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Interannual controls on oxygen isotope variability in Asian monsoon precipitation and implications for paleoclimate reconstructions

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Abstract Orbital to millennial-scale variations in Asian monsoon speleothem δ18O have been widely interpreted as records of monsoon intensity and/or rainfall amount. To assess the influence of these and other mechanisms on higher-frequency δ18O variability, we utilize simulations from a spectrally nudged isotope-enabled general circulation model coupled with instrumental climate data to investigate the climatic controls on interannual precipitation δ18O (δ18Oo) variability at four key cave locations affected by the Asian monsoon: Qunf Cave, Oman; Mawmthue Cave, India; Tham Mai Cave, Laos; and Dongge Cave, China.

Comparison with instrumental climate data shows that interannual δ18Oo variations are only weakly related to local precipitation amount at the four sites and are instead controlled primarily by large-scale monsoon intensity and upstream precipitation over the tropical Indo-Pacific region, which influence the δ18O of incoming moisture. Spatial correlations with sea surface temperature and precipitation, composite analyses, and time series analyses show that the El Niño–Southern Oscillation (ENSO) also plays a key role in modulating interannual precipitation δ18O variability in the region, especially in northern India and Southeast Asia, with positive δ18O anomalies during El Niño years reflecting increased contribution of high δ18O moisture from the nearby Bay of Bengal. Coherent interannual to decadal δ18O variations seen in high-resolution proxy records from across the Asian monsoon region, likely record monsoon intensity and upstream rainfall, whereas ENSO related variability is likely to be strongest in records from northern India and Southeast Asia, with the largest anomalies expected when weak monsoons and El Niño occur together.

1. Introduction

The Asian monsoon (AM) is an important component of the global climate system that plays a major role in the transport of heat and moisture from the tropics to higher latitudes. Even small variations in the strength and/or timing of seasonal rainfall can have significant impacts on the billions of people living within the AM domain. Recent analyses of instrumental and reanalysis data have shown pronounced spatial and temporal variability in regional precipitation patterns across Asia [B. Wang et al., 2001; Conroy and Overpeck, 2011], yet our knowledge of the past regional behavior of the monsoon system, and the varying influence from modes of ocean-atmosphere circulation [e.g., Madden-Julian Oscillation (MJO), El Niño/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO)], is significantly lacking. The increasing availability of high-resolution, oxygen isotope (δ18O) based terrestrial paleoclimate records from across the AM region offers a significant opportunity to improve our understanding of the physical links between regional AM variability and interannual to decadal-scale coupled climate modes, such as ENSO [Zhang et al., 2008; Myers et al., 2015]. However, the factors influencing the δ18O of precipitation (δ18Oo) are numerous and complex and likely vary both in space and time; hence, a more complete understanding of the climatic influences on δ18Oo over different time scales is needed for robust interpretation of δ18Oo based paleoclimate records.

Numerous terrestrial and marine paleoclimate records of past AM variability have helped to broaden our understanding of orbital to millennial-scale monsoon dynamics over the past several glacial-interglacial cycles [Porter, 2001; Clemens and Prell, 2003; Wang et al., 2008; Cheng et al., 2009]. Recently, the most detailed records have been based on oxygen isotope variations preserved in cave calcite deposits or speleothems [Wang et al., 2008; Cai et al., 2015]. Assuming deposition under equilibrium conditions, the δ18O of the calcite is dependent only on that of the dripwater, which is closely related to δ18Oo and cave temperature. In the tropics and AM region, the cave dripwater signal dominates and mainly reflects changing δ18Oo, though
some noise may be introduced through transport and mixing in the epikarst [Baker and Bradley, 2010]. While orbital to millennial-scale variations in speleothem \( \delta^{18}O \) have been widely interpreted as proxies for local or regional precipitation amount (the so-called “amount effect”) and/or monsoon intensity [Sinha et al., 2005; Fleitmann et al., 2007; Cheng et al., 2009], the precise mechanism responsible for the broadly consistent signals seen across the AM region, even in locales with very different modern precipitation patterns, is still highly debated [LeGrande and Schmidt, 2009; Clemens et al., 2010; Doyem et al., 2010; Pausata et al., 2011; Caley et al., 2014; Liu et al., 2014; Chiang et al., 2015]. Most studies invoke some combination of changing rainfall seasonality [Y. J. Wang et al., 2001; Clemens et al., 2010; Chiang et al., 2015], rainfall amount [Fleitmann et al., 2004; Berkelhammer et al., 2010], and/or changes in the isotopic composition of incoming water vapor due to upstream processes such as rainout [Yuan et al., 2004; Johnson et al., 2006; LeGrande and Schmidt, 2009; Pausata et al., 2011] to explain the strong precession signal and millennial-scale excursions in speleothem \( \delta^{18}O \) in the AM region. Some recent studies also highlight the possible influence of global ice volume, Southern Hemisphere forcing, and tropical Pacific SST gradients on orbital-scale Asian monsoon variability, which could potentially explain the different timing of speleothem \( \delta^{18}O \) data when compared with some other AM records [Clemens et al., 2010; Caley et al., 2014].

While speleothem \( \delta^{18}O_p \) variability over orbital to millennial scales generally reflects large-scale monsoon variability, some recent studies suggest that higher-frequency \( \delta^{18}O \) variability may be dominated by other factors, such as local precipitation amount [Zhang et al., 2008; Tan et al., 2010] or ENSO [Tan, 2014; Myers et al., 2015]. Previously, analyses of data from the Global Network for Isotopes in Precipitation (GNIP) have been conducted to investigate the climatic controls on \( \delta^{18}O_p \) in the AM region. For instance, multiple regression analysis of monthly GNIP data indicates that the seasonal variations in \( \delta^{18}O_p \) at sites across China are significantly related to precipitation amount and temperature, with southern sites, in general, more related to rainfall amount and northern sites more related to temperature [Johnson and Ingram, 2004]. The magnitude of the observed effects is not large enough to explain the observed speleothem data, however, likely reflecting the fact that the seasonal cycle is not a good analog for interannual-scale variability. In a more recent analysis of GNIP data, it was determined that ENSO-driven changes in atmospheric-oceanic circulation are the dominant source of interannual \( \delta^{18}O_p \) variability in the monsoon regions of China [Tan, 2014]. Analysis of instrumental meteorological data indicated that this signal likely reflects the variation in the ratio of water vapor originating from distant oceans (relatively negative \( \delta^{18}O_p \)) versus the local ocean (relatively positive \( \delta^{18}O_p \)) [Tan, 2014]. Recent paleoclimate records based on \( \delta^{18}O_p \), variations preserved in fast-growing speleothems or in tree-ring cellulose from the AM region have supported this latter interpretation, with significant relationships seen between proxy \( \delta^{18}O \) and tropical Pacific SSTs during the instrumental period at some sites [Sano et al., 2012; Myers et al., 2015].

