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LETTER • OPEN ACCESS

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## Environmental Research Communications



## LETTER

## Speleothem records of monsoon interannual-interdecadal variability through the Holocene

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Modern observations show considerable interannual to interdecadal variability in monsoon precipitation. However, there are few reconstructions of variability at this timescale through the Holocene, and there is therefore less understanding of how changes in external forcing might have affected monsoon variability in the past. Here, we reconstruct the evolution of the amplitude of interannual to interdecadal variability (IADV) in the East Asian, Indian and South American monsoon regions through the Holocene using a global network of high-resolution speleothem oxygen isotope ( $\delta^{18}\text{O}$ ) records. We reconstruct changes in IADV for individual speleothem records using the standard deviation of  $\delta^{18}\text{O}$  values in sliding time windows after correcting for the influence of confounding factors such as variable sampling resolution, growth rates and mean climate. We then create composites of IADV changes for each monsoon region. We show that there is an overall increase in  $\delta^{18}\text{O}$  IADV in the Indian monsoon region through the Holocene, with an abrupt change to present-day variability at  $\sim 2$  ka. In the East Asian monsoon, there is an overall decrease in  $\delta^{18}\text{O}$  IADV through the Holocene, with an abrupt shift also seen at  $\sim 2$  ka. The South American monsoon is characterised by large multi-centennial shifts in  $\delta^{18}\text{O}$  IADV through the early and mid-Holocene, although there is no overall change in variability across the Holocene. Our regional IADV reconstructions are broadly reproduced by transient climate-model simulations of the last 6 000 years. These analyses indicate that there is no straightforward link between IADV and changes in mean precipitation, or between IADV and orbital forcing, at a regional scale.

**1. Introduction**

More than two thirds of the global population live in regions which are dependent on monsoon rainfall; interannual variability in precipitation has a significant impact on the livelihoods of these people (Wang *et al* 2021). The variability of precipitation in the tropics on interannual to interdecadal timescales (interannual to interdecadal variability: IADV) is influenced by sea surface temperature (SST) changes: the El Niño Southern Oscillation (ENSO) has a major influence on monsoon precipitation IADV (McPhaden *et al* 2006, Messié and Chavez 2011, Wang *et al* 2012). SST variability in the extratropical Pacific (Pacific Decadal Oscillation, PDO, Krishnan and Sugi 2003, Yoon and Yeh 2010), Indian Ocean (Indian Ocean Dipole, IOD, Ashok *et al* 2001, Saji and Yamagata 2003, Ummenhofer *et al* 2011;) and Atlantic Ocean (Atlantic Multidecadal Oscillation, AMO, Grimm and Zilli 2009) also influence the IADV of monsoon precipitation. These modes interact with one another to drive complex and considerable interannual fluctuations in precipitation. They are often associated with extreme events over monsoon regions (Kane 1999, Kirono *et al*, 1999) with major impacts on water resources, crop production (Phillips *et al* 2012, Iizumi *et al* 2014, Ray *et al* 2015) and long-term impacts on health (Bouma and Kaay, 1996, Gagnon *et al* 2001, Hashizume *et al* 2012).

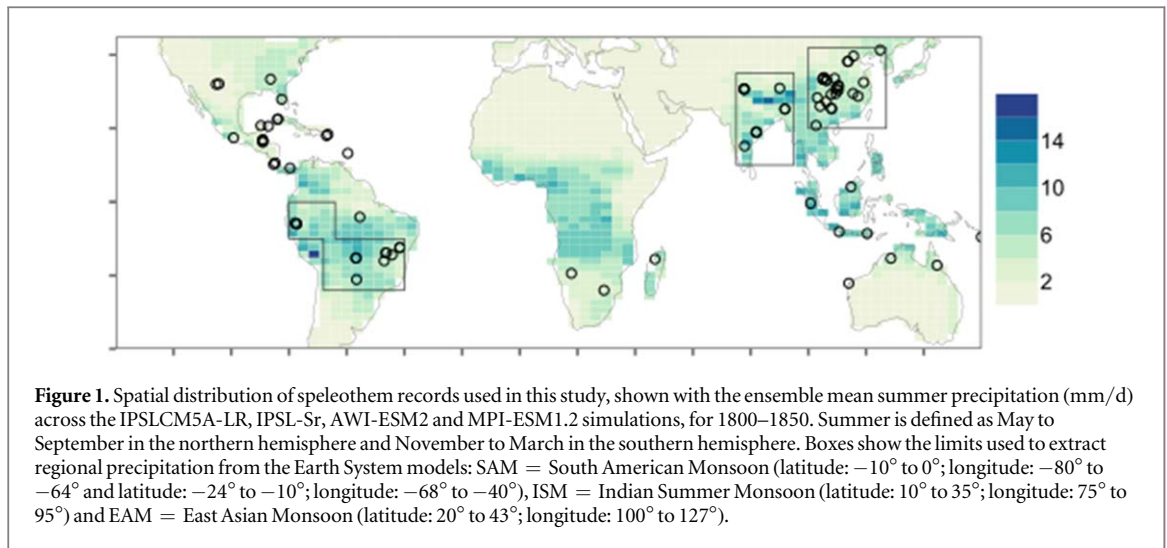
Although there has been considerable focus on changes in monsoon IADV in the recent period (Wang *et al* 2012, Yim *et al* 2014), observational records are too short to sample IADV sufficiently and it is therefore difficult to examine how this variability responds to external forcing. Future changes in monsoon precipitation IADV in response to increasing CO<sub>2</sub> concentrations are difficult to predict because of the large uncertainties related to internal variability (Wang *et al* 2021). Climate models disagree, for example, on the how the variability of both ENSO (Stevenson 2012, Chen *et al* 2017, Brown *et al* 2020) and the IOD (Hui and Zheng 2018, Zheng *et al* 2013, Ng *et al* 2018) will change in the future. The palaeorecord provides an alternative way of examining how changes in external forcing have influenced IADV in monsoon regions. Specifically, the Holocene (11.7 thousand years ago, ka, to present) provides an opportunity to examine how monsoon IADV responds to changes in the seasonal and latitudinal distribution of insolation resulting from changes in the Earth's orbit. In the early Holocene, northern hemisphere summer insolation was greater than today whilst southern hemisphere summer insolation was reduced compared to present. Through the Holocene, summer insolation gradually declined (increased) to present-day levels in the northern (southern) hemisphere. These insolation changes altered the mean climate (Wang *et al* 2014, Zhang *et al* 2021) and likely had a marked impact on IADV.

There are only a few reconstructions of Holocene changes in precipitation IADV from tropical continents. Lake records of hydrological variability from the circum-Pacific region show changing precipitation variability through the Holocene, interpreted as ENSO variability. Records show lower precipitation variability in the mid-Holocene than today, with higher variability during the late Holocene (Riedinger *et al* 2002, Conroy *et al* 2008, Zhang *et al* 2014, Thompson *et al* 2017). The time when IADV increases from the MH minimum varies between records. For example, in the Galapagos Islands, Bainbridge Crater Lake shows increasing ENSO variance from 2 ka onwards (Riedinger *et al* 2002) and El Junco Lake shows an increase at ~4 ka (Conroy *et al* 2008, Zhang *et al* 2014). The red-light reflectivity record (Moy *et al* 2002) from lake Pallcacocha, Ecuador, indicates the increase in variability begins at ~7 ka, whilst a grey-scale record from the same site (Rodbell 1999) shows this change beginning at ~5 ka. Reconstructions of early Holocene IADV also vary: an algal lipid concentration and hydrogen isotope record from El Junco Lake shows fluctuations between high and low variability (Zhang *et al* 2014), whilst sediment records from El Junco and Pallcacocha lakes show low variability through the early Holocene (Rodbell 1999, Moy *et al* 2002, Conroy *et al* 2008).

