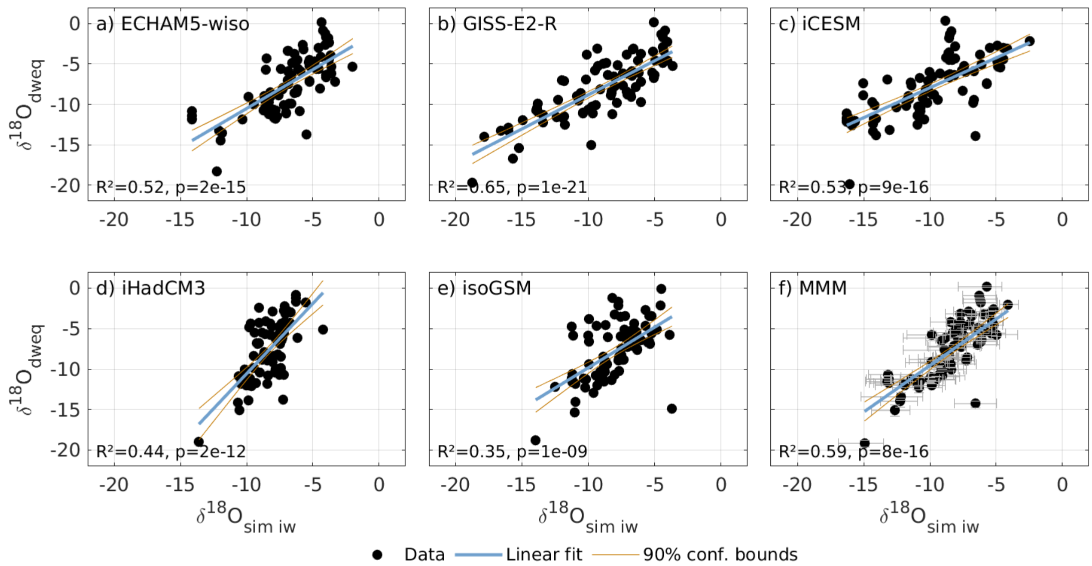

Figure A2: Speleothem $\delta^{18}\mathrm{O}_{dweq}$ and simulated $\delta^{18}\mathrm{O}_{iw}$ in a) ECHAM5-wiso, b) GISS-E2-R, c) iCESM, d) iHadCM3, e) isoGSM, and f) multi-model mean.

exist on a regional scale (McDermott et al., 2001), there is no global coherence of cold or warm periods over the Common Era (Neukom et al., 2019). Modelled global mean isotopic signatures of the models used in this analysis maximally differ by 0.1‰between the LIA and the MCA, and not even all models agree in the direction of the change. The intra-model comparison between the two periods are also still within the general inter-model range of global mean isotopic concentration which is well above 2‰. Other model-data comparisons also didn't include specific analysis on the LIA and MCA (Werner et al., 2016). Regional studies with spatially higher resolved models are necessary to analyse if signatures are visible. The current anthropogenic warming is of course visible in both model and data (Shukla et al., 2019), which is however not part of this study, where we only analyzed the last millennium until 1850CE. Different climatic backgrounds e.g. between LGM and the Holocene are also visible in both model and data and offsets and biases is analysed in multiple studies (Comas-Bru et al., 2019; Tierney et al., 2020; Parker et al., 2021). We will add these thoughts to our discussion.

Page 12. Please check the description for Figure 3. It is difficult to find ECHAM5-wiso with more strongly depleted mid-latitude oceans than in the other simulations and iCESM and iHadCM3 with stronger depletion towards the poles compared to the other simulations; Modifying48 ‰to -8.48 ‰.