Yu and Kao [2007] recently distinguished two types of ENSO in the tropical Pacific: Eastern Pacific (EP) and Central Pacific (CP) El Niño events. CP El Niño events typically have SST and surface wind anomalies confined to the central Pacific (Niño 4 and Niño 3.4 regions) and are more likely to generate warming in the southern Indian Ocean, resulting in overall stronger teleconnections with SE Asia [Yu and Kao, 2007; Kao and Yu, 2009]. By contrast, EP El Niño events are generally characterized by SST anomalies centered in the eastern tropical Pacific and tend to have a more muted response (with respect to CP El Niño events) in SE Asia (Niño 3 region) [Kao and Yu, 2009]. Some recent studies have looked at the different effects of these two ENSO “flavors” on \( \delta^{18}O_p \)-based paleorecords in the AM region. For example, Myers et al. [2015] published a subannual resolution speleothem \( \delta^{18}O \) record from Mawmluh Cave, India, which exhibits a significant correlation with northern Pacific decadal variability and central equatorial Pacific SSTs. They found that variations in moisture transport during CP El Niño events led to positive \( \delta^{18}O \) anomalies at their site, in NE India [Myers et al., 2015]. In addition to ENSO, the IOD [Saji et al., 1999] is known to influence rainfall and monsoon intensity across the AM region [Ding et al., 2010; Ummenhofer et al., 2013]. For instance, positive IOD events, characterized by cool SST anomalies off Sumatra and warm SST anomalies in the western Indian Ocean, are associated with a strengthened monsoon over India and East Asia. Furthermore, the IOD conditions may modulate the ENSO-monsoon response over interannual to decadal timescales. Detailed investigation of the influence of ENSO type and IOD conditions on \( \delta^{18}O_p \) in the AM region have not yet been conducted.

Due to the sparseness, short duration, and often discontinuous nature of available \( \delta^{18}O_p \) data in the AM region, recent studies have utilized isotope-enabled general circulation models (GCMs) to further investigate
the mechanisms of interannual \( \delta^{18}O_p \) variability [Midhun and Ramesh, 2015]. Analysis of simulated \( \delta^{18}O_p \) allows for systematic investigation of the numerous parameters that are known to influence \( \delta^{18}O_p \) variability, such as local precipitation amount [Dansgaard, 1964], moisture source region [Bhattacharya et al., 2003; Griffiths et al., 2009; Baker et al., 2015], upstream rainout [Hoffmann and Heimann, 1997; Yoshimura et al., 2003; Vuille et al., 2005], and recycling of water by land surface exchange processes [Gat and Matsui, 1991].

Multiple isotope-enabled GCM simulations were recently analyzed to assess their ability in simulating the spatiotemporal patterns of precipitation amount and \( \delta^{18}O_p \) variability and to assess the influence of the amount effect on \( \delta^{18}O_p \) in the Indian summer monsoon (ISM) region over the period 1981–1999 [Midhun and Ramesh, 2015]. All models showed significant skill in simulating precipitation amount and \( \delta^{18}O_p \), though in contrast to a similar study of tropical \( \delta^{18}O_p \) [Conroy et al., 2013], models that were nudged with observed winds, such as the IsoGSM model of Yoshimura et al. [2008], showed better skill. This result possibly reflects the greater importance of atmospheric circulation and moisture transport history over continental regions. On interannual timescales, most sites showed weak or insignificant correlations between summer (June, July, August, and September (JJAS)) precipitation amount and \( \delta^{18}O_p \), suggesting that the local amount effect has limited influence over the interannual signals likely to be preserved in speleothems or tree-ring cellulose in this region. Looking specifically at four cave sites in the Indian monsoon domain, Midhun and Ramesh [2015] found significant relationships with summer (JJAS) rainfall upstream from the cave sites, including at one of the caves we investigate here (Mawmluh Cave), suggesting that the upstream rainout effect influences precipitation \( \delta^{18}O_p \) over interannual timescales, but the magnitude of this effect varied between models and observations.

Recent modeling studies have also investigated the physical processes underlying the amount effect, which is thought to be the dominant control on \( \delta^{18}O_p \) at some AM locations. Several studies have attributed the observed negative correlation between \( \delta^{18}O_p \) and precipitation rate to direct and indirect effects associated with unsaturated downdrafts, where increased convection strength and relative humidity lead to less evaporation and equilibration of falling rain drops and increased downdraft recycling which manifest as lower \( \delta^{18}O_p \) values on the ground [Bony et al., 2008; Risi et al., 2008; Kurita et al., 2011]. Other studies have argued that these effects are small compared to \( \delta^{18}O_p \) variability driven by changes in low-level moisture convergence and/or the isotopic composition of this moisture flux [Lee, 2009; Moore et al., 2014]. This latter interpretation is similar to the upstream rainout effect [Pausata et al., 2011], which alters the \( ^{18}O \) of advected water vapor. Most of these process studies were focused on oceanic regions in the tropics, so we should note that the amount effect in the Asian monsoon region, where it has been shown to exist, is likely influenced by additional factors, such as moisture recycling.

To improve the interpretation of \( \delta^{18}O_p \) based proxy records, especially but not limited to \( \delta^{18}O \) from speleothems, we utilize the twentieth century reanalysis nudged isotope-incorporated global spectral model (IsoGSM) simulations of \( \delta^{18}O_p \) [Yoshimura et al., 2008] and observed climate data from the past 30 years to explore the interannual relationship between \( \delta^{18}O_p \) and multiple climatic factors within the AM region. We focus on four locations that in addition to being strongly influenced by the AM have key paleoclimate records based on speleothem \( \delta^{18}O \). These four sites are located in the Arabian peninsula (Oman), India, Southeast Asia (Laos), and China (Figure 1). Spatial correlation analysis, time series analysis, and composite maps are used to reveal the relationship between \( \delta^{18}O_p \) and climatic parameters over interannual timescales.

2. Data and Study Sites
2.1. Site Description and Climatology
To investigate the mechanisms of interannual \( \delta^{18}O_p \) variability in the AM region, we have chosen four cave sites for our study: Tham Mai Cave, Laos (20.75°N, 102.65°E, elevation 360 m); Dongge Cave, China (25.28°N, 108.08°E, elevation 680 m); Mawmluh Cave, India (25.26°N, 91.71°E, elevation 1290 m); and Qunf Cave, Oman (17.17°N, 54.3°E, elevation 650 m). These cave sites are all influenced by distinct monsoon subsystems [Conroy and Overpeck, 2011], including the ISM (Qunf Cave; Mawmluh Cave), East Asian summer monsoon (EASM; Dongge Cave), and Southeast Asian summer monsoon (SEAM; Tham Mai Cave). Figure 1 shows the location of all study sites together with outgoing longwave radiation (OLR) data from the National Oceanic and
Atmospheric Administration (NOAA) [Liebmann and Smith, 1996], which demonstrates that three of the four sites (all except Qunf Cave) are characterized by large-scale convective systems during the summer monsoon months. Rather than strong convective monsoon precipitation, Qunf Cave primarily experiences fine drizzle (<5 mm/d) during the summer monsoon season [Fleitmann et al., 2003].