The differences between existing reconstructions highlights the limitations of lake sediment records. For example, the interpretation of the Pallcacocha records has been questioned because the highly non-linear response of sediment accumulation to precipitation could bias the reconstructions (Emile-Geay and Tingley 2016). The lack of a clear wet-dry pattern to ENSO events in the area (Schneider *et al* 2018, Kiefer and Karamperidou 2019) and the influence of catchment differences on lake sediment records (Schneider *et al* 2018) also reduces the reliability of these records as indicators of IADV and ENSO. Furthermore, the spatial complexity of IADV necessitates regional-scale reconstructions to understand differences in IADV changes.

The Gallapagos and Pallcacocha records were a focus for reconstructions of IADV because, compared to most other terrestrial records, they have quasi-annual resolution. Speleothems provide an alternative source of high-resolution data in monsoon regions and can therefore be used to investigate precipitation IADV over land. Speleothems record changes in the strength of the monsoon, via a combination of changes in regional precipitation and circulation changes that cause changes in moisture source and transport pathway (Sinha *et al* 2015, Cheng *et al* 2019, Parker *et al* 2021). However, there are several factors that influence the oxygen isotopic composition of speleothems and might complicate the interpretation of short-term climate variability, including changing growth rates and the mixing of meteoric water in the epikarst (Lachniet 2009) although compositing of speleothem records can be used to minimise the impact of such local factors when deriving regional climate signals (Comas-Bru *et al* 2019, Parker *et al* 2021).

In this paper, we use speleothem oxygen isotope ( $\delta^{18}\text{O}$ ) records from the second version of the Speleothem Isotopes Synthesis and Analysis (SISAL) database (Atsawawanunt *et al* 2018, Comas-Bru *et al* 2020a, 2020b) to reconstruct changes in IADV in monsoon regions through the Holocene. We first investigate the potential influence of confounding factors on  $\delta^{18}\text{O}$  variability using multiple regression. We then reconstruct changes in the amplitude of IADV through the Holocene using the standard deviation (s.d.) of  $\delta^{18}\text{O}$  values. We construct regional-scale composite changes in IADV through time for individual monsoon regions and compare these to trends in IADV shown by four transient climate model simulations. Previous data-model comparisons of Holocene IADV have focused on ENSO variability (e.g. Carré *et al* 2021) but have not examined the wider implications for monsoon precipitation IADV. Although we do not associate the changes in IADV with specific climate modes, we compare regional monsoon IADV changes to changes in summer insolation and long-term trends in monsoon precipitation to investigate the relationship with external climate forcing.



## 2. Methods

### 2.1. Speleothem oxygen isotope data

We use speleothem  $\delta^{18}\text{O}$  data from the SISAL database (Atsawawaranunt *et al* 2018, Comas-Bru *et al* 2020a, 2020b), selected using the following criteria:

- The record is located in a monsoon region, between  $40^{\circ}\text{N}$  and  $35^{\circ}\text{S}$ ;
- The mineralogy is known and does not vary because oxygen isotope fractionation depends on speleothem mineralogy, introducing a non-climatic influence on  $\delta^{18}\text{O}$  s.d.;
- The record covers at least 3 000 years of the Holocene;
- The record has a mean sampling resolution of at least 20 years;

This resulted in the selection of 144 records from 79 sites (figure 1). We interpret speleothem  $\delta^{18}\text{O}$  records ( $\delta^{18}\text{O}_{\text{spel}}$ ) as changes in the strength of the summer monsoon, via regional precipitation and moisture source pathway and source changes (including oceanic versus land-derived moisture), which likely reinforce one another to give more negative  $\delta^{18}\text{O}$  when the summer monsoon is stronger (Vuille *et al* 2003, Yang *et al* 2016, Cai *et al* 2017, Kathayat *et al* 2021).

### 2.2. Investigating the impact of potential confounding factors

The use of  $\delta^{18}\text{O}_{\text{spel}}$  variability as an indicator of IADV in regional precipitation relies on showing that other factors have a minimal impact on this variability. Smoothing of the  $\delta^{18}\text{O}$  signals occurs when groundwater of different ages mixes in the epikarst above the cave (Lachniet 2009). Differences in precipitation amount through time could influence the time taken for water to reach the cave, with epikarst transmission times being faster in wetter climates. Apparent  $\delta^{18}\text{O}_{\text{spel}}$  variability could also be affected by changes in sampling frequency across the record and changes in speleothem growth rate. We used multiple linear regression (MLR) to investigate if confounding factors such as mean climate, speleothem growth rate or sampling frequency show a significant relationship with  $\delta^{18}\text{O}_{\text{spel}}$  variability. The s.d. of  $\delta^{18}\text{O}_{\text{spel}}$  values, calculated for a sliding 100-year window (with 50% overlap) across individual records, was used to represent  $\delta^{18}\text{O}$  interannual to interdecadal variability ( $\text{IADV}_{\text{spel}}$ ). We used mean growth rate, number of samples (n-samples) and mean  $\delta^{18}\text{O}_{\text{spel}}$  (as an index of mean climate) for each window as predictors. Mean growth rate was calculated as the gradient of the relationship between distance along a speleothem and age. Initial analyses showed that growth rate and n-samples are correlated ( $R^2 = 0.33$ ), whereas mean  $\delta^{18}\text{O}$  is not strongly correlated with either growth rate ( $R^2 = -0.04$ ) or n-samples ( $R^2 = 0.07$ ). We therefore constructed two separate MLR models, one using growth rate and mean  $\delta^{18}\text{O}$  and the other using n-samples and mean  $\delta^{18}\text{O}$  as predictors. Northern and southern hemisphere (NH, SH) records were analysed separately since the trajectory of the mean climate differs between the NH and SH as a result of differences in insolation forcing. The use of multiple geographically separated records in the MLR model captures the influence of confounding factors on composite regional IADV reconstructions. We examined whether variables were normally distributed using the Shapiro-Wilk test and log transformed non-normal variables. Examination of the residuals from the fitted values showed no pattern and confirms that an

MLR is appropriate. We used P-values to assess the significance of each predictor and  $R^2$  to determine the influence on  $\delta^{18}\text{O}_{\text{speI}}$  variability. Partial residual plots were used to show the relationship between each predictor variable and  $\text{IADV}_{\text{speI}}$  when other variables were held constant.

### 2.3. Regional-scale IADV amplitude evolution

We reconstructed IADV amplitude through the Holocene for individual monsoon regions by calculating  $\text{IADV}_{\text{speI}}$  for a 100-year sliding window with 50% overlap (as described in section 2.2). We corrected for the influence of confounding factors by subtracting the MLR slope and intercept values from the  $\text{IADV}_{\text{speI}}$  values. Regional composites were constructed by fitting a running median and interquartile range through the  $\text{IADV}_{\text{speI}}$  values. These composites represent the evolution of the overall amplitude of IADV represented by numerous sites in each region.