Thank you for finding the missing minus sign. The first reviewer also noticed it and we will correct it in the revised manuscript. Also, following the suggestions of the first reviewer, we will revise the section as follows:

"... The global mean $\delta^{18}O_{iw}$ values are fairly similar in area-weighted global mean of 8.48‰ (90% CI: −8.61, −8.36) and −8.41‰ (−8.62, −8.2) for isoGSM and GISS-E2-R, respectively. The ECHAM5-wiso run is less depleted with a global $\delta^{18}O_{sim}$ mean of −7.27‰ (−7.46, −7.09), ~~but~~ **and** with ~~clearly~~ visibl**y** ~~more~~**less** ~~strongly~~ depleted mid-latitude oceans than in the other simulations. iCESM and iHadCM3 show a stronger depletion of −9.39‰ (−9.51, −9.28) and −9.15‰ (−9.29, −9.01) respectively, with **iCESM showing** stronger depletion **in the mid-latitudes and iHadCM3** towards the **Antarctic** compared to the other simulations. **Although GISS-E2-R shows strong depletion especially in the arctic region, the less depleted mid-latitudes dominate the global mean.** ..."

Page 13. It is better to indicate the latitude and longitude of the cave locations mentioned in the text.

Thank you for your suggestion. This will surely enhance information to readers, who want to compare with other caves. We will add longitude, latitude and elevation information to the cave sites.

Page 14, Figure 5. it is not enough to obtain the driver relationship from the corre-

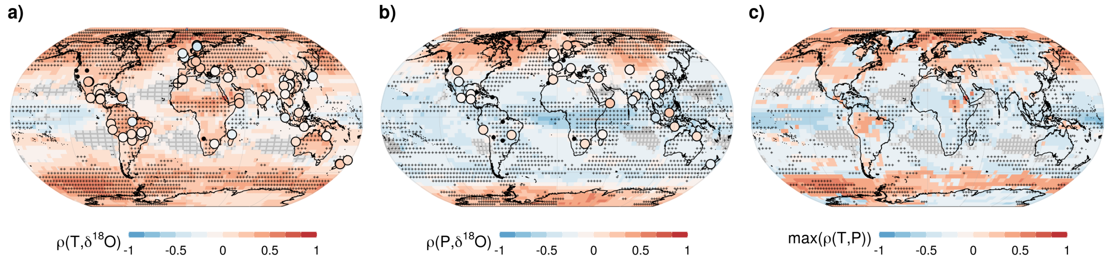

Figure A3: a-b) as Fig. 5 in the manuscript. c) shows red colors, wherever absolute correlation estimates to temperature are larger than absolute correlation estimates to precipitation and vice versa in blue.

lation in Figure 5. There is also a high correlation between precipitation and isotopes in the high latitudes of the northern hemisphere in Figure 5. The further feedback or circulation analysis is suggested. Moreover, it is worth noting that the sign of correlations between simulated $\delta^{18}O_{sim}$ and temperature is consistent with many correlations between measured $\delta^{18}O_{speleo}$ and modelled temperature, but this is not same for precipitation. A possible reason is also welcome.

We agree with the reviewer, that Fig. 5 is not enough to draw the conclusions. We revised the figure to Fig. A3, where we added Fig. A3c) compared to the original figure. Red colors indicate higher absolute correlation estimates to temperature, blue colors indicate higher absolute correlation estimates to precipitation. The patterns that we described are much better visible here. Temperature is still the main driver of isotope variability in the higher latitudes while precipitation dominates in the lower latitudes. We add, however, that precipitation also dominates isotope variability in the Antarctic surrounded by a dominant temperature zone in the Southern Ocean.

We stated the exact numbers for sign agreement between correlation estimates for the simulation and the speleothem isotopes further down the text and also in the discussion. We will however add more explanation in the results section. We change the section as follows:

"... The inter-model comparison shows more agreement in the correlation fields to temperature than to precipitation, when focusing only on cave locations: the sign of correlation between $\delta^{18}\mathrm{O}_{sim}$ and simulated temperature agree for three and more simulations at 60% of locations, and for four and more simulations even at 26% of locations. For precipitation on the other hand, only 11 % of locations agree in sign for three and more simulations, while it is only 1.1 % with agreement in four or more simulations. **The more uniform temperature response to external forcing may increase the total number of significant correlation estimates and thus also the number of locations that agree in sign.** ..."