Speleothem records have been obtained from each of these four caves, and millennial to orbital-scale variations in δ18Op time series have been interpreted as reflecting Asian monsoon intensity [Fleitmann et al., 2003, 2007; Dykoski et al., 2005; Wang et al., 2005; Berkelhammer et al., 2013; Yang, 2016]. Here we investigate the mechanisms underlying interannual variations in δ18Op that may be recorded in fast-growing speleothems, tree rings, and other archives from these regions.

Qunf cave in southern Oman is at the northern limit of the summer migration of the Intertropical Convergence Zone (ITCZ) and is influenced by the Indian summer monsoon. Approximately 90% of annual precipitation (400 to 500 mm at cave site) falls during the monsoon season from July to September. A 4–5 year resolution Holocene δ18O record from Qunf Cave has been interpreted to reflect the amount of monsoon precipitation from 10.3 to 2.7 and 1.4 to 0.4 kyr B.P., with more negative δ18O values reflecting increased monsoon strength and vice versa [Fleitmann et al., 2003]. This record is dominated by orbital-scale variability, with monsoon intensity closely tracking Northern Hemisphere summer insolation, but it also records monsoon changes during more abrupt events such as the 8.2 kyr event.

Mawmluh Cave is located in Cherrapunji, Meghalaya, in northeastern India and has an annual average precipitation of 11,000 mm, 70% of which falls during the summer monsoon months (June to September). In addition to monsoon precipitation, this location is highly sensitive to the northward propagating convective systems that originate in the Bay of Bengal. A speleothem δ18O record that spans the period 3.6 to 12.5 kyr B.P. was interpreted as reflecting local precipitation amount related to ISM intensity via the amount effect [Berkelhammer et al., 2013]. This is supported by the inverse relationship between monsoon precipitation amount and δ18Op identified in IsoGSM simulations. However, Berkelhammer et al. [2013] also indicate that precipitation amount only accounts for 20% to 30% of the total δ18Op variability; thus, other climate processes, such as shifts in the location of convective activity in the Bay of Bengal and seasonality, may also influence δ18Op at Mawmluh Cave. This speleothem record has now been replicated and extended back to 33.8 kyr B.P. [Dutt et al., 2015]. In addition, Myers et al. [2015] published a subannual resolution speleothem δ18Op record that spans from 1964 to 2011 A.D. from Mawmluh Cave, which exhibits a significant correlation with north Pacific decadal variability and central equatorial Pacific SSTs. They suggested that variations in moisture transport during central Pacific-type El Niño (CP El Niño) events are primary controls on interannual δ18Op variability in this region.

Tham Mai Cave is located in the SEAM region of Northern Laos, near the interface of the ISM and EASM regions. The mean annual precipitation is 1195 mm, with 67% of precipitation falling during the summer monsoon months (June to September). A speleothem δ18Op record spanning the period 0.8 to 13.0 kyr B.P.
Yang et al. [2016] shows strong similarities with other Asian speleothem records [Wang et al., 2005; Hu et al., 2008; Dong et al., 2010] and is interpreted as primarily reflecting SEAM intensity. The record shows characteristically low values in the early Holocene followed by increasing values toward the present, indicating the strong influence of precessional forcing. Superimposed on this orbital-scale variability is a millennial-scale Younger Dryas excursion and significant interannual- to multidecadal-scale variability which may reflect other factors, such as ENSO, IOD, and other coupled climate modes.

Dongge Cave is located in Guizhou province in southern inland China, in the East Asian monsoon region. Annual mean precipitation is 1753 mm, with 60% of the rainfall occurring during the summer monsoon months (June to September). A number of speleothem records have been published from Dongge Cave ranging from interannual to orbital scales [Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2005; Zhao et al., 2015]. A last interglacial speleothem δ18O record [Yuan et al., 2004] and a 16 kyr deglacial to Holocene speleothem δ18O record [Dykoski et al., 2005] from Dongge Cave exhibit orbital and millennial-scale δ18O variations which were interpreted as reflecting low latitude and monsoon precipitation, where increased rainout between the tropical Indo-Pacific and southeastern China lead to more negative speleothem δ18O values. Dongge Cave is located in a region of China where precipitation is predominantly sourced from the Indian Ocean; hence, the orbital to millennial scale δ18O variations are likely dominated by ISM variability and rainout between the Indian Ocean and the cave site [Yang et al., 2014; Baker et al., 2015]. However, δ18O data at this site may also be influenced by EASM variability [Ding and Chan, 2005] and interannual to decadal-scale climate modes, such as ENSO.

2.2. IsoGSM Data

IsoGSM is a water isotope-incorporated general circulation model with the spectral dynamical core [Yoshimura et al., 2008]. We used the quasi-reanalysis product of IsoGSM nudged toward the NCEP/DOE Reanalysis 2 (R2) [Kanamitsu et al., 2002] atmosphere and forced with observed sea surface temperatures (SSTs) and sea ice [Yoshimura et al., 2008]. In this product, large-scale atmospheric wind and temperature fields are constrained by the spectral nudging technique [Yoshimura et al., 2008]. The data contain all conventional atmospheric variables (wind, temperature, humidity, pressure, radiation, flux, etc.) and isotopic variables, i.e., isotopic ratio of atmospheric vapor, liquid and solid water storages (snow, soil moisture, river storage, etc.), and water fluxes (precipitation, evaporation, runoff, etc.) since 1979 to 2014 in 6-hourly intervals. In this study, we also utilize a similar IsoGSM product nudged toward twentieth century reanalysis data [Compo et al., 2011], which extends from 1871 to 2009 [Yoshimura, 2015]. We use these two IsoGSM products to explore the influence of multiple climatic factors on interannual δ18O variability at each of the four cave sites.

2.3. Observed Isotopic and Climate Data

The International Atomic Energy Association/World Meteorological Organization GNIP database is the most complete instrumental data source available for studying precipitation isotopic variations [IAEA/WMO, 2016], but it is limited by sparse temporal and spatial resolution. Therefore, we utilize interpolated data calculated from raw GNIP data [Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003] to estimate the monthly mean oxygen isotope composition of precipitation at our four study sites. We compare the interpolated GNIP δ18O data with modeled IsoGSM δ18O at each cave site.