We analysed  $\text{IADV}_{\text{speI}}$  changes through the Holocene using breakpoint analysis to distinguish intervals with coherent behaviour (Bai and Perron 2003). Breakpoint analysis was carried out using the *strucchange* package in R (Zeileis *et al* 2002, Zeileis *et al* 2003). We identified breakpoints in mean and slope to identify periods with significantly higher or lower IADV (changes in mean) and whether IADV was stable or showed a trend (changes in slope) during these intervals. We determined whether the  $\text{IADV}_{\text{speI}}$  of each segment was significantly different using t-tests.

### 2.4. Relationship between IADV and monsoon long-term evolution

The relationship between IADV and mean climate was investigated by comparing the long-term changes in  $\delta^{18}\text{O}_{\text{speI}}$  with the  $\text{IADV}_{\text{speI}}$  for each region through the Holocene. Long-term changes were calculated by converting  $\delta^{18}\text{O}_{\text{speI}}$  to z-scores, with mean and variance standardised relative to a base period of 3 to 5 ka, then calculating the mean  $\delta^{18}\text{O}_{\text{speI}}$  z-score for each 100-year bin (across each site) to standardise sampling resolution. Mean z-scores were calculated for 100-year windows for each region and a 500-year half-window locally weighted regression (Cleveland and Devlin 1988) was constructed to emphasise multi-millennial scale variability.

### 2.5. Simulated monsoon IADV evolution

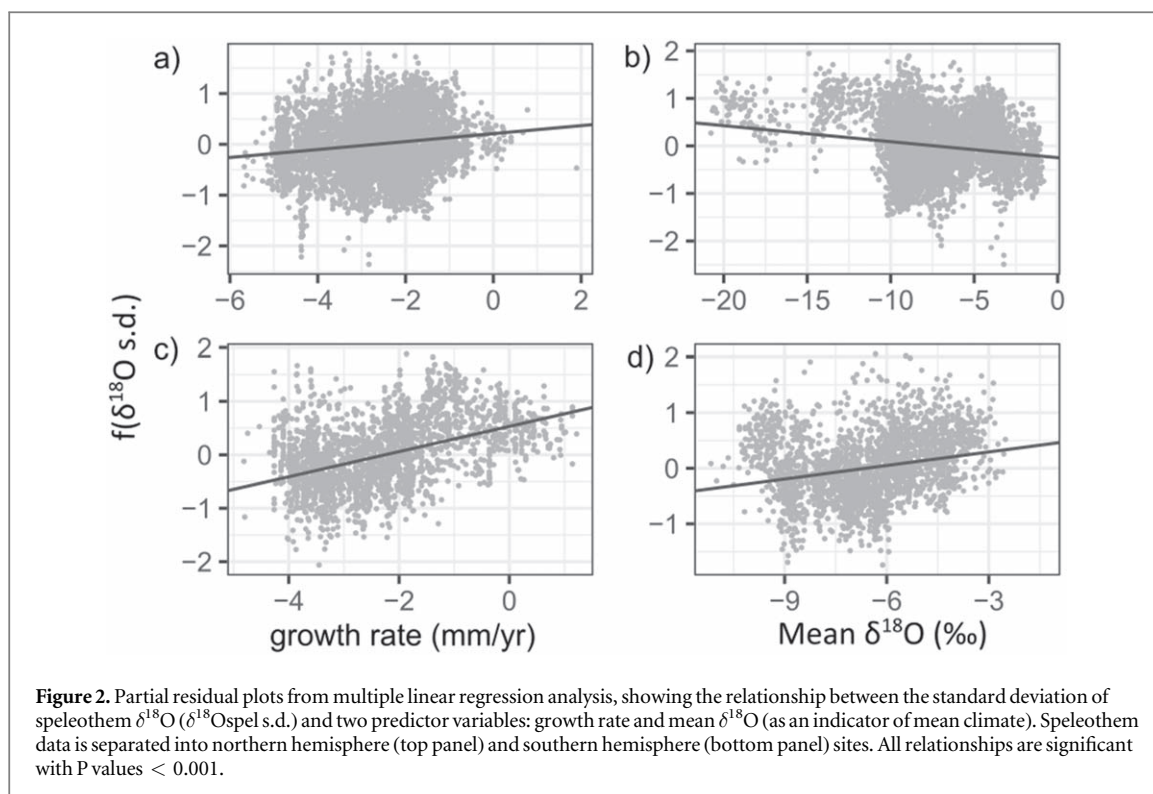
We use transient simulations from four climate models: version 2 of the AWI (Alfred Wegener Institute) Earth System model (Sidorenko *et al* 2019), version 1.2 of the MPI (Max Planck Institute) Earth System model (Dallmeyer *et al* 2020) and two versions of the IPSL (Institut Pierre Simon Laplace) Earth system model. The first IPSL simulation uses the IPSLCM5A-LR version, with prescribed vegetation, whilst the second simulation (here termed IPSL-Sr) uses a modified version of IPSLCM5A with a dynamical vegetation module (Dufresne *et al* 2013, Braconnot *et al* 2019b). Simulated IADV from IPSLCM5A-LR and IPSL-Sr have been discussed in Braconnot *et al* (2019a) and Crétat *et al* (2020). The IPSL and AWI simulations were run from 6 ka to 1950 CE; the MPI simulation from 7.95 ka to 1850 CE. All simulations were spun up using boundary conditions appropriate for the start year. Appropriate orbital parameters (Berger 1978) and greenhouse gases were prescribed annually through the transient runs (See Supplementary Information). The use of an ensemble of four different model simulations provides a way of identifying signals that are consistent across the models (Carré *et al* 2021). Model performance has been evaluated for these simulations previously, considering climate mean state and variability (Dufresne *et al* 2013, Duvel *et al* 2013, Hourdin *et al* 2013, Mauritsen *et al* 2019, Sidorenko *et al* 2019, Braconnot *et al* 2019b). Despite common model biases (e.g. Tian and Dong, 2020, Good *et al*, 2021), these comparisons indicate that they capture the tropical climate variability.

We calculated area-averaged summer precipitation over the regional monsoons for each simulation using the region limits in figure 1, where summer was defined as May to September for the NH and November to March for the SH (Wang and Ding 2008). We calculated the s.d. of area-averaged precipitation for 100-year sliding windows with 50% overlap to determine the changes in IADV (termed  $\text{IADV}_{\text{precip}}$ ). We analysed the overall evolution of  $\text{IADV}_{\text{precip}}$  from the mid-Holocene onwards using linear regression. We compared changes in  $\text{IADV}_{\text{precip}}$  to  $\text{IADV}_{\text{speI}}$  by imposing the breakpoints detected from the speleothem records for each region and comparing whether coeval changes in slope and mean were similar. We calculated the relationship between  $\text{IADV}_{\text{precip}}$  and long-term changes by correlating IADV against mean summer regional precipitation for 100-year windows.

## 3. Results

### 3.1. Influence of confounding factors on $\delta^{18}\text{O}_{\text{speI}}$ variability

The MLR model using growth rate and mean  $\delta^{18}\text{O}$  and the alternative model, using n-samples and mean  $\delta^{18}\text{O}$ , produced similar results. The models show a significant ( $P < 0.001$ ) relationship between  $\text{IADV}_{\text{speI}}$  and both



**Table 1.** Results of the multiple linear regression analysis, separated into northern hemisphere (NH) and southern hemisphere (SH) sites. Significant relationships ( $P < 0.01$ ) are shown in bold.

