Response to referee #1

Major comments

1.1 Give some overall view and more physical interpretation

The paper directly dives into complicated statistical diagnostics. But before this, I think some overview would be useful. For example, a few **basic figures showing the maps** of simulated δ 18Oprecip anomalies for a few key periods would be useful before showing the regional averages. When describing the results of the statistical methods, it would be useful to better guide the reader in the **physical interpretation of the figures**: what does it mean when values are more negative, positive, larger, smaller... (more details in minor comments.) At the end of each sub-section, a few sentences would be useful to **summarize the results** in terms of physical understanding of the processes driving the isotopic variability. A statistical analysis is not enough to identify causality and thus isotopic "drivers", so the discussion should rely more on the huge body of literature devoted to the interpretation of water isotopic records in monsoon regions.

The focus of this paper is not to use isotope-enable models directly to explain observed changes in the speleothem records but rather to use statistical approaches to explore patterns in the observations and model outputs, on the assumption that consistency between the two reveals physically plausible explanations of regional speleothem changes. We will modify the introduction to make the logic of using statistical analyses combining observations and model outputs clearer (please see specific modifications below). Since we are using previously published model results, it does not seem necessary to include a separate section describing these results. However, we will include anomaly maps of simulated $\delta^{18}O_{precip}$ and speleothem $\delta^{18}O$ data from SISAL v2 in the supplementary material and refer to these maps in the main text.

Although the statistical approaches we are using (PCoA, multiple regression, z-scores) are not commonly applied to speleothem records, they are standard techniques for analysing other kinds of environmental data. However, to guide readers through these statistical analyses, we will revise the text in the methods and results sections to clearly describe what each analysis or figure shows, as follows:

*Section 2.3 (line 167): "*PCoA results were displayed as a biplot, where sites ordinated close to one another (i.e., with similar PCoA scores) show similar trends and sites ordinated far apart have dissimilar trends."

Section 3.1 (line 268): "PCoA shows the (dis)similarity of Holocene $\delta^{18}O_{spel}$ evolution across individual records, and thus allows an objective regionalisation of these records."

Section 3.2 (line 280): "To investigate the causes of glacial-interglacial shifts in $\delta^{18}O$, we compare simulated and observed regional $\delta^{18}O$ signals during the LIG, LGM and MH with shifts in climate variables (precipitation and temperature)."

Section 3.4 (line 319): "The MLR analyses of simulated $\delta^{18}O_{precip}$ trends identify the impact of an individual climate variable on $\delta^{18}O_{precip}$ in the absence of changes in other variables."

We agree with the reviewer that statistical relationships do not necessarily indicate causal relationships. Generally, explanations of the causes of observed $\delta^{18}O_{spel}$ variability either rely on modern $\delta^{18}O$-climate observations and assume that these are constant through time (e.g. Sinha et *al., 2015), or interpret changes by comparison with other palaeoclimate reconstructions (e.g. Maher, 2008; Ward et al., 2019). However, $\delta^{18}O$-climate relationships may not have remained constant through the past and cross-comparison between palaeoclimate reconstructions is complicated by the fact that different archives record climate in different and non-linear ways. We therefore tackle this problem with a data-model approach that has two main advantages:*

- *By using a large number of coexistent speleothem records to identify the large-scale coherent trends, we reduce the impact of non-climatic factors (i.e. soil and karst processes) on $\delta^{18}O_{spel}$. This approach focuses on the trends consistent across records that are inherited from $\delta^{18}O_{precip}$.*
- *We use model simulations that explicitly include water isotope physics to reproduce large-scale orbital trends in $\delta^{18}O$. These therefore provide a physically plausible explanation of $\delta^{18}O$ trends under past climate conditions. Congruence between the observed and simulated trends suggests that the drivers of regional changes in the model world are plausible explanations of these changes in the observations. Multiple regression analysis is a convenient way of exploring the various drivers of $\delta^{18}O$.*

Our approach to explain past isotope changes in terms of specific climate drivers is robust as it takes into account large-scale trends in $\delta^{18}O_{spel}$ using a known understanding of isotope physics.