We also compare the IsoGSM δ18O data with observed climatic data including (i) instrumental precipitation data from the Global Precipitation Climatology Project (GPCP) data version 2.2 [Adler et al., 2003]; (ii) SST data from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) data set [Rayner et al., 2003]; (iii) sea level pressure data from the Hadley Centre Sea Level Pressure data set (HadSLP2r) [Allan and Ansell, 2016]; (iv) wind shear data, defined as the difference in zonal wind fields between 850 hPa and 200 hPa (U850-U200), from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis1 [Kanney et al., 2015]; and (v) vertically integrated atmosphere moisture transport data, defined as the vertical integral of monthly mean zonal and meridional moisture flux, based on the reanalysis monthly data from NCEP-NCAR and obtained from http://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html. Unless otherwise noted, we utilize weighted annual mean δ18O data for our analyses, as this is the most likely signal to be recorded in paleoclimate proxy records, such as speleothems [Fairchild et al., 2006].
3. Results and Discussion

3.1. IsoGSM Model Validation

Yoshimura et al. [2008] showed that IsoGSM simulated $\delta^{18}O_p$ agrees well with GNIP data for both annual and seasonal climatology, although they find that the amount of precipitation simulated in IsoGSM is systematically smaller than NCEP/DOE R2. The nudged IsoGSM model has also been validated over the Indian monsoon region and shown good agreement between observed and simulated rainfall and $\delta^{18}O_p$ [Midhun and Ramesh, 2015]. We further assess the skill of IsoGSM in simulating the precipitation and amount-weighted $\delta^{18}O_p$ seasonal cycle at our study sites through comparison with GPCP and interpolated GNIP data, respectively. All four locations show strong seasonality in rainfall amount and $\delta^{18}O_p$ values, with summer monsoon moisture being significantly depleted in $^{18}O$ with respect to boreal winter rainfall. The maximum monthly precipitation for Tham Mai Cave, Laos, and Mawmluh Cave, India, both occur in June, while precipitation peaks earlier at Dongge Cave, China (May), and later at Qunf Cave, Oman (July). The lowest $\delta^{18}O_p$ values exhibit a lag of 2–3 months behind maximum precipitation in both GNIP and IsoGSM data. IsoGSM shows good skill at simulating monthly precipitation climatology, with significant correlations ($r > 0.84$, $p < 0.1$) between IsoGSM precipitation and GPCP for all sites (Figure 2 and supporting information Table S1). IsoGSM monthly $\delta^{18}O_p$ values are also significantly correlated with interpolated GNIP $\delta^{18}O_p$ data for all sites (Qunf Cave $r = 0.68$, $p < 0.1$; other sites, $r > 0.88$, $p < 0.1$), though IsoGSM monthly $\delta^{18}O_p$ is lower than the interpolated GNIP data for some sites, especially for Qunf Cave (Figure 2 and Table S1). This could potentially reflect inaccuracies in IsoGSM and/or the interpolated GNIP data sets.

We also assess the ability of IsoGSM to simulate interannual precipitation variability through comparison of mean annual GPCP precipitation and modeled IsoGSM precipitation (Figure 3 and Table S2). IsoGSM shows good skill at simulating realistic interannual precipitation variability at Mawmluh Cave ($r = 0.30$, $p = 0.1$), Tham Mai Cave ($r = 0.33$, $p = 0.07$), and Dongge Cave ($r = 0.40$, $p = 0.01$). The correlation is less strong for Qunf Cave ($r = 0.20$, $p = 0.3$), perhaps reflecting the difficulty of simulating light precipitation in arid regions with complex topography. Yoshimura et al. [2008] found similar correlations between GPCP and NCEP/DOE reanalysis precipitation in low to midlatitude regions, with slight improvement observed when comparing IsoGSM and GPCP precipitation. These relatively weak correlations are not surprising given the uncertainties associated with reanalysis precipitation. Nevertheless, the similar spatial correlation patterns indicate that IsoGSM can simulate a comparable, or even improved, hydrologic cycle relative to the NCEP/DOE Reanalysis2.

3.2. Climatic Controls on Precipitation $\delta^{18}O_p$ Variability

3.2.1. The Amount Effect

To investigate the relationship between local precipitation amount and $\delta^{18}O_p$, we compared GPCP precipitation data and amount-weighted $\delta^{18}O_p$ time series from IsoGSM. On seasonal timescales, we observe negative
correlations between monthly precipitation amount and both observed (GNIP) and modeled (IsoGSM) amount-weighted $\delta^{18}O_p$ (Figure 2 and Table S1), but the seasonal cycle is not likely a good analog for interannual variability. To investigate the influence of precipitation amount on interannual timescales, we compare time series (1979–2009) of mean annual GPCP precipitation and IsoGSM amount-weighted annual mean $\delta^{18}O_p$ (Figure 3). Results indicate that for all four cave locations, $\delta^{18}O_p$ is not significantly correlated with local precipitation amount ($r$ values range from 0 to 0.2). Comparison of IsoGSM simulated $\delta^{18}O_p$ with simulated precipitation, however, yields stronger correlations (Table S2), so we cannot rule out some influence from the local amount effect, especially at Tham Mai, Mawmluh, and Dongge caves. Midhun and Ramesh [2015] also investigated the amount effect in multiple isotope-enabled climate models and found that on a seasonal timescale, significant negative correlations are observed between monthly JJAS precipitation rate and $\delta^{18}O_p$ at Mawmluh Cave, though they mention that this relationship is only significant when September and October are included in the monsoon rainfall season; this suggests that the timing of monsoon withdrawal is an important factor for $\delta^{18}O_p$ at this site. Contrary to this, here we use annual precipitation amount and annual weighted $\delta^{18}O_p$, which may explain the lack of a strong correlation between local precipitation amount and $\delta^{18}O_p$ at Mawmluh Cave. Overall, the low to moderate correlations between $\delta^{18}O_p$ and precipitation amount suggest that the local amount effect may have some influence but that additional factors are likely necessary to explain the full range of interannual $\delta^{18}O_p$ variability at the four cave sites, such as upstream rainout, monsoon strength, and circulation changes related to coupled climate modes, such as ENSO and IOD. 3.2.2. Nonlocal Precipitation A spatial correlation map with gridded GPCP data (Figure 4) shows that amount-weighted annual mean $\delta^{18}O_p$ at each site may be linked to nonlocal precipitation amount. All sites show some negative correlation with precipitation over the Indo-Pacific warm pool region, suggesting that increased convection over the warm pool is associated with more negative $\delta^{18}O_p$ values, perhaps reflecting the influence of Rayleigh distillation during tropical convection on the $\delta^{18}O$ of advected water vapor. In addition, $\delta^{18}O_p$ at Dongge Cave exhibits some negative correlation with regional precipitation upstream from the cave location, suggesting that a regional amount effect or upstream rainout could explain some of the interannual $\delta^{18}O_p$ variability.
δ^{18}Op at Qunf Cave, Mawmluh Cave, and Tham Mai Cave all show a positive correlation (r = 0.2 to 0.4) with tropical central Pacific precipitation, indicating a potential link with ENSO (Figure 4). This positive correlation is particularly strong between δ^{18}Op at Tham Mai Cave, Laos, and precipitation in the Niño 4 (5°S–5°N, 160°E–150 W) and Niño 3.4 (5 N–5°S, 120–170 W) regions. These are the regions characterized by positive SST and precipitation anomalies during central Pacific-type ENSO events [CP El Niño] [Kao and Yu, 2009]. Historical records have suggested that CP El Niño events, rather than those associated with the eastern equatorial Pacific (EP El Niño), are more likely to be associated with Indian monsoon rainfall reduction [Kumar et al., 2006; Ashok and Yamagata, 2009].