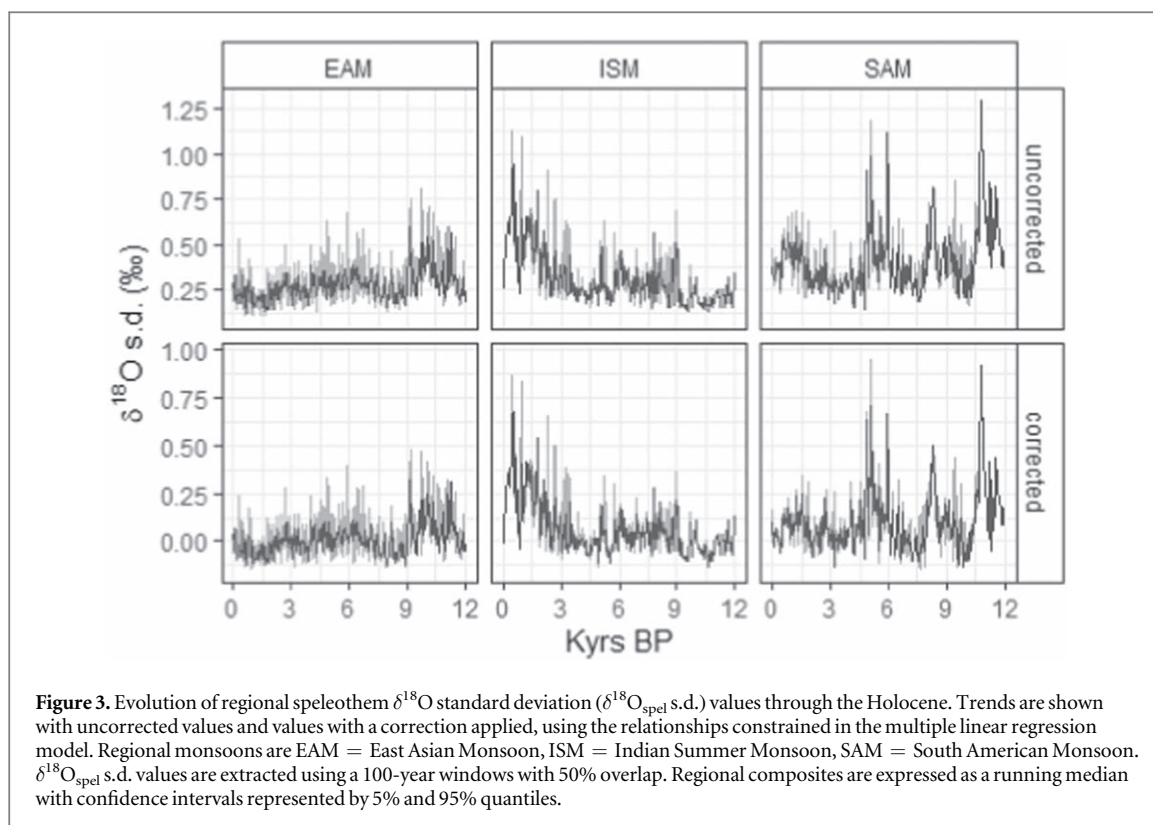
	NH	SH
Growth rate	<b>0.08</b>	<b>0.23</b>
Mean $\delta^{18}\text{O}$	<b>-0.03</b>	<b>0.08</b>

growth rate (or n-samples) and mean  $\delta^{18}\text{O}_{\text{spel}}$  (table 1, table S1 available online at [stacks.iop.org/ERC/3/121002/mmedia](https://stacks.iop.org/ERC/3/121002/mmedia)). Growth rate has a significant positive relationship with  $\text{IADV}_{\text{spel}}$  (figures 2, S1). There is a significant negative relationship in the NH and a significant positive relationship in the SH between  $\text{IADV}_{\text{spel}}$  and mean  $\delta^{18}\text{O}_{\text{spel}}$  (figure 2). The models have low  $R^2$  (NH: 0.06; SH: 0.27) suggesting that confounding factors only have a limited influence on  $\text{IADV}_{\text{spel}}$ .

### 3.2. Regional $\delta^{18}\text{O}_{\text{spel}}$ variability evolution

Three regions have sufficient data to reconstruct composites of  $\text{IADV}_{\text{spel}}$ : the Indian Monsoon (ISM), East Asian Monsoon (EAM) and South American Monsoon (SAM) (figure 1). The Central American and Indonesian-Australian monsoon regions are excluded because they contain too few records of a sufficient length. The regional evolution of corrected and uncorrected  $\text{IADV}_{\text{spel}}$  is very similar (figure 3), confirming that changes in growth rate (or n-samples) and mean  $\delta^{18}\text{O}_{\text{spel}}$  are not the main cause of the reconstructed changes in  $\delta^{18}\text{O}_{\text{spel}}$  variability during the Holocene. Any uncertainty arising from combining records of different lengths is small, based on bootstrap resampling (figure S2). Regional composites show a significant amount of centennial-scale variability, nevertheless broad trends can be seen, with differing  $\text{IADV}_{\text{spel}}$  evolution between the three regions.

The EAM  $\text{IADV}_{\text{spel}}$  record is decomposed into four segments (figure 4(a), table S2): The early Holocene interval (12 to 8.9 ka) has significantly higher  $\text{IADV}_{\text{spel}}$  than any subsequent period. The following interval between 8.9 and 7.1 ka has significantly lower  $\text{IADV}_{\text{spel}}$  than the early Holocene interval. The mid-Holocene interval (7.1 to 2 ka) shows a significant increase in  $\text{IADV}_{\text{spel}}$ . The last 2 000 years has significantly lower  $\text{IADV}_{\text{spel}}$  than any preceding interval. The ISM  $\text{IADV}_{\text{spel}}$  record is decomposed into three segments (figure 4(b), table S2): the early Holocene (12 to 9 ka) has significantly lower  $\text{IADV}_{\text{spel}}$  values than the other two periods. The mid-Holocene period (9 to 1.7 ka) has significantly lower  $\text{IADV}_{\text{spel}}$  than the period after 1.7 ka. Breakpoint analysis of



the slopes (figure S3, table S3) show stable  $\text{IADV}_{\text{speleth}}$  values, except between 2.05 and 0 ka when they show a significant increase over time. The SAM  $\text{IADV}_{\text{speleth}}$  record is decomposed into four segments (figure 4(c), table 3). The highest values of  $\text{IADV}_{\text{speleth}}$  occur in the mid-Holocene (6 to 4.2 ka) and the early Holocene (12 to 10.15 ka). The interval between these two peaks is characterised by  $\text{IADV}_{\text{speleth}}$  values that are statistically indistinguishable from the past 4 000 years. Although the recent interval shows stable variability (figure S3, table S3), the earlier part of the SAM record shows increases in variability with rapid transitions to lower variability at 10.15, 7.9 and 4.75 ka.