To clarify how our approach investigates the underlying mechanisms of $\delta^{18}O_{spel}$ trends, we will amend the introduction (from line 79):

"These interpretations generally rely on modern $\delta^{18}O_{precip}$-climate observations, which may not have remained constant through time. The sources of $\delta^{18}O$ variability can also be explored using isotope-enabled climate models (e.g. Hu et al., 2019), which incorporate known isotope effects and therefore provide plausible explanations for $\delta^{18}O_{spel}$ trends."

And from line 91:

"In this study, we combine speleothem $\delta^{18}O$ records from version 2 of the Speleothem Isotopes Synthesis and Analysis (SISAL) database with isotope-enabled palaeoclimate simulations from two climate models to investigate the plausible mechanisms driving changes in $\delta^{18}O$ in monsoon regions through the Holocene (last 11,700 years) and between interglacial (mid-Holocene and Last Interglacial) and glacial (Last Glacial Maximum) states."

Given the inherent limitations, discussed above, in interpreting the speleothem records based on modern relationships and/or comparison with other reconstructions, our statistical approach offers new insights into the interpretation of regional changes. Nevertheless, we have included a discussion (from line 380 to 396) of how our results fit with existing literature.

1.2 Evaluate and discuss the model realism and robustness

The models are used in the regression analysis but what is the realism of the simulations? To what extent can they be trusted? Some comparison between SISAL and the models are shown in the figures, but the variables and diagnostics are different, so it's hard to compare (more details in minor comments). The observations and simulations should be compared in a more rigorous way. Also, figure 1 could be redone with the models, as an additional check of the realism of the simulations. An entire sub-section should be devoted to model evaluation. Every time it is possible, both models should be used for the same diagnostics to assess to robustness. It's a great opportunity to have two models, and it should be used more systematically. After the evaluation section, the reader should have a clear opinion on what feature in the simulations can or cannot be trusted. Then when the regression analysis is performed, there should be some discussion on what specific results can be trusted or not.

Climate models produce internally physically consistent changes in the simulated variables and our goal in this paper is not to evaluate the model simulations as such. This has been done to a greater or lesser extent in previous publications (e.g. LeGrande and Schmidt, 2009; Wackerbarth et al., 2012, Gierz et al., 2017; Werner et al., 2018; Comas-Bru et al., 2019). Here we assume that the broadscale trends shown in these simulations are robust and that they can be used to diagnose what factors might contribute to observed changes in speleothem $\delta^{18}O$ *between glacial and interglacial states and through the Holocene. We will make this clearer by rewriting the sentence in line 101 to explain this logic as follows:*

"We exploit the fact that models produce internally physically consistent changes to explore potential and plausible causes of the trends observed in speleothem records across specific monsoon regions, using multiple regression analysis."

Since we are using previously published simulations, our description of the models focuses on the model set-up boundary conditions. However, we agree that it would be worthwhile to expand these descriptions in order to comment on their reliability on the basis of previously published analyses and will amend the model description text. We will also include figures showing relevant model outputs in Supplementary.

We agree that directly comparing multiple models would be a good way to test the robustness of our findings, but this is currently not possible. There are only a few isotope-enabled palaeoclimate simulations and they often use different modelling protocols. Here, for example, the only time period which was run by both models was the mid-Holocene (6 ka) and the experimental protocols by each modelling group were different. This makes it difficult to isolate the reasons behind any differences between the two simulations (~0.5‰, line 425). This is why we decided to focus on comparing glacial-interglacial trends using the ECHAM simulations, and the trends through the Holocene using the GISS simulations. We will re-order and rewrite the model description section (section 2.2; from line 121) to make this logic clearer as follows:

