Response to referee #2

Major comments

1) The introduction does not reflect the current understanding of the speleothem δ18O, particularly in the East Asian monsoon domain. For example, it basically follows the previous misunderstanding(s) from modeling and other research communities, especially on orbital-scale, that the speleothem δ18O was interpreted as a rainfall amount proxy by the Chinese speleothem community over the past two decades. In fact, the mainstream idea from the speleothem community has never been the 'amount affect' (e.g., Cheng et al., 2019), and therefore, one of main scientific issues addressed here is groundless.

We understand from the reviewer's concerns that the introduction requires rewording to make clear how Chinese speleothem records have been interpreted as monsoon signals in the literature, i.e. as an upstream precipitation signal (Hu et al., 2008; Yuan et al., 2004) or a rainfall seasonality signal (Cheng et al., 2006, 2009; Wang et al., 2001).Other interpretations of Chinese monsoon $\delta^{18}O_{spel}$ have included rainfall source changes (Tan 2009, 2011, 2014) or local rainfall changes in specific areas (Cai et al., 2010; Tan et al., 2015). Changes to the text to address this are proposed under comment 3.

However, we would like to clarify that our focus here is not simply on the East Asian monsoon domain but rather to investigate all regional monsoons with sufficient speleothem data available in the SISALv2 database. Our discussion in the introduction was to highlight the fact that multiple mechanisms have been proposed in the existing literature to explain $\delta^{18}O_{spel}$ trends in monsoon regions, and we use the East Asian monsoon region as one example of this. We also provide examples from other regions, including the Indonesian-Australian monsoon (line 74 et seq.) and the South American monsoon (line 76 et seq.). To better emphasise this point, we will expand our discussion of other regions in the introduction (under comment 3), rather than mostly discussing the interpretation of East Asian speleothems. It is not uncommon in the literature to propose only one (dominant) mechanism to explain $\delta^{18}O_{spel}$ variability when in reality there could be several mechanisms acting in combination. Furthermore, the proposed mechanisms are often based on modern-day observed relationships, which may not have remained constant in the past. In this study, we utilise model simulations that incorporate known isotope effects/physics, under considerably different conditions to today and we use multiple regression analysis to account for multiple possible isotope drivers in combination. We will clarify this point when describing the aims of this paper in the introduction as follows (after 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.

And after line 98: We use isotope-enabled model simulations to investigate the main drivers of $\delta^{18}O_{spel}$ variability in regions where the models reproduce the large-scale $\delta^{18}O$ changes shown by observations. 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."

2) The authors mentioned that "a composite record can minimize the influence of site specific karst and cave processes" (with real spatial variations?). However, the results and/or assumptions from the PCoA method are tentative, which lacks a underlying mechanism. The same monsoon system (e.g., the ISM and EAM boxes in the figure 1) could have different speleothem δ18O patterns on orbital-scale, as illustrated by a number of modeling results (e.g., Liu et al., 2014; Battisti et al., 2014).

The reviewer has misunderstood the purpose of the PCoA analysis. We use PCoA to investigate the (dis)similarity of Holocene $\delta^{18}O_{spel}$ trends in order to be able to determine whether there is any large-scale coherency between individual monsoon speleothem records and thus whether it is possible to group records based on the similarity of their Holocene trends in a quantitative and objective way. By showing that records show geographic coherency, we are able to construct regional composites which we subsequently use to study mechanisms through multiple regression.

We will clarify the purpose of the PCoA by amending the text from 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."

3) Lines 66-68: This is really a misleading statement. I suggest that the authors should read the original papers they cited here more carefully (as well as Cheng et al., 2016, 2019; Zhang et al., 2018; Zhang et al., 2020) and quote the original statements in these papers if necessary. For example, Cheng et al. (2009) (cited in the sentence) clearly asserted: "Thus, neither the temperature- δ18O relationship, commonly used to interpret ice-core data, nor the interpretation based on the "amount effect" is justified".