### 3.3. Comparison with simulated monsoon variability

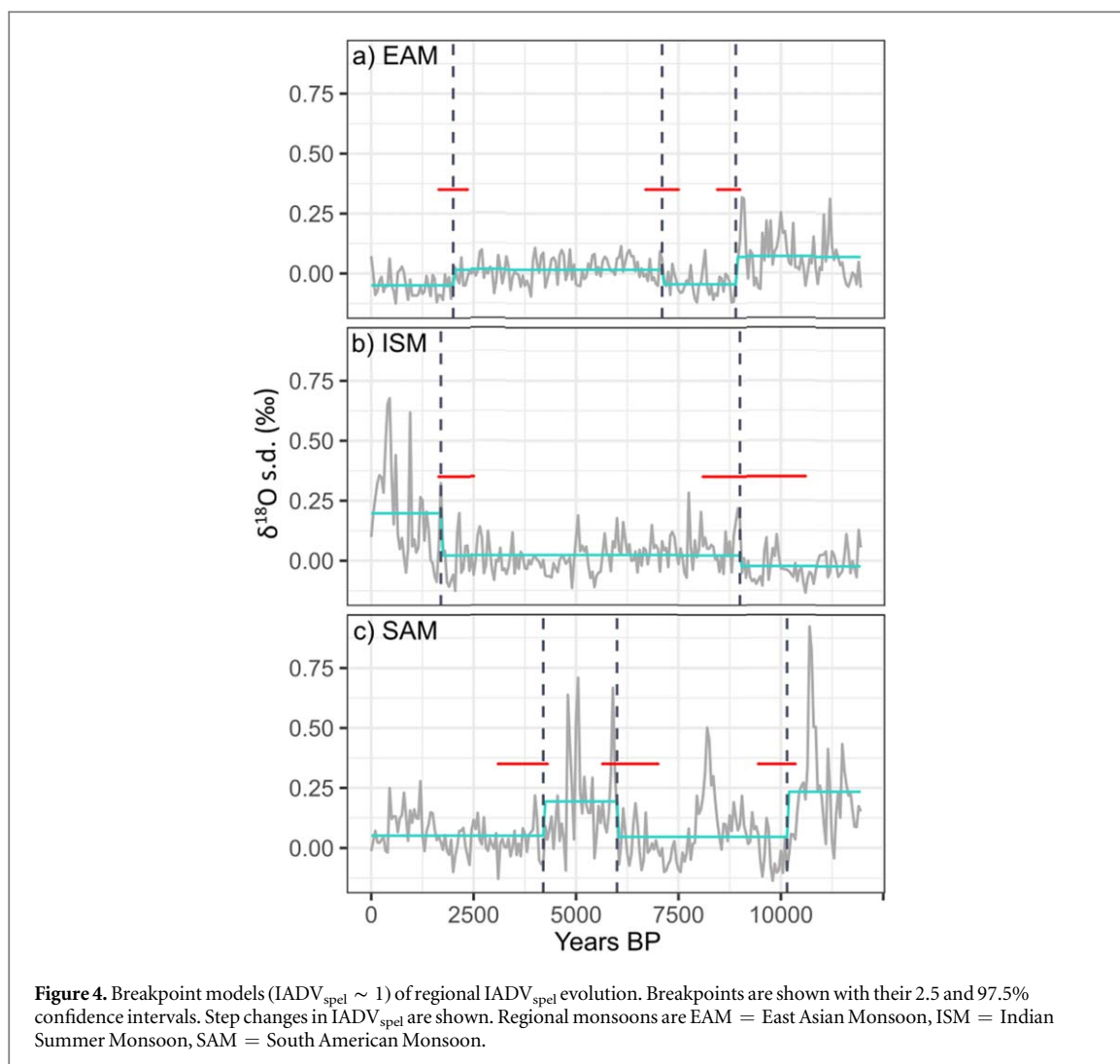
There is no overall change in  $\text{IADV}_{\text{speleth}}$  over the last 6 000 years in the EAM (table 2), reproduced by the AWI and MPI simulations (table 2). The IPSL simulations show a small but significant increase in  $\text{IADV}_{\text{precip}}$  through time. The significant increase in  $\text{IADV}_{\text{speleth}}$  from 6 onwards in the ISM is reproduced by all four simulations (figure 5, table 2). There is no significant change in  $\text{IADV}_{\text{precip}}$  through time in the SAM in any simulation (figure 5, table 2), whereas  $\text{IADV}_{\text{speleth}}$  increases significantly through time. However, this is driven by the peak at 4.2 to 6 ka; a linear regression from 5 ka onwards shows no significant change.

There are significant changes in simulated  $\text{IADV}_{\text{precip}}$  between the segments identified from the speleothems (table 4). In the ISM, all four simulations show significantly higher  $\text{IADV}_{\text{precip}}$  in the 1.7 to 0 ka period than the preceding period (table 4), consistent with the  $\text{IADV}_{\text{speleth}}$  record. All simulations show a significant increase in  $\text{IADV}_{\text{precip}}$  values from 1.7 ka onwards, but no significant trend prior to this (Table S4). This is consistent with the marked increase in  $\text{IADV}_{\text{speleth}}$  during the most recent 1 700 years. In the EAM, the AWI and MPI simulations show no significant difference in either slope or magnitude between the two intervals. (tables 4, S4), whilst the IPSL simulations show higher  $\text{IADV}_{\text{precip}}$  values for the most recent 2 000 years compared to the prior period. There is no significant difference between the intervals before and after 4.2 ka in SAM  $\text{IADV}_{\text{precip}}$  and neither interval shows significant changes in  $\text{IADV}$  through time (tables 4, S4). This is not consistent with the speleothem record, which shows higher variability before 4.2 ka than after.

### 3.4. Relationship between monsoon variability and long-term evolution

Speleothems and simulations show no consistent relationship between  $\text{IADV}$  and long-term changes in monsoon precipitation. There is declining summer monsoon strength and regional precipitation from the mid-Holocene onwards in the EAM and ISM, with a slower decline from  $\sim 2$  ka, following NH summer insolation (figure 6). However,  $\text{IADV}$  evolution differs between these two regions. In the EAM, the decreasing monsoon strength is mirrored by a decrease in  $\text{IADV}_{\text{speleth}}$  (figure 7(a), table 5). This relationship is reproduced by the AWI





**Figure 4.** Breakpoint models ( $IADV_{spel} \sim 1$ ) of regional  $IADV_{spel}$  evolution. Breakpoints are shown with their 2.5 and 97.5% confidence intervals. Step changes in  $IADV_{spel}$  are shown. Regional monsoons are EAM = East Asian Monsoon, ISM = Indian Summer Monsoon, SAM = South American Monsoon.

**Table 2.** Linear regression relationships of regional  $\delta^{18}O_{spel}$  s.d. versus time and simulated precipitation s.d. trends versus time ( $\text{mm}/\text{month yr}^{-1}$ ) from the mid-Holocene (6 000 years BP) to 0 years BP. Negative relationships represent lower variability (s.d.) at the mid-Holocene than at present. Significant relationships ( $P < 0.0001$ ) are shown in bold. EAM = East Asian monsoon, ISM = Indian Summer monsoon, SAM = South American monsoon.

	spel 6–0ka	IPSLCM5A-LR	IPSL-Sr	AWI-ESM2	MPI-ESM1.2
EAM	0.015	<b>−1.17E-05</b>	<b>−1.01E-05</b>	9.96E-07	−2.34E-07
ISM	<b>−0.061</b>	<b>−1.22E-05</b>	<b>−2.51E-05</b>	<b>−1.96E-05</b>	<b>−1.26E-05</b>
SAM	0.020	1.49E-07	−4.85E-06	<b>−6.40E-06</b>	−1.89E-06

and MPI simulations, although only MPI shows a significant relationship between mean precipitation and IADV. In contrast, the declining summer monsoon strength from the mid-Holocene onwards is accompanied by increasing IADV amplitude in the ISM. This relationship is reproduced by all four simulations. SAM observations and simulations show a strengthening monsoon from the mid-Holocene onwards (figure 6(e)), mirroring SH summer insolation (figure 6(d)). There is no significant relationship between the long-term changes and  $IADV_{spel}$  in the SAM. The lack of a relationship is reproduced by three of the four simulations (table 5).