### 3.2.3. Asian Monsoon Intensity

Variability in large-scale monsoon circulation has been a favored explanation for the orbital- and millennial-scale variations in speleothem δ^{18}O in the AM region [Wang et al., 2008]. To investigate the influence of large-scale AM circulation on interannual δ^{18}Op variations, we conducted spatial correlation analysis of amount-weighted annual mean δ^{18}Op at each site with sea level pressures (SLP) and NCEP-vertical wind shear (VWS). Spatial correlation maps between δ^{18}Op and SLP data (Figure 5) show that δ^{18}Op values at all cave sites are positively correlated with SLP in the Bay of Bengal and Indian Ocean, as well as over some parts of continental India and Southeast Asia. Tham Mai, Mawmluh, and Dongge Cave δ^{18}Op values exhibit positive correlations with Bay of Bengal, eastern Indian Ocean, and subtropical west Pacific SLP, in particular. The positive correlation between SLP and δ^{18}Op in the region of the Western North Pacific Subtropical High is likely a function of the complex relationship between the strength of this feature and Indo-Pacific SSTs, ENSO, and the East Asian summer monsoon [Xiang et al., 2013]. By contrast, Qunf exhibits the strongest correlation with SLP over the western Indian Ocean and Arabian Sea, reflecting more influence from local conditions. Overall though, similar patterns are observed at all sites, suggesting a common dynamical mechanism could explain the interannual δ^{18}Op variability. The association between low sea level pressures over the ocean and negative δ^{18}Op anomalies likely reflects stronger surface convergence and increased convection over the ocean and upstream land areas, which lead to increased precipitation upstream and more negative δ^{18}Op at the cave sites.

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**Figure 4.** Maps showing the correlation coefficients (r) of annual amount-weighted IsoGSM δ^{18}Op from each site versus annual precipitation (GPCP) throughout the Indo-Pacific and Asian monsoon region for the period 1979–2009, for (a) Qunf Cave, Oman (triangle), (b) Mawmluh Cave, India (diamond), (c) Tham Mai Cave, Laos (star), and (d) Dongge Cave, China (circle). The light blue rectangle indicates the Niño 4 region (5°S–5°N, 160°E–150 W), the black dashed rectangle indicates the Niño 3.4 region (5°S–5°N, 120–170 W), and the pink rectangle indicates the Niño 3 region (5°S–5°N, 90 W–150 W). Colors represent significant r values at the 90% level.
Figure 5. Maps showing the correlation coefficients ($r$) of annual amount-weighted IsoGSM $\delta^{18}O_p$ from each site versus annual sea level pressure (HadSLP2) throughout the Indo-Pacific and Asian monsoon region for the period 1979–2009, for (a) Qunf Cave, Oman (triangle), (b) Mawmluh Cave, India (diamond), (c) Tham Mai Cave, Laos (star), and (d) Dongge Cave, China (circle). Colors represent significant $r$ values at the 90% level.

Figure 6. Maps showing the correlation coefficients ($r$) of annual amount-weighted IsoGSM $\delta^{18}O_p$ from each site versus annual NOAA vertical wind shear ($U_{850}$-$U_{200}$) throughout the Indo-Pacific and Asian monsoon region for the period 1979–2009, for (a) Qunf Cave, Oman (triangle), (b) Mawmluh Cave, India (diamond), (c) Tham Mai Cave, Laos (star), and (d) Dongge Cave, China (circle). Colors represent significant $r$ values at the 90% level. The black dashed line outlines the region used to determine the Webster-Yang monsoon index [Webster and Yang, 1992].
Another widely utilized measure of large-scale AM intensity is the VWS (U850-U200) between upper and lower tropospheric zonal flow. Webster and Yang [Webster and Yang, 1992] proposed a broad-scale monsoon index based on the magnitude of the mean summer VWS over the 0°–20 N and 40°–110°E AM domain (Figure 6, dashed box), whereas Wang and Fan [Wang and Fan, 1999] proposed two separate regions to characterize Indian versus Southeast Asian monsoon strength. Either way, an increase in VWS, which reflects increases in both the upper level easterlies and the lower level westerlies, can be observed during strong monsoon seasons, while a relaxation is more likely during weaker monsoon seasons [Webster and Yang, 1992]. Spatial correlation of δ18Op at each cave site with annual VWS reveals significant negative correlations (r < 0.2 to 0.6) over the Indian Ocean for all sites (Figure 6). In particular, Tham Mai δ18Op exhibits the strongest negative correlation (r < −0.5) with VWS in the northern and eastern Indian Ocean, while δ18Op at Qunf and Dongge caves primarily exhibits weaker negative correlations over the northern Indian Ocean. Mawmluh Cave δ18Op exhibits a negative correlation with VWS over the Northwest Indian Ocean, in the Arabian Sea domain (5°–20 N, 40°–80°E) proposed to be the best measure for Indian monsoon strength [Wang and Fan, 1999]. Employing the ECHAM-4 GCM fitted with isotopic tracers, Vuille et al. [2005] also found a significant correlation (r = 0.75) between δ18Op over the broad AM region and VWS over the region 7.5 N–2.5°S and 45°–20 W, consistent with our results.

Further investigation of the spatial δ18Op–VWS correlation patterns (Figure 6) reveal a dipole mode, with all cave sites exhibiting a positive correlation with VWS over the tropical west Pacific region in addition to the negative correlations seen over the Indian Ocean. This dipole pattern suggests that a weaker Walker circulation, which is characterized by positive VWS anomalies in the Pacific and negative anomalies in the central and eastern Indian Ocean [Kuleshov et al., 2009; Cherchi and Navarra, 2013], is associated with higher δ18Op values at each site, providing additional evidence for a link between ENSO and δ18Op in the AM region. Taken together, the SLP and VWS spatial correlation results suggest a strong linkage between a weaker Walker circulation, a weaker monsoon, and increased δ18Op at each locale, with the strongest relationships observed for Tham Mai Cave, Laos. This negative ENSO-monsoon relationship has been interpreted as a
modulation of the Walker circulation [Ju and Slingo, 1995] and may together explain the observed positive \( \delta^{18}O_p \) at our study sites during the El Niño years.