"There are relatively few paleoclimate simulations made with models that incorporate oxygen isotope tracers, and the available simulations do not necessarily focus on the same periods or use the same modelling protocols. Here we use simulations of opportunity from two isotope-enabled climate models: ECHAM5 (version 5 of the European Centre for medium range weather forecasting model in HAMburg) and GISS E-R (Goddard Institute for Space Studies Model version E-R). The ECHAM5 simulations provide an opportunity to examine large-scale changes between glacial and interglacial states, using simulations of the MH, LGM and LIG. The GISS Model E-R Ocean-Atmosphere Coupled General Circulation Model was used to investigate the evolution of $\delta^{18}O$ evolution during the Holocene, using eight time slice (9 ka, 6 ka, 5 ka, 4 ka, 3 ka, 2 ka, 1 ka and 0 ka) experiments. Although simulations of the MH 6ka time slice are available with both models, there are differences in the protocol used for the two experiments which preclude direct comparison of the simulations.

The ECHAM5-wiso MH experiment (Wackerbarth et al., 2012; Werner, 2019) was forced by orbital parameters (based on Berger and Loutre, 1991) and greenhouse gas (GHG) concentrations (CO_2 = 280 ppm, CH_4 = 650 ppb, N_2O = 270 ppb) appropriate to 6 ka. Changes in sea-surface temperature (SST) and sea-ice were derived from a transient Holocene simulation (Varma et al., 2012). The control simulation for the MH experiment was an ECHAM-wiso simulation of the period 1956-1999 (Langebroek et al., 2011), using observed SSTs and sea-ice cover. This control experiment was forced by SSTs and sea-ice only, with atmospheric circulation free to evolve. The ECHAM5-wiso LGM experiment (Werner, 2019; Werner et al., 2018) was forced by orbital parameters (Berger and Loutre, 1991), GHG concentrations (CO_2 = 185 ppm, CH_4 = 350 ppb, N_2O = 200 ppb), land-sea distribution and ice sheet height and extent appropriate to 21 ka; SST and sea-ice cover were prescribed from the GLAMAP dataset (Schäfer-Neth and Paul, 2003). Sea surface water and sea-ice $\delta^{18}O$ were uniformly enriched by 1 ‰ at the start of the experiment. The control simulation for the LGM experiment used present-day conditions, including orbital parameters and GHG concentrations set to modern values, and SSTs and sea-ice cover from the last 20 years (1979-1999). Both the MH and LGM simulations were run at T106 horizontal grid resolution, approximately 1.1°by 1.1°. Comparison of the MH and LGM simulations with speleothem data globally (Comas-Bru et al., 2019; Fig. S1 and Fig. S2) show that the ECHAM model reproduces the broadscale spatial gradients and the sign of isotopic changes at the majority of cave sites (MH: 72%; LGM: 76%). However, the changes compared to present are generally more muted in the simulations than shown by the speleothem records.

The LIG experiment (Gierz et al., 2017a, 2017b) was run using the ECHAM5/MPI-OM Earth System Model, with stable water isotope diagnostics included in the ECHAM5 atmosphere model (Werner et al., 2011), the dynamic vegetation model JSBACH (Haese et al., 2012) and the MPI-OM ocean/sea-ice module (Xu et al., 2012). This simulation was run at T31L19 horizontal grid resolution, approximately 3.75° by 3.75°. The LIG simulation was forced by orbital parameters derived from Berger and Loutre (1991) and GHG concentrations (CO_2 = 276 ppm, CH_4 = 640 ppb, N_2O = 263 ppb) appropriate to 125 ka, but it was assumed that ice sheet configuration and land-sea geography is unchanged from modern and therefore no change was made to the isotopic composition of sea water. The LIG simulation is compared to a pre-industrial (PI) control with appropriate insolation, GHG and ice sheet forcing for 1850 CE. The sign of simulated isotopic changes in the LIG is in good agreement with ice core records from Antarctica and Greenland and speleothem records from Europe, the Middle East and China (Gierz et al., 2017b) although, as with the MH and LGM, the observed changes tend to be larger than the simulated changes (Fig. S3).