#### 4. Discussion and conclusions

We have shown that variable growth rate, sampling frequency and mean climate have a minimal impact on  $\delta^{18}O_{spel}$  variability overall. Although cave monitoring studies have emphasised the influence of site-specific

**Table 3.** P-values for pairwise t-test, with the null hypothesis that the mean difference between two segments is zero. Segments are separated for each regional monsoon by breakpoint analysis, where the timings of abrupt changes ( $IADV_{spei} \sim 1$ ) were determined. Regional monsoons are: EAM, East Asian monsoon, ISM, Indian summer monsoon, SAM, South American monsoon. Bold values indicate P-values  $\leq 0.001$ , where the null hypothesis can be rejected.

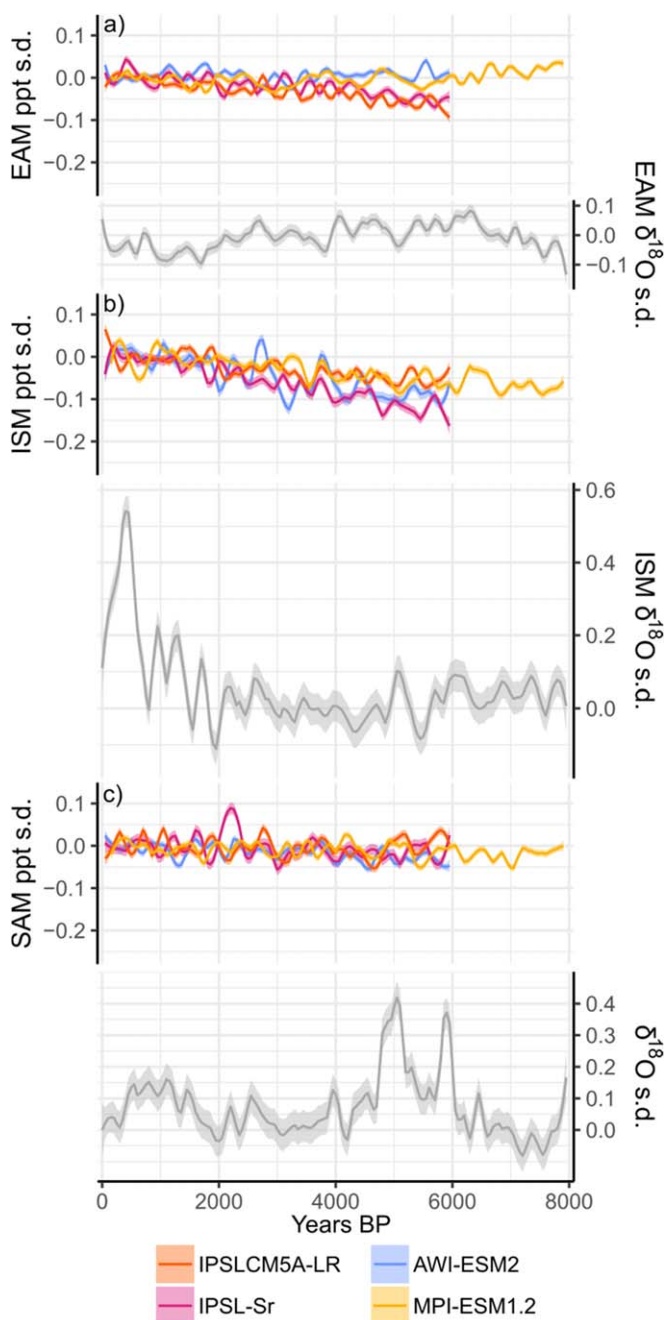
Segments (years BP)	Mean s.d.	P-values			
<i>EAM</i>		0–2000	2000–5950	5950–8800	8800–12000
0–2000	–0.049	/			
2000–7100	0.015	<b>7.88E-07</b>	/		
7100–8900	–0.045	7.78E-01	<b>6.13E-06</b>	/	
8900–12000	0.069	<b>5.20E-16</b>	<b>2.28E-06</b>	<b>3.44E-14</b>	/
<i>ISM</i>		0–2150	2150–9000	9000–12000	
0–1700	0.198	/			
1700–9000	0.022	<b>1.10E-17</b>	/		
9000–12000	–0.024	<b>2.21E-20</b>	<b>4.62E-03</b>	/	
<i>SAM</i>		0–4200	4200–7900	7900–10150	10150–12000
0–4200	0.051	/			
4200–6000	0.1942	<b>1.40E-06</b>	/		
6000–10150	0.046	8.20E-01	<b>8.83E-07</b>	/	
10150–12000	0.234	<b>1.04E-09</b>	1.49E-01	<b>8.65E-11</b>	/

factors on  $\delta^{18}O_{spei}$  (Luo *et al* 2014, Wu *et al* 2014, Pu *et al* 2016), these factors are unimportant when records from different speleothems and cave sites are combined. This is expected because, unlike climate signals, site-specific factors that might affect growth rate are unlikely to be consistent across sites. It might be useful to take account of the residence time of water in the epikarst directly in reconstructing  $\delta^{18}O_{spei}$  variability, but this is hard to quantify under the changing climate conditions of the geological past and may be unnecessary given that climate conditions that influence residence time may be indirectly incorporated via mean  $\delta^{18}O_{spei}$ . Despite the simplicity of our MLR model, the relationships between  $IADV_{spei}$  and the predictor variables are physically plausible and corrected  $IADV_{spei}$  evolution is similar between speleothems and sites.

Regional  $IADV_{spei}$  changes cannot be compared with the Galapagos Islands and Ecuador lake records which are interpreted as ENSO frequency rather than  $IADV$  amplitude. However, the hydrogen isotope record from El Junco (Zhang *et al* 2014), which is interpreted as a record of El Niño amplitude, shows large multi-centennial scale fluctuations in the early to mid-Holocene like those in SAM  $IADV_{spei}$ . Indeed, numerous records show fluctuations of a similar nature, including tropical Pacific reconstructions (Carré *et al*, 2021) and the Lake Pallacocha records (Moy *et al* 2002). The low amplitude variability recorded at El Junco during the mid-Holocene and the abrupt shift to present-day variability at  $\sim 3.5$  ka is also similar to the ISM  $IADV_{spei}$  record. ISM and SAM  $IADV_{spei}$  shows similarities with regional reconstructions of  $IADV$  amplitude from the tropical Pacific (Carré *et al* 2021). The western Pacific shows lower  $IADV$  through the early to mid-Holocene, then an abrupt shift to modern levels at  $\sim 2$  ka, similar to ISM  $IADV_{spei}$ , whilst central Pacific records show a peak in  $IADV$  at  $\sim 6$  ka, similar to the peak in SAM  $IADV_{spei}$  at this time. Thus, the speleothem composites provide a coherent picture of regional changes in  $IADV$  that are broadly consistent with other Holocene  $IADV$  reconstructions.