### 3.2.4. Coupled Climate Modes

To further examine the potential link between \( \delta^{18}O_p \) and ENSO, suggested by the observed correlations with precipitation, SLP, and VWS, we also constructed spatial correlation maps between \( \delta^{18}O_p \) and SST for each study site (Figure 7). Annual \( \delta^{18}O_p \) at the four sites, especially Qunf, Mawmluh, and Tham Mai caves, shows a positive correlation with Pacific SSTs over the Niño 4 and 3.4 regions, suggesting that positive \( \delta^{18}O_p \) anomalies at these sites may occur during El Niño years, even though no significant precipitation decrease is seen during El Niño events (Table S3 and Figure S1). In particular, \( \delta^{18}O_p \) of Qunf Cave and Tham Mai Cave has a strong positive correlation with broad central Pacific and southwestern Indian Ocean SSTs, which bear resemblance to the typical spatial pattern of SST anomalies observed during CP El Niño events [Kao and Yu, 2009]. Similar spatial correlation patterns between \( \delta^{18}O_p \) and both Pacific Ocean and Indian Ocean SSTs are also evident for the Mawmluh and Dongge Cave sites, but the relationships are not as strong and show slightly different spatial patterns in the Pacific, potentially reflecting greater sensitivity to EP type El Niño events. In addition to ENSO, spatial correlations between \( \delta^{18}O_p \) and SST (Figure 7) suggest possible additional influence from the IOD. A positive correlation between \( \delta^{18}O_p \) and SSTs in the western Indian Ocean and a negative correlation with SSTs in the eastern Indian Ocean suggest that positive \( \delta^{18}O_p \) anomalies may occur during positive IOD events. This IOD pattern is particularly strong for Mawmluh, Tham Mai, and Dongge caves, whereas \( \delta^{18}O_p \) at Qunf Cave is positively correlated with SSTs across broader portions of the Indian Ocean. Some recent paleorecords from the AM domain support a link between \( \delta^{18}O_p \) and ENSO. For example, a 300 year tree-ring cellulose \( \delta^{18}O \) record from Vietnam [Sano et al., 2012], which is highly correlated with another tree-ring record from Laos [Xu et al., 2011], exhibits a strong positive correlation with SSTs in the central tropical Pacific and Indian Oceans and has been primarily interpreted as an ENSO record, though the authors did not distinguish between CP and EP type events. Myers et al. [2015] published a subannual resolution speleothem \( \delta^{18}O \) record from Mawmluh Cave, India, which exhibits a significant correlation with northern Pacific decadal variability and central equatorial Pacific SSTs. They suggested that variations in moisture transport during CP El Niño events, in particular, is a primary control on \( \delta^{18}O_p \) in this region, which differs slightly from our spatial correlation results, which show a more EP-like pattern.

To investigate the pattern of spatial \( \delta^{18}O_p \) anomalies associated with ENSO and IOD events, we constructed a composite AM season (JJAS) \( \delta^{18}O_p \) map for two strong El Niño years, 1982 and 1997 (both EP type), and also examine \( \delta^{18}O_p \) of the following years: 1983, which was a positive IOD, neutral ENSO year, and 1998, which was a La Niña year (Figure 8). During composited El Niño years, a strong positive JJAS \( \delta^{18}O_p \) anomaly extends over the Indo-Pacific warm pool region and parts of continental India and southeast Asia, whereas negative anomalies occur over the central equatorial Pacific, consistent with other observational and modeling studies [Conroy et al., 2013]. Tham Mai Cave and Mawmluh Cave both exhibit positive \( \delta^{18}O_p \) anomalies in the El Niño composite, consistent with our spatial correlation map results, while no strong anomalies are seen at Qunf Cave or Dongge Cave. Conversely, during the La Niña year, negative JJAS \( \delta^{18}O_p \) anomalies were observed over the Indo-Pacific, while positive anomalies were observed over the tropical west Pacific and South China Sea. Mawmluh Cave and Tham Mai Cave both exhibit negative \( \delta^{18}O_p \) anomalies during the La Niña year, whereas no clear signal was seen at Qunf Cave and a positive anomaly was seen at Dongge Cave. The positive IOD event showed greater regional variability, with positive \( \delta^{18}O_p \) anomalies, as predicted by spatial SST correlations, occurring near Dongge, Tham Mai, and Mawmluh caves, though other regions close to these sites showed the opposite pattern and no signal was seen at Qunf Cave. This analysis shows that while our spatial correlation results suggest that while our spatial correlation maps suggest that CP-type El Niño events may exert a stronger influence on \( \delta^{18}O_p \), at some sites; EP events are also associated with positive \( \delta^{18}O_p \) anomalies in the AM region, especially in northern India (Mawmluh) and Southeast Asia (Tham Mai). Furthermore, our results suggest that additional studies are needed to fully investigate the isotopic signals associated with the IOD and how these interact with ENSO or monsoon driven variations.

Previous studies have implicated changes in atmospheric circulation and moisture transport to explain the observed \( \delta^{18}O_p - \text{ENSO} \) relationship in the AM region [Tan, 2014; Myers et al., 2015]. To assess the role of these processes, we constructed a composite map of AM season (JJAS) vertically integrated atmosphere moisture transport anomalies (Figure 9) during the two strong El Niño years (1982 and 1997) for comparison with the
La Niña (1998) and positive IOD year (1983). A slight decrease in moisture transport over the western Indian Ocean and tropical Pacific (Figure 9a, red boxes), together with increasing moisture transport over the Bay of Bengal, was exhibited during composited El Niño years. By contrast, a slight increase of moisture from the western Indian Ocean and tropical west Pacific (Figures 9b and 9c, blue boxes), together with decreasing

Figure 8. Anomalies of JJAS amount-weighted δ\textsuperscript{18}O\textsubscript{p} for (a) a composite of two strong El Niño years (1982 and 1997), (b) a strong La Niña year (1998), and (c) a strong positive IOD year (1983). Red areas show regions with positive δ\textsuperscript{18}O\textsubscript{p} anomalies and blue areas show regions with negative δ\textsuperscript{18}O\textsubscript{p} anomalies. Anomalies are calculated by subtracting the mean of JJAS amount-weighted δ\textsuperscript{18}O\textsubscript{p} (1979–2009) from JJAS amount-weighted δ\textsuperscript{18}O\textsubscript{p} for each year. The location of the four cave sites are also shown: Qunf Cave, Oman (triangle), Mawmluh Cave, India (diamond), Tham Mai Cave, Laos (star), and Dongge Cave, China (circle).
moisture from the Bay of Bengal, Andaman Sea, Gulf of Thailand, and South China Sea (Figures 9b and 9c; red boxes), were observed during the La Niña and positive IOD year. These results suggest that the positive $\delta^{18}O_p$ anomalies observed at Mawmluh Cave and Tham Mai Cave during the El Niño years could reflect increased moisture transport from the more proximal Bay of Bengal and decreased moisture transport from the more remote Indian Ocean (Figure 9). This change in moisture sources leads to a shorter vapor transport distance (and thus more positive $\delta^{18}O_p$) to the site of monsoon rainout during El Niño years. By contrast, during the La Niña and positive IOD year, there is an observed increase in the moisture flux from the Indian Ocean and opposing decrease from the Bay of Bengal, indicating that most of the moisture transported to SE Asia now travels a greater distance, and as a result becomes more depleted in $^{18}O$ due to enhanced rainout. These alternating shifts in moisture source and transport pathways provide a mechanistic explanation linking