Our purpose here, as explained above, was simply to demonstrate that there are alternative interpretations of the records from specific regions rather than to review the literature from any one region exhaustively. However, we will expand this text to reflect what these various papers meant when discussing summer precipitation changes (from line 66):

"In the East Asian monsoon, for example, speleothem $\delta^{18}O$ records have been interpreted as a summer monsoon signal, manifested as either a change in the amount of water vapour removed along the precipitation trajectory (Yuan et al., 2004), and/or as a change in the contribution of summer precipitation to annual totals (Cheng et al., 2006, 2009, 2016; Wang et al., 2001), based on the relationship between modern $\delta^{18}O_{precip}$ and climate. Other interpretations of Chinese monsoon $\delta^{18}O_{spel}$ have included rainfall source changes (Tan 2009, 2011, 2014) or changes in monsoon precipitation amount (Cai et al., 2010; Tan et al., 2015). Maher (2008) interpreted $\delta^{18}O_{spel}$ as reflecting changes in moisture source area, based on differences between $\delta^{18}O_{spel}$ and loess/palaeosol records of rainfall and the strong correlation between East Asian and Indian monsoon speleothems. Maher and Thompson (2012) used a mass balance approach to show that the changes in precipitation (either local or upstream) or rainfall seasonality required to reproduce $\delta^{18}O_{spel}$ trends would be unreasonably large. They therefore argued that changes in moisture source were required to explain shifts in $\delta^{18}O$ both on glacial/interglacial time scales and during interglacials. There are also multiple interpretations of the causes of $\delta^{18}O_{spel}$ variability in other monsoon regions. In the Indonesian-Australian monsoon region, for example, $\delta^{18}O_{spel}$ variability has been interpreted as a precipitation amount signal (Carolin et al., 2016; Krause et al., 2019) or a precipitation seasonality signal (Ayliffe et al., 2013; Griffiths et al., 2009), based on modern $\delta^{18}O_{precip}$ and climate observations (Cobb et al., 2007; Moerman et al., 2013), and/or as a moisture source/trajectory signal (Griffiths et al., 2009; Wurtzel et al., 2018). South American speleothem records have been interpreted as records of monsoon intensity, due to changes in the amount of precipitation over the region (Cruz et al., 2006; Wang et al., 2006; Cheng et al., 2013), changes in the degree of upstream precipitation and evapotranspiration (Cheng et al., 2013) or changes in the ratio of precipitation sourced from the low-level jet versus the Atlantic (Cruz et al., 2005; Wang et al., 2006). In the Indian monsoon region, speleothem $\delta^{18}O$ records are interpreted primarily as an amount effect signal (Berkelhammer et al., 2010; Fleitmann et al., 2004), supported by $\delta^{18}O_{precip}$/climate observations (e.g. Battacharya et al., 2003). However, other studies have suggested that $\delta^{18}O_{precip}$ changes in this region are driven primarily by large-scale changes in monsoon circulation and hence, Indian monsoon $\delta^{18}O_{spel}$ should be interpreted as a moisture source/trajectory signal (Breitenbach et al., 2010; Sinha et al., 2015). "

4) Lines 229-236 and figure 4: What are the simulated precipitation δ18O values in the EAM, ISM, IAM, SW-SAM domains? Are they amount-weighted annual mean precipitation δ18O values, annual mean precipitation δ18O values or only summer (MJJAS) mean precipitation δ18O values? In addition, please give the boundary coordinate of these monsoon regions (the EAM, ISM, IAM, SW-SAM. . .) for the calculations. Give a detail explanation about the δ18O amplitude differences between observation and model results in the figure 4 if significant.

All simulated $\delta^{18}O_{precip}$ values are annual precipitation-weighted $\delta^{18}O$ anomalies with respect to a control simulation. We will amend the text as follows:

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."

Line 229: "We calculated Holocene regional composites from annual precipitation-weighted mean $\delta^{18}O_{precip}$ anomalies simulated by the GISS model."

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.