Some features of the  $IADV_{spei}$  records are reproduced by the models. Simulated  $IADV$  evolution reproduces the higher  $IADV$  of the last 1700 years compared to the mid-Holocene seen in ISM  $IADV_{spei}$  and the lack of an overall long-term Holocene changes in  $IADV_{spei}$  in SAM. The AWI and MPI simulations show differing trends between the ISM and EAM, as seen in the  $IADV_{spei}$  records. There are, however, differences between speleothem and simulated  $IADV$  changes. The IPSL simulations show increasing  $IADV$  from the mid-Holocene to present for the EAM, whereas  $IADV_{spei}$  decreases. However, these simulations show smaller changes in  $IADV$  in the EAM than the ISM and thus there is a difference in ISM and EAM simulated  $IADV$  even though this differentiation is less marked than the opposite changes seen in regional  $IADV_{spei}$ . The models do not show the large multi-centennial scale fluctuations seen in SAM  $IADV_{spei}$ . Comparisons of simulated and reconstructed SST  $IADV$  in the tropical Pacific also show that these models exhibit less multi-centennial variability than coral and bivalve records (Carré *et al* 2021). These discrepancies between simulated and reconstructed  $IADV$ , and indeed between different models, strongly suggests that the controls on monsoon precipitation are only indirectly tied to changes in external forcing.

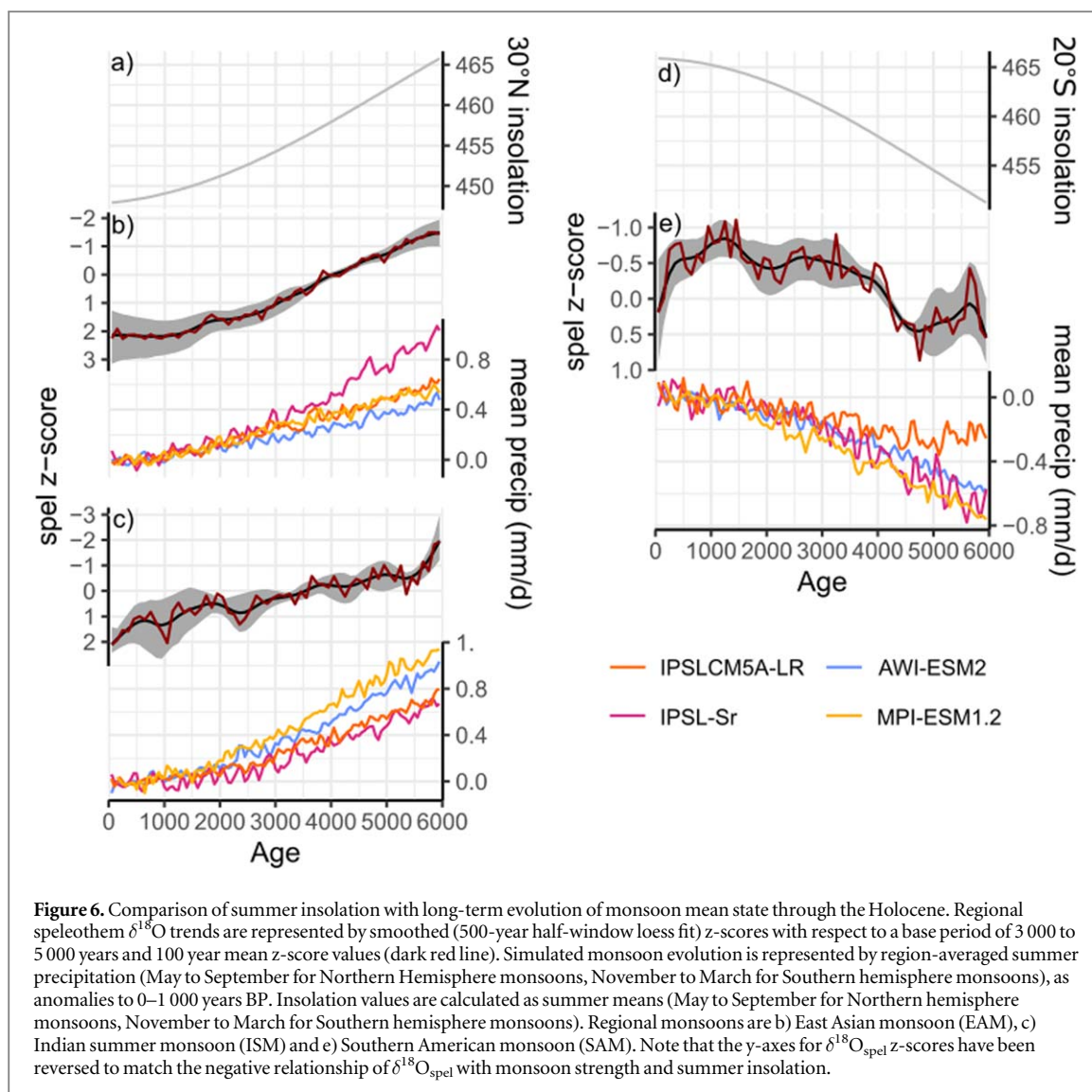
The long-term evolution of regional precipitation follows summer insolation (figure 6), but changes in regional monsoon  $IADV$  do not show a direct relationship with insolation. Long-term precipitation changes in the EAM and ISM are similar, but  $IADV$  evolution differs and even the abrupt change in  $IADV$  at  $\sim 2$  ka has a different sign in the two regions. Analyses of marine records from the Pacific (Carré *et al* 2021) suggests that



**Figure 5.** Evolution of regional speleothem  $\delta^{18}\text{O}$  standard deviation ( $\delta^{18}\text{O}_{\text{speleth s.d.}}$ ) values through the Holocene, compared to regional precipitation standard deviation simulated by four transient Earth System Models. Regional monsoons are: (a) EAM, East Asian Monsoon, (b) ISM, Indian Summer Monsoon, (c) SAM, South American Monsoon. Precipitation and  $\delta^{18}\text{O}_{\text{speleth s.d.}}$  values are extracted for 100-year windows with 50% overlap. Precipitation s.d. values are calculated as anomalies to the last 1000 years. Trends are fitted with a smoothed loess fit (500-year window).