![Figure 9. Anomalies of JJAS vertically integrated atmosphere moisture transport (kg/m/s) for (top) a composite of two strong El Niño years (1982 and 1997), (middle) a strong La Niña year (1998), and (bottom) a strong positive IOD year (1983). Blue boxes highlight regions with increased moisture transport and red boxes denote regions with decreased moisture transport as discussed in the text. Anomalies are calculated by subtracting the mean of JJAS vertically integrated moisture transport (1979–2009) from JJAS values for each year. The location of the four cave sites are also shown: Qunf Cave, Oman (triangle), Mawmluh Cave, India (diamond), Tham Mai Cave, Laos (star), and Dongge Cave, China (circle).](image-url)
tropical Pacific SSTs (and hence ENSO) with $\delta^{18}O_p$ variability in SE Asia and northern India, though we cannot assess whether the patterns are substantially different during CP-type events.

To further assess the observed ENSO-$\delta^{18}O_p$ relationships, we calculated mean $\delta^{18}O_p$ at all four cave sites, for all El Niño, La Niña, and ENSO neutral years between 1979 and 2009 and found that for Mawmluh, Tham Mai, and Dongge caves, El Niño years were characterized by the highest mean $\delta^{18}O_p$ values, whereas La Niña years had the lowest values, though the differences were not statistically significant (Table S3). Similarly, we find that these three sites exhibited the lowest mean precipitation during El Niño years, but only Mawmluh Cave shows increased precipitation during La Niña years. Qunf Cave showed no clear ENSO related differences, potentially reflecting its position far from the regions of greatest moisture flux changes and/or the difficulty of modeling precipitation accurately in this region (Table S3).

Given that we only examined annual spatial correlations and JJAS composites for a relatively short time period and in light of the ongoing debates on the different methods of identifying the two types of El Niño [Ashok et al., 2007; Yeh et al., 2009; Yu et al., 2012], fully determining the relationship between ENSO type (CP or EP) and $\delta^{18}O_p$ in the AM region will require additional observational and modeling studies. For instance, our analysis did not account for the seasonal timing of the ENSO teleconnection to the AM precipitation, wherein ENSO typically peaks in NH winter yet the majority of precipitation falls in the summer. In addition, the relatively short period of our study and the potential for variability in the ENSO-IOD-monsoon relationship, both over interdecadal timescales and in response to anthropogenic forcing, may contribute to uncertainty and bias in our identified relationships [Li and Ting, 2015]. Overall, while our results suggest that there may be spatially varying influences of the two types of El Niño and the IOD on the different subsectors of Asian monsoon $\delta^{18}O_p$, it is clear that both types of El Niño likely exert strong influence over interannual $\delta^{18}O_p$ variability in the AM region, with positive anomalies during El Niño years and negative anomalies during La Niña years, especially over Southeast Asia and northern India (Figure 8 and Table S2).

3.3. Interpretation of $\delta^{18}O$ Based Paleorecords From the Southeast Asian Monsoon Region

While paleoclimate records have significantly advanced our understanding of East Asian summer monsoon and Indian summer monsoon variability [Wang et al., 2008; Berkelhammer et al., 2010], we still know very little about the range and mechanisms of variability in the SEAM domain, in part because of the paucity of paleoclimate records from this region. The SEAM region is of particular importance as this highly populated area sits at the interface of the EASM and ISM systems and exhibits substantial hydrologic variability related to changing monsoon strength and interannual to decadal climate modes such as ENSO and the IOD [Buckley et al., 2007, 2010; Conroy and Overpeck, 2011]. As discussed above, interannual $\delta^{18}O_p$ variations at Tham Mai Cave, located in the Southeast Asian monsoon region, while not strongly related to local precipitation amount (Figure 3), are influenced by upstream rainout over the Indo-Pacific warm pool regions and the Bay of Bengal (Figure 4), large-scale Asian monsoon intensity (Figures 5 and 6), and coupled climate modes, such as ENSO and IOD (Figures 7–9). In general, positive $\delta^{18}O_p$ anomalies at this site occur as a result of decreased upstream precipitation, decreased monsoon intensity, and/or El Niño conditions, with the opposite being true for negative $\delta^{18}O_p$ anomalies. The upstream rainout and monsoon signals are closely related and primarily manifest through increased convection and precipitation over the Indo-Pacific warm pool, Indian Ocean, and Bay of Bengal, which decrease the $\delta^{18}O$ of incoming water vapor. The El Niño signal likely manifests through increased contribution of isotopically heavy moisture from the nearby Bay of Bengal, whereas La Niña events receive more isotopically light moisture from the more distal Indian Ocean region (Figure 9).

To better determine the potential for obtaining high-resolution (interannual to decadal scale) paleoclimate records using speleothem or tree-ring cellulose $\delta^{18}O_p$ from the SEAM region, we have conducted a case study to further evaluate the climatic controls on interannual $\delta^{18}O_p$ variability at Tham Mai Cave, Laos. To assess the robustness of the climate-$\delta^{18}O_p$ relationships observed through spatial correlations (Figures 4–8) we repeated these analyses using the average of the three closest grid cells to Tham Mai Cave (Figure S2). Results show very similar patterns to those constructed using only the single grid cell, indicating that the observed relationships with precipitation, sea level pressure, vertical wind shear, and sea surface temperatures are robust features. In addition, we compared the twentieth century reanalysis nudget
IsoGSM simulated $\delta^{18}O_p$ time series [Yoshimura, 2015] with IsoGSM precipitation data from the grid point closest to Tham Mai Cave and with the Niño 3.4 index. Correlation analyses were done using monthly data with the seasonal cycle and low frequency trend removed (see Text S1). The Tham Mai monthly $\delta^{18}O_p$ time series from 1949 to 2009 exhibits a weak negative correlation with local precipitation anomalies ($r = -0.21$, $p < 0.01$) and a positive correlation with the Niño 3.4 index ($r = 0.53$, $p < 0.01$) (Figures 10 and S3). For visual comparison, we smoothed each series with a 5 year running average, which shows that these relationships appear to hold up over interannual to quasi-decadal timescales, such as those that are most likely preserved in cave dripwater (Figure 10, colored lines). Additional examination of the IsoGSM $\delta^{18}O_p$ and precipitation trend over the full twentieth century nudged simulation period (1871–2009) shows an increasing precipitation rate and decreasing $\delta^{18}O_p$ trend since ~1925 and a negative correlation between $\delta^{18}O_p$ and precipitation rate ($r = -0.57$, $p < 0.001$), hinting that the amount effect could potentially become more significant over decadal timescales (Figure S4), but we expect that this relationship would be stronger than our earlier analyses (Figure 3) as it compares simulated $\delta^{18}O_p$ with simulated (rather than observed) precipitation rate.