There are GISS ModelE-R (LeGrande and Schmidt, 2009) simulations for eight time slices during the Holocene (9 ka, 6 ka, 5 ka, 4 ka, 3 ka, 2 ka, 1 ka and 0 ka). The 0 ka experiment is considered as the pre-industrial control (ca 1880 CE). Orbital parameters were based on Berger and Loutre (1991) and GHG concentrations were adjusted based on ice core reconstructions (Brook et al., 2000; Indermühle et al., 1999; Sowers, 2003) for each time slice. A remnant Laurentide ice sheet was included in the 9 ka simulation, following Licciardi et al. (1998), and the corresponding adjustment was made to mean ocean salinity and ocean water $\delta^{18}O$ to account for this (Carlson et al., 2008). The ice sheet in all the other experiments was specified to be the same as modern, and therefore no adjustment was necessary. The simulations were run using the M20 version of GISS ModelE-R, which has a horizontal resolution of 4° by 5°. Each experiment was run for 500 years and we use the last 100 simulated years for the analyses. Comparison of the simulated trends in $\delta^{18}O$ show good agreement with Greenland ice core records, marine records from the tropical Pacific and Chinese speleothem records (LeGrande and Schmidt, 2009). However, as is the case with the ECHAM simulations, the model tends to produce changes less extreme than shown by the observations (Fig. S4, S5 and S6)."

Minor comments

- l 48: “The temperature effects stem from the temperature dependance of oxygen isotope fractionation during condensation and ...” -> “The temperature effects stem from the oxygen isotope fractionation during condensation and ...”. The contribution of the temperature dependance of the fractionation coefficient in the temperature effect is small (e.g. realistic results can be obtained even with constant isotopic fractionation: Galewsky and Hurley (2010)).

We will reword this sentence as follows: “The temperature effect stems from the cooling required for progressive rainout during Rayleigh distillation (Dansgaard, 1964; Rozanski et al., 1993).”

- l 59: “depleted” -> “enriched”? Actually, it depends depleted or enriched compared to what, but the specificity of evapo-transpiration is to be enriched relatively to the overlying water vapor, and thus to have an enriching effect of the water vapor (Gat and Matsui (1991)).

We will reword this sentence as follows: “The isotopic composition of atmospheric water vapour may also be modified by precipitation recycling over land, since evapotranspiration returns moisture from precipitation back to the atmosphere thereby reducing the $\delta^{18}O_{precip}$/distance gradient along an advection path that occurs with Rayleigh distillation (Gat, 1996; Salati et al., 1979).”

- l 64: you can also add Caley et al. (2014) in the citations.

This section of the introduction summarises the various ways speleothem $\delta^{18}O$ records were interpreted in the original publications. Caley et al. (2014) does not publish or interpret a new speleothem d18O record but is a model-based analysis of factors driving changes in the Asian monsoon $\delta^{18}O_{spel}$ using an isotope-enabled model. We do not think it is relevant to cite it here.

- l 189: define “OIPC”: is it the dataset described above?

Yes, this is the data set described in line 185-186. We apologise for not naming it there and will amend the text to do so, as follows: “... using as reference the Online Isotopes in Precipitation Calculator (OIPC: Bowen, 2018; Bowen and Revenaugh, 2003), a global gridded dataset of interpolated mean annual precipitation-weighted $\delta^{18}O_{precip}$ data.”

- Figure 3: I have trouble reading this figure. For δ18O, is it possible to have the same y-scale for Δδ 18Oprecip and Δδ 18Ospel? This would allow a direct visual comparison of these 2 quantities. I also have trouble seeing whether anomalies are negative or positive: could you draw an horizontal line to indicate the 0? The 0 line could be shared for all potted variables. In addition, why do you compare observed Δδ 18Ospel to simulated Δδ 18Oprecip? Why not converting simulated Δδ 18Oprecip into δ 18Ocalcite for a more rigorous comparison?