We will add the latitude/longitude limits of the regional monsoons to the caption of figure 1:

Figure 1: Spatial distribution of speleothem records used is this study. Colours indicate the sites used in Principal Coordinates Analysis and Redundancy Analysis (PCoA, RDA) to separate monsoon regions, and sites not used in PCoA and RDA but used in subsequent analyses. The individual regional monsoons are shown by boxes: CAM = Central American Monsoon (latitude: 10 to 33°; longitude: -115 to -58°) , SW-SAM = southwestern South American Monsoon (latitude: -10° to 0°; longitude: -80° to -64° and latitude: -30° to -10°; longitude -68° to -40°), NE-SAM = northeastern South American Monsoon (latitude: -10° to 0°; longitude: -60° to -30°), SAfM = southern African Monsoon (latitude: -30° to -17°; longitude: 10° to 40°), ISM = Indian Summer Monsoon (latitude: 11° to 32°; longitude: 50° to 95°), EAM = East Asian Monsoon (latitude: 20° to 39°; longitude: 100° to 125°), IAM = Indonesian-Australian Monsoon (latitude: -24° to 5°; longitude: 95° to 135°). Source region limits

used in the multiple linear regression analysis are also shown. The background carbonate lithology is from the World Karst Aquifer Mapping (WOKAM) project (Goldschneider et al., 2020).

5) Lines 376-379: ". . .there is little different in the δ18O values between the MH and the LIG in the ISM and EAM regions. . .", "Given that the increase in summer insolation is much larger during the LIG than the MH, this finding is again consistent with the idea that other factors play a role in modulating the monsoon response to insolation forcing". What are the other factors and the processes? Moisture source and/or pathway? Or some kind of thresholds (e.g., Cheng et al., 2012; Cai et al., 2015)? In addition, the summer insolation is indeed higher during the LIG than during the MH, but the monsoon circulation or intensity is influenced by the temperature (thus pressure?) gradient between land and sea as well. What is the difference of the land-sea temperature (pressure) gradients for the MH and the LIG periods? Or monsoon circulation scales? A more comprehensive discussion of the issue with a help of climate models would be very welcome.

An in-depth discussion of the influences on the East Asian and Indian monsoons is beyond the scope of this paper, since it requires consideration of the monsoons as an integral part of the global atmospheric overturning circulation (see e.g. Schneider et al., 2014; Biasutti et al., 2018; Seth et al., 2019) and associated energy, angular momentum, and moisture budgets. Given that the monsoons cannot simply be considered as regional land-sea breeze circulations, analysis of the land-sea temperature/pressure gradients in the MH and LIG would be insufficient. Our point here was to support the idea, expressed in this paragraph, that there is no simple correspondence between insolation forcing and monsoon response. We have argued that land and ocean feedbacks might have played a role in modulating the response to insolation changes during the Holocene - and the pattern of change through the LIG would also support this. We will clarify our argument about the role of insolation on monsoon changes as follows (line 377):

"The evolution of regional monsoons during the LIG shows patterns similar to those observed during the Holocene, including the lagged response to insolation and the persistence of wet conditions after peak insolation. This is again consistent with the idea that internal feedbacks play a role in modulating the monsoon response to insolation forcing. We have also shown that there is little difference in the isotopic values between the MH and the LIG in the ISM and EAM regions, which is also observed in individual speleothem records (Kathayat et al., 2016; Wang et al., 2008). Given that the increase in summer insolation is much larger during the LIG than the MH, this finding indicates that other factors play a role in modulating the monsoon response to insolation forcing and may reflect the importance of global constraints on the externally-forced expansion of the tropical circulation (Biasutti et al., 2018)."