These results provide further evidence that the interannual variability of $\delta^{18}O_p$ in northern Laos is likely dominated by the combined influence of monsoon intensity, ENSO, and possibly the IOD, which together act to modify the $\delta^{18}O$ of incoming water vapor, even if local precipitation amount does not change much. In addition to understanding the controls on $\delta^{18}O_p$, robust interpretation of paleoclimate data requires consideration of the response times, seasonal biases, and noisiness of the processes through which the $\delta^{18}O_p$ signal is encoded in paleoclimate archives, such as speleothem calcite and tree-ring cellulose [Dee et al., 2015]. For instance, the suitability of speleothems for reconstructing high-frequency climate variability is dependent on the degree of mixing and hydrologic “smoothing” that takes place as precipitation infiltrates down through the epikarst, a factor which can vary from site to site [Duan et al., 2016]. The similarity between the 5 year smoothed $\delta^{18}O_p$ and Niño 3.4 index time series (Figure 10) from Tham Mai Cave indicates that this relationship likely holds over the interannual to decadal timescales that are more likely to be recorded in speleothem calcite, so these proxies should indeed be useful indicators of past ENSO variability.

Similarly, the isotopic composition of terrestrial plant tissue depends not only on the source water $\delta^{18}O$ but also plant physiological processes as well as on some environmental variables, mainly temperature and precipitation, which affect the isotopic fractionation taking place during photosynthesis [McCarroll and Loader, 2004]. Furthermore, cellulose $\delta^{18}O$ variations likely exhibit different seasonal biases compared with speleothems, which are usually formed from dripwater with a composition similar to annual mean $\delta^{18}O_p$. 

Figure 10. Comparison of monthly (a) HadISST IOD index and (b) HadISST Niño3.4 index with (c) IsoGSM precipitation and (d) amount-weighted $\delta^{18}O_p$ anomalies from the Tham Mai Cave site from 1949 to 2009. IsoGSM data are from the twentieth century nudged simulation [Yoshimura, 2015]. Grey lines are monthly data with the seasonal cycle removed, and bold colored lines are 5 year running means. The y axis for $\delta^{18}O_p$ values is reversed. Correlation coefficients ($r$) are shown for unsmoothed precipitation, Niño 3.4, and IOD versus $\delta^{18}O_p$. 


YANG ET AL. OXYGEN ISOTOPES OF ASIAN MONSOON PRECIPITATION 8424
Overall, the most reliable δ¹⁸O_p-based paleoclimate reconstructions will account for the various climatic controls on δ¹⁸O_p and also utilize a precise and accurate chronology [Zhang et al., 2008], detailed proxy calibration studies [Moerman et al., 2014], instrumental calibration [McCabe-Glynn et al., 2013], and/or proxy system modeling [Baker and Bradley, 2010; Dee et al., 2015] to generate robust annual- to multidecadal-scale climate records from speleothems [Berkelhammer et al., 2010; Zhao et al., 2016] or tree-ring cellulose δ¹⁸O [Xu et al., 2011]. The results presented here represent a first step toward the development of high-resolution records that will allow for detailed investigation of the past history of monsoon and ENSO/IOD-related climate variability in Southeast Asia.

4. Conclusions

Our comparison of simulated IsoGSM δ¹⁸O_p with observed climate data reveals the influence of local and regional precipitation amount, monsoon intensity, and coupled climate modes (ENSO and IOD) on interannual δ¹⁸O_p variability at four key cave sites spanning the broad Asian monsoon region: Qunf Cave, Oman; Mawmluh Cave, India; Tham Mai Cave, Laos; and Dongge Cave, China. Comparisons with precipitation data suggest that while the local amount effect has only minor influence, interannual δ¹⁸O_p variations at each site are influenced by upstream rainout over the Indo-Pacific warm pool, Indian Ocean, and/or Bay of Bengal, which influences the δ¹⁸O of water vapor advected to the study sites. In addition, the δ¹⁸O_p at all four sites, especially Qunf, Mawmluh, and Tham Mai caves, exhibits a strong correlation with SLP and wind shear in the broad tropical Indian Ocean, reflecting the influence of large-scale monsoon intensity [Webster and Yang, 1992], with stronger monsoon years with increased upstream rainout characterized by more negative δ¹⁸O_p at each site. The broadly similar spatial correlation patterns observed between precipitation, sea level pressure, and vertical wind shear with δ¹⁸O_p at each site points to a common dynamical mechanism underlying interannual δ¹⁸O_p variability at each location. Furthermore, these results are consistent with recent findings that widespread regions of the AM region likely share a common moisture source region. For instance, Baker et al. [2015] used a Lagrangian model to diagnose different precipitation moisture sources for several Chinese cave sites and demonstrated that the Indian Ocean is the primary moisture source for the EASM, while the Pacific Ocean is only a minor contributor to monsoonal precipitation. These results highlight that similar to orbital and millennial-scale variations observed in speleothems, changes in monsoon strength and upstream rainout should lead to consistent patterns of higher-frequency (annual to decadal) variability in δ¹⁸O_p-based proxy records from sites across the AM region, though with a smaller amplitude.

We also find that coupled climate modes, especially ENSO, exert control on interannual δ¹⁸O_p variability at each site, with the largest effects seen in northern India (Mawmluh Cave) and Southeast Asia (Tham Mai Cave). Spatial correlation maps indicate that δ¹⁸O_p at each site is positively correlated with precipitation and sea surface temperature over the central tropical Pacific Ocean, with Tham Mai Cave in particular showing patterns that appear similar to SST anomalies observed during CP El Niño events. Composite maps reveal that two large EP El Niño years (1982 and 1997) were characterized by positive δ¹⁸O_p anomalies at Mawmluh Cave and Tham Mai Cave, further vindicating our results that δ¹⁸O_p in these regions is particularly sensitive to ENSO. Composites of vertically integrated moisture transport point toward shifts in moisture source regions to explain these ENSO related δ¹⁸O_p anomalies, with positive δ¹⁸O_p anomalies during El Niño events reflecting increased contribution of isotopically heavy moisture from the nearby Bay of Bengal relative to