Page 15, Figure 6. The caption of Figure 6 misses the description of (b) and (d). Significance levels should be added when discussing correlations.

We will adjust the caption as follows

"Speleothem $\delta^{18}O_{dweq}$ **(first row)** and $\delta^{13}C_c$ **(second row)** against latitude **(first column)** and altitude **(second column)** as provided by the database. Linear regression lines are shown separately for northern and southern hemisphere in (a) and (c), while the R^2 and p corresponds to the global linear regressions. **Confidence bounds are 90 %.**"

Page 20, lines 11-12. and Page 21 lines 24-25. It is too arbitrary to obtain the conclusion of the "major driver" for the climate model study.

We agree with the reviewer, that some passages are not concluded detailed enough. The passages will also be enhanced throught the added evidence in the recised Fig. A3. We change the section as follows:

"... Similarly, most of the strong regional differences in $\delta^{18}O_{sim}$ between models could be explained by regional differences in simulated temperature (SFig. 3)~~, as temperature was shown to be a major driver of $\delta^{18}O_{sim}$ (Fig. 5a)~~..."

"... For all simulations, temperature variability was the dominant driver in $\delta^{18}O_{sim}$ at high latitudes and precipitation variability at low latitudes **and parts of the Antarctic**(Fig. 5**c and SF.5**). ..."

Page 21, line 27. What is "cave locations for 3 and more simulations"? Is it "3 or more simulated cave locations"?

Sorry for the misleading formulation. We meant cave locations for ≥ 3 simulations and will adjust the sentence accordingly.

Page 22, lines 34-35. A possible reason is welcome. We will change the section as follows:

"... We found that 86% of speleothems have a significant temporal correlation between speleothem oxygen and carbon isotopes, with 47% even showing strong significant (anti-) correlations of $|c| > 0.5$. **High co-variability between both isotopes can either be caused by kinetic fractionation processes (Hendy, 1971) in the cave environment or may be externally forced. For example, (Fohlmeister et al., 2017) studied a stalagmite in a very arid region and found strong correlation between the isotopes. They** ~~The co-variability of both isotopes has been studied for a very arid region stalagmite by Fohlmeister et al. (2017) who also found strong correlation between both isotopes. High correlation between the isotopes could hint at kinetic isotope fractionation effects (Hendy, 1971). Fohlmeister et al. (2017)~~ attribute increased correlation to times of strong variations in cave-internal processes triggered by variations of external conditions. This simultaneity agrees with our findings that generally no extreme event in isotopes precedes the other, which can, however, also be attributed to low sampling resolution. **More local cave monitoring studies are necessary to potentially exclude kinetic fractionation effect as the dominant driver.** ..."

Page 24, lines 22-23. What is the evidence to support this conclusion?

We thank the reviewer for raising this question. To clarify our statement further, we will refine the specific paragraph in the conclusion as follows:

"... We presented a multi-model comparison over five last millennium isotope-enabled simulations (ECHAM5-wiso, GISS-E2-R, iCESM, iHadCM3 and isoGSM) and compared their representation of isotopic signatures in mean and variability to paleoclimate data from a large speleothem database (a last millennium subset of SISALv2). We found that $\delta^{18}O_{sim}$ differed substantially between models on a regional scale as well as at speleothem cave sites, **which could in part be attributed to differences in simulated temperature, model biases in implementing water isotopes or topography, but also cave- and site-specific controls on speleothem isotopes. To compensate for these differences, we used multi-model means in spatial comparisons.** The isoGSM simulation showed the lowest absolute mean offset to the speleothems at cave locations, while all other simulations show only slightly higher offsets...."

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