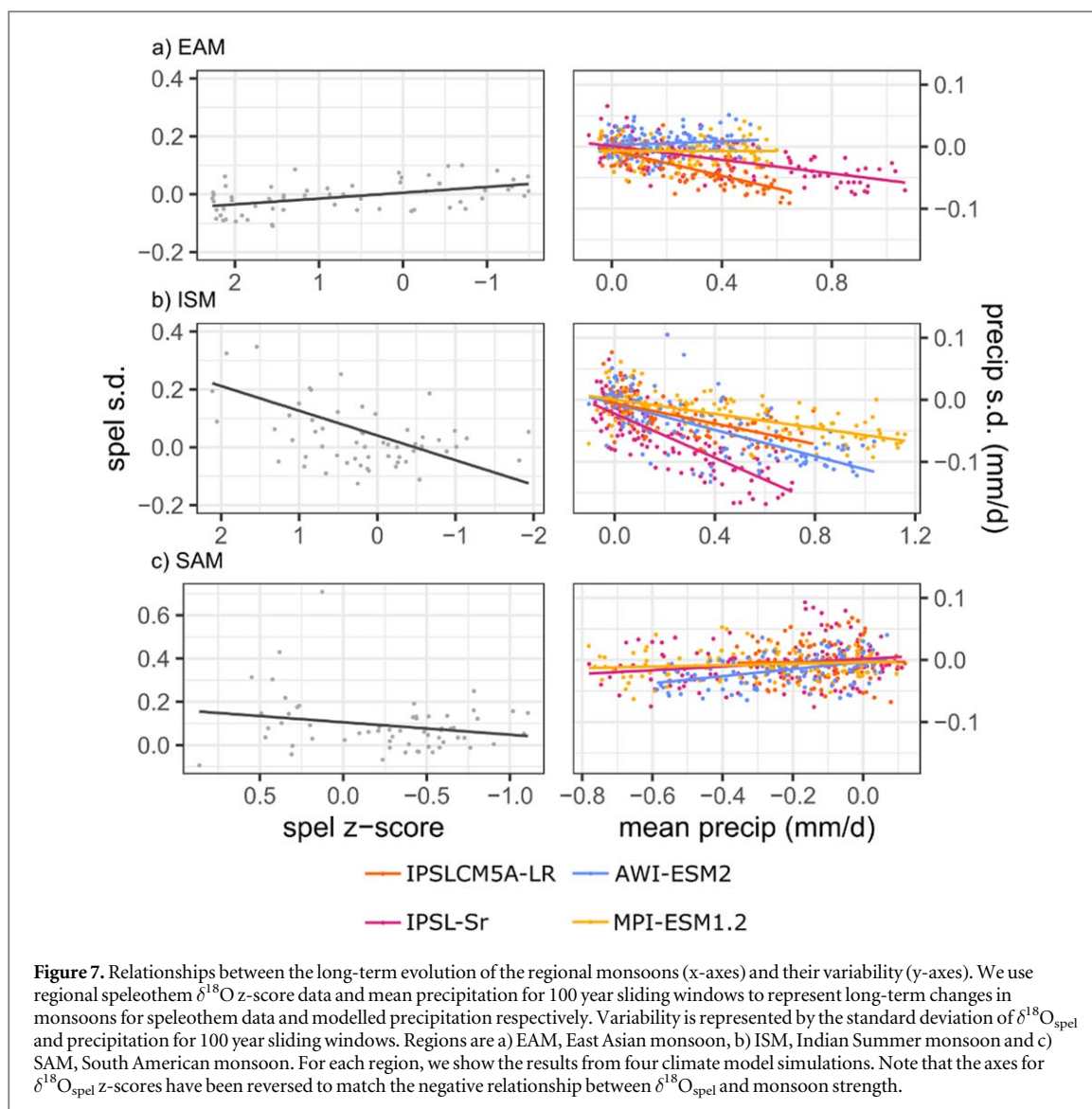
**Table 4.** Mean regional precipitation s.d. values for Holocene segments, identified in the breakpoint analysis of the speleothem trends. Bold values show segments (within an individual region and model) that are significantly different from the other ( $P < 0.0001$ ), determined using pairwise t-test. Regional monsoons are: EAM, East Asian monsoon, ISM, Indian summer monsoon and SAM, South American monsoon.

Region	Segments	IPSLCM5A-LR	IPSL-Sr	AWI-ESM2	MPI-ESM1.2
EAM	0–2000	<b>0.310</b>	<b>0.357</b>	0.274	0.271
	2000–6000	<b>0.274</b>	<b>0.327</b>	0.271	0.277
ISM	0–1700	<b>0.355</b>	<b>0.465</b>	<b>0.479</b>	<b>0.413</b>
	1700–6000	<b>0.313</b>	<b>0.389</b>	<b>0.418</b>	<b>0.370</b>
SAM	0–4200	0.442	0.448	0.277	0.305
	4200–6000	0.441	0.434	0.255	0.293



there is a link between orbital forcing and ENSO variability, but ENSO is not the only cause of changes in rainfall IADV in monsoon regions.

Differences in the relationship between simulated long-term evolution and precipitation IADV between the Indian and west African monsoons have been explained as reflecting the important role of ENSO over India and Atlantic modes over west Africa for precipitation variability (Braconnot *et al* 2019a). Differences in regional IADV<sub>spel</sub> evolution presumably also reflects the importance of different modes for IADV in each region. In the present-day, IADV over the EAM is influenced by ENSO signals that may also be modulated by the Pacific Decadal Oscillation (Feng *et al* 2014, Zhang *et al* 2018), whilst the ISM may also be influenced by changes in the Indian ocean (Ashok *et al* 2004, Krishnaswamy *et al* 2015). SAM IADV is influenced by changes in the tropical Atlantic and Indian Ocean, as well as ENSO (Grimm and Zilli 2009, Yoon and Zeng 2010, Jimenez *et al* 2021). Furthermore, each monsoon region has a distinct relationship with ENSO, with the nature and strength of the precipitation responses depending strongly on the location of SST anomalies in the tropical Pacific (Kumar *et al* 2006, Tedeschi *et al* 2015, Zhang *et al* 2016). All these regions show a changing relationship with ENSO in recent decades (Samanta *et al* 2020, Seetha *et al* 2019, Zhang *et al* 2018, Wang *et al* 2020) and this was likely the case during the Holocene. In the ISM region, for example, a weakening of the monsoon precipitation-ENSO relationship in recent decades has been attributed to a warming Eurasian continent (Kumar *et al* 1999), changes in tropical Atlantic SSTs (Kucharski *et al* 2007) and influence from the IOD (Ashok *et al* 2001). Analysis of ISM IADV evolution in the IPSL simulations (Crétat *et al* 2020) emphasised the interaction between ENSO, IOD and ISM precipitation variability. In the East Asian monsoon, the observed changing relationship between monsoon precipitation and ENSO over the last millennium is attributed to interaction with the PDO (Zhang *et al* 2018). Reconstructions and model simulations show changing PDO-like variability through the Holocene, including a positive phase during the early Holocene (Chen *et al* 2021). It is therefore likely that the relationship between



**Table 5.** Linear regression relationships of s.d. values ( $\delta^{18}\text{O}_{\text{spel}}$  s.d., regional precipitation s.d.) versus long-term evolution ( $\delta^{18}\text{O}_{\text{spel}}$  z-score, mean 100-year regional precipitation). Significant relationships ( $P < 0.0001$ ) are shown in bold. Regions are EAM = East Asian monsoon, ISM = Indian Summer monsoon, SAM = South American monsoon. Note that more negative  $\delta^{18}\text{O}$  z-scores and higher regional precipitation values represent a stronger monsoon, therefore agreement between speleothem data and models will be opposite direction trends.

Region	Spel	IPSLCM5A-LR	IPSL-Sr	AWI-ESM2	MPI-ESM1.2
EAM	<b>-0.0245</b>	<b>-0.102</b>	<b>-0.055</b>	0.016	<b>0.027</b>
ISM	<b>0.0556</b>	<b>-0.083</b>	<b>-0.178</b>	<b>-0.105</b>	<b>-0.051</b>
SAM	0.105	0.004	0.03	<b>0.059</b>	0.017

EAM precipitation variability and Pacific SSTs was significantly different during this period. Since regional monsoon precipitation variability is influenced by numerous modes that can interact with one another, it is likely that the lack of a direct and linear relationship between monsoon IADV and insolation through the Holocene reflects the complexity of these influences on regional precipitation and the potential for changes in the importance of different climate modes through time. More emphasis should therefore be placed on modes of variability other than ENSO to improve our understanding of the evolution of monsoon climate during the Holocene, using high resolution terrestrial records and model simulations.

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### Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5281/zenodo.5084426> (Parker 2021).

### Data and code availability

The code used to generate the results and figures in this study are available at ([doi.org/10.5281/zenodo.5084426](https://doi.org/10.5281/zenodo.5084426); Parker 2021). SISAL version 2 is available at <http://doi.org/10.17864/1947.256>. We use R for analyses (R Core Team 2019). The main packages used are tidyverse (Wickham *et al* 2021), ggplot2 (Wickham 2016), RMySQL (Ooms *et al* 2020) and ncd4 (Pierce 2019).

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