6) The main conclusion is that "East Asian monsoon speleothem δ18O evolution through the Holocene relates to changes in atmospheric circulation (i.e. changes in moisture pathway and/or source). Changes in precipitation amount are the predominant driver of Holocene δ18Ospel evolution in the Indian, southwestern South American and Indonesian-Australian monsoons, although changes in atmospheric circulation also contribute in the Indian and Indonesian-Australian monsoon regions and changes in precipitation recycling in southwestern South America". This conclusion is not well supported and problematic as well. First, the 'amount effect' discussed here is not the same 'amount effect' as

conventionally defined in the tropics (see Zhao et al., 2019 for instance). The authors implies that the local rainfall amount drive the orbital-scale variations in speleothem δ18O value. They really need to provide a mechanism/calculation for the Indian, southwestern South American and Indonesian-Australian monsoon systems to explain how the oxygen isotopic fractionation under different conditions of rainfall amounts at each cave site could result in the observed δ18Ospel changes on orbital-scale without significant monsoon circulation (including the moisture pathway and/or source) changes. On the other hand, the "East Asian monsoon speleothem δ18O evolution through the Holocene relates to changes in atmospheric circulation" is just a reinforcement of the previous view on the East Asian monsoon evolution inferred by speleothem δ18O records published in a large number of speleothem works over the past two decades. In short, it is the monsoon circulation that to first order drives the orbital δ18Ospel changes, not only for the East Asian monsoon, but also (most likely) for other monsoon systems.

The reviewer is correct that we are talking about regionally averaged precipitation changes rather than changes in what is conventionally understood as the precipitation amount effect and we will change this wording to "changes in regional precipitation". However, the reviewer has misunderstood the purpose of our analyses. We acknowledge that there may be concurrent changes in multiple factors. However, the aim of multivariate analysis is to separate out the various $\delta^{18}O_{precip}$-climate relationships and investigate which variables (it may be a combination of several) are most important in a given region. For example, if circulation and regional precipitation were changing in a way that both together can explain $\delta^{18}O_{precip}$ trends, the MLR model would show this. On the other hand, if there was a significant change in atmospheric circulation (and hence source area) without a corresponding change in regional precipitation, there would be conformity with the global circulation relationship, but not with precipitation, as is seen for the EAM. This would be possible if circulation changes drove a precipitation change outside of the region where the speleothem sites are located, as has been proposed by several papers focusing on the EAM (e.g. Hu et al., 2008; Liu et al., 2014). In all cases, these varying atmospheric and/or precipitation changes are underpinned by the physics incorporated in the climate model simulations. One point that the reviewer appears to have missed is that our aim is not to disprove or reinforce conclusions based on previous EAM speleothem studies. Rather we are using multivariate analysis to provide an alternative way of examining the potential causes of observed changes, independently from the assumption that underpins most interpretations in the literature that modern relationships provide a robust guide to what has happened in the past. By analysing the individual effects of different variables using isotope-enabled models that reproduce the large-scale monsoon trends shown by the observations, we are able to determine what factors are important in a robust way.

We will make the following amendments to the text in order to make the purpose of our analyses clearer:

In the introduction, we will reword to make clearer the goal of this study (under comment 1).

In the results, we will more clearly state what the multiple linear regression shows (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."

When discussing the multiple linear regression (line 389):

Changes in regional precipitation (where the cave sites are located) do not seem to explain the observed changes in $\delta^{18}O_{spel}$ in the EAM during the Holocene, where Holocene $\delta^{18}O_{precip}$ evolution is largely driven by changes in atmospheric circulation (indexed by changes in surface winds). This is consistent with existing studies that emphasise changes in moisture source and/or pathway rather than local precipitation changes (Maher, 2016; Maher and Thompson, 2012; Tan, 2014; Yang et al., 2014).

7) Please illustrate the x- and y-axes of the figure 2a in the section 3.1 or describe them in the section 2.3. In the section 3.1, the authors illustrated that Southern Hemisphere monsoon regions are characterized by low PCoA1 scores, while Northern Hemisphere monsoon regions are characterized by higher PCoA1 scores. Please explain these terms in the context of instrumental data or modern climatology, which may be more interesting for the paleoclimate community.