In figure 3, each variable has different units and axes have been adjusted so that glacial-interglacial patterns are aligned for easier reading of trends, rather than comparison of quantitative values. Adding zero lines for each variable would make the figure more difficult to read. However, we will modify it so that boxes are grouped together by variable ($\delta^{18}O_{spel}$, $\delta^{18}O_{precip}$, precipitation, temperature) instead of by time period. We will order each group by time slice (MH, LGM, LIG). We think that this will make it easier for readers to see and interpret the trends. The $\delta^{18}O_{precip}$ has not been converted to its speleothem-equivalent (i.e., $\delta^{18}O_{calcite}$) as this requires knowing mean cave temperature which would have to be estimated by using model-simulated temperature, thereby adding more uncertainty to the data.

- l 270: "consistently low PCoA1 scores": what does it physically mean?

We will expand this text as follows: "The PCoA scores differentiate records geographically (Fig. 2a): southern hemisphere monsoon regions such as the southwestern South American Monsoon (SW-SAM) and South African Monsoon (SAfM) are characterised by low PCoA1 scores, whilst northern hemisphere monsoons such as the Indian Summer Monsoon (ISM) and the East Asian Monsoon (EAM), are characterised by higher PCoA1 scores. This indicates that regions can be differentiated based on their temporal evolution as captured by the first PCoA axis."

- l 300: "The regional composites are z-scores, i.e. anomalies with respect to the base period (3000-7000 yr BP)." Are these just anomalies or true z-scores? Please clarify how you calculate those z-scores and what they physically mean. And why using z-scores in the first place? Why not just simple anomalies?

Speleothem $\delta^{18}O$ values are converted to z-scores when constructing regional composites as this method standardises both the mean and the variance (unlike anomalies). We will emphasise this in the text adding the equation for the calculation of z-scores in the methods section to make it clearer, as follows (from line 219):

"The δ^{18}O data for individual speleothems were transformed to z-scores, so all records have a standardised mean and variance:

$$z\text{-}score_i = \left(\delta\,^{18}O_i - \overline{\delta\,^{18}O}_{\,(base\ period)}\right)/s\delta\,^{18}O_{\,(base\ period)}$$

Where $\overline{\delta\,^{18}O}$ is the mean and $s\delta\,^{18}O$ is the standard deviation of δ^{18}O for a common base period. A base period of 7,000 to 3,000 years BP was chosen to maximise the number of records included in each composite."

In the results section 3.3 (from line 300) when describing what the z-scores show, we will reword to more clearly state that z-scores show a standardised mean and variance with respect to the base period. We believe this will address the reviewer's concerns by allowing readers to interpret the regional speleothem composites of fig 4:

"The regional composites are expressed as z-scores, i.e. changes with respect to the mean and variance of δ^{18}O for the base period (3000-7000 yr BP)."

- Fig 4: what are the units of the plotted variables? Please add the units on the y-labels. I have trouble to compare the simulated and observed δ 18O: please use similar diagnostics and units for both. For example, convert precip δ 18O into calcite δ 18O for the model, and use simple δ 18O anomalies for the speleothem observations.

We will add units to the axis labels of fig 4 (W m^{-2} for insolation, ‰ for $\Delta\delta^{18}O_{precip}$, z-scores are unitless).

The goal of this figure is to compare the large-scale (regional) temporal trends in observed $\delta^{18}O_{spel}$ and simulated $\delta^{18}O_{precip}$, rather than to make a direct quantitative comparison. The z-scores used for the speleothem composite trends standardise the variance of the records and are unitless. Anomalies are used for simulated $\delta^{18}O_{precip}$ without a conversion to $\delta^{18}O_{calcite}$ as the latter would require *information on the cave temperature which could only be inferred using simulated air temperature, which in turn would add more uncertainty to the comparison.*

- Fig 6: can you explain better how these diagrams should be interpreted? What do they physically mean?

We define partial residual plots in the methods section (line 263). However, we will modify the text (at line 324) to provide a physical interpretation of these plots:

"The global model for the Holocene (1 to 9ka) $\delta^{18}O_{precip}$ trends has a pseudo-R^2 of 0.80 and shows statistically significant relationships between the anomalies in $\delta^{18}O_{precip}$ and anomalies in regional precipitation, temperature and surface wind direction (Table 3). The partial residual plots (Fig. 6) show there is a strong negative relationship with regional precipitation (t value = -8.75) and a strong positive relationship (t value = 8.03) with surface wind direction over the moisture source region, an index of changes in either source area or moisture pathway. This indicates that increases in regional precipitation alone will lead to a decrease in $\delta^{18}O$ while changes in source area/moisture pathway, in the absence of changes in other variables, will lead to a significant change in $\delta^{18}O$. The relationship with temperature over the moisture source region is weaker, but positive (t value = 2.05), i.e. an increase in temperature over the moisture source region will lead to an increase in $\delta^{18}O$ if there are no changes in other climate variables. Precipitation recycling is not significant in this global analysis."

- Fig 6, section 3.4: on which model was this regression analysis done? GISS or ECHAM? More generally, why doing each diagnostic with only one model? Why not doing each diagnostic with each model (when the period of interest is available), to assess the robustness of the results?

As explained in our answer to major comment 1.2, there are only a few isotope-enabled palaeoclimate simulations, and they use different protocols even when they run simulations for the same time period. Thus, it is difficult to compare the simulations or assess their robustness because there are multiple possible causes for any differences between them. We use ECHAM for glacial-interglacial shifts and GISS for Holocene evolution. This has been clarified in our proposed amendment to the text. We will also amend the methods section describing our statistical analyses of simulated $\delta^{18}O$ and climate variables to clarify which models are being used. Amendments are for line 174:

"We examined glacial-interglacial shifts in $\delta^{18}O_{spel}$ observations and in annual precipitation-weighted mean $\delta^{18}O_{precip}$ from ECHAM-wiso in regions influenced by the monsoon. We focus on regional differences between MH, LGM and LIG with respect to the present-day for speleothems or the control simulation experiment for model outputs."

And line 238:

"We investigate the drivers of regional $\delta^{18}O_{precip}$, and by extension $\delta^{18}O_{spel}$, through the Holocene using multiple linear regression (MLR) of annual precipitation-weighted mean $\delta^{18}O_{precip}$ anomalies and climate variables from GISS modelE-R. Climate variables were chosen to represent the four potential large-scale drivers of regional changes in the speleothem $\delta^{18}O$ records."

- l 380: “drivers” -> “meteorological variables”. This is just a statistical analysis, so no causality can be identified, so the meteorological variables cannot be assumed to be drivers.

Please see comment above related to this. We will change “drivers” to “climate variables”

- l 389: “changes in precipitation amount” -> “changes in local precipitation amount”: changes in upstream precipitation amount has been shown to be very important in previous studies (e.g. Battisti et al. (2014)) but were not analyzed here.

Simulated precipitation changes in this study are regional averages over the monsoon regions, thus they are not equivalent to “local precipitation amount”. To clarify this point, we will revise the occurrences of “precipitation amount” throughout to “regional precipitation”, including at line 389:

“Changes in regional precipitation do not seem to explain the observed changes in $\delta^{18}O_{spel}$ in the EAM during the Holocene.”

- Table 1: too many digits in the numbers.

We will reduce values in table 1 to two decimal places

Refs:

Comas-Bru, L., Harrison, S. P., Werner, M., Rehfeld, K., Scroxton, N. and Veiga-Pires, C.: Evaluating model outputs using integrated global speleothem records of climate change since the last glacial, Clim. Past., 15(4), 1557-1579, https://doi.org/10.5194/cp-15-1557-2019, 2019.

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Maher, B. A.: Holocene variability of the East Asian summer monsoon from Chinese cave records: A re-assessment, Holocene, 18(6), 861–866, https://doi.org/10.1177/0959683608095569, 2008.

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Werner, M., Jouzel, J., Masson-Delmotte, V. and Lohmann, G.: Reconciling glacial Antarctic water stable isotopes with ice sheet topography and the isotopic paleothermometer, Nat. Commun., 9(1), 1–10, https://doi.org/10.1038/s41467-018-05430- y, 2018.