The aim of the PCoA is to investigate the (dis)similarity of Holocene $\delta^{18}O_{spel}$ trends amongst speleothem sites. We then use RDA to investigate whether the distribution of site (dis)similarity relates to geographic location (latitude and longitude). This allows us to investigate whether there is a regional and global-scale coherency to Holocene $\delta^{18}O_{spel}$ records, and thus to regionalise the records based on the observations themselves rather than any assumption of regional synchroneity in the speleothem records. We make no assumption that these trends are related to modern climatology, or that regions should be defined on the basis of their modern climatology. We have modified our description of the purpose of the PCoA analyses (in response to comments from reviewer 1) and this will hopefully make the purpose of these analyses clearer.

8) The authors used the anomaly for comparison from different model results. However, readers might also want to see a detailed comparison between model results, particularly between the model results from this study and those from previous studies.

There are relatively few isotope-enabled palaeoclimate simulations, and they are generally run under different protocols/boundary conditions, thus precluding a rigorous comparison between them since it is difficult to attribute differences to model structure or experimental protocol. Furthermore, an analysis of model-based results per se is not the goal of this paper. In response to comments by reviewer 1, we have included anomaly maps of simulated $\delta^{18}O_{precip}$ from the simulations we are using for our analyses in the supplementary material.

9) Lines 397-400 and the figure 3: "The LGM is characterised by a similar orbital configuration to today, however global ice volume was at a maximum and GHG concentrations were lower than present. The δ18Ospel anomalies are more positive during the LGM than the MH or LIG, suggesting drier conditions in the ISM, EAM and IAM, supported by simulated changes in δ18Ospel and precipitation (Fig. 3)." This sentence is again misleading. While the authors highlighted a similar orbital configuration between the LGM and today, they actually discussed the issue related to a comparison of the LGM with the MH or LIG, presumably implying that they have similar orbital configurations. The LGM (21±1ka) is near a Northern Hemisphere insolation minimum whereas the MH/LIG are near the insolation maxima. As such the related discussions should be rephrased, and so does the related conclusion, since the insolation difference should be taken into account together with GHG and the global ice

volume, because one could also argue that the δ18Ospel just follows the insolation with effect to a lesser extent from GHG and the global ice volume.

We agree that it is not ideal to describe the LGM boundary conditions with respect to the modern day when the purpose of this paragraph is to contrast the LGM signals with those of the MH and LGM, so we will rephrase this to read (line 397):

The LGM is characterised by lower northern hemisphere summer insolation, globally cooler temperatures, expanded global ice volumes and lower GHG concentrations than either the MH or the LIG.

And rephrase the conclusion (line 405) as:

Enriched $\delta^{18}O_{precip}$ and $\delta^{18}O_{spel}$ values during the LGM must therefore be caused by a significant decrease in atmospheric moisture and precipitation that resulted from the cooler conditions.

Minor comments

Lines 97, 112 and 160, 'the Principal Coordinate Analysis (PCoA)', the abbreviation occurred three times, keep the first one.

We will amend the text so that PCoA is only defined at its first mention (at line 97).

Line 121, please give the full name of the climate models: ECHAM5 and GISS E-R

We will modify the text to define these acronyms as follows:

"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)."

Line 163, '. . .missing data that . . .' , 'that' should be 'than'?

Yes, we will correct the text here.

Line 189, what is the 'OIPC'?

OIPC 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."

Lines 268-277, the abbreviations (EAM, SW-SAM, SAfM, CAM, IAM) occurred too late in the section 3.1, it's better put them in the introduction.

The regional monsoons, and their abbreviations are not introduced until section 3.1, as the results from PCoA justify our grouping of the data in regional monsoons. We therefore introduce them here. However, abbreviations are also available in the caption of Figure 1, which is first cited in line 116.

Line 358 'southern China Sea' should be 'South China Sea'.

We will amend the text accordingly

Figure 5, the time series for Dongge Cave can be replaced by a high-resolution timeseries, please double check with the database.

We use speleothem records from the SISALv2 database because these have been standardised, quality-controlled, and the age models have been verified. The higher resolution records of the LIG from Dongge cave (Kelly et al., 2006) are not in the SISAL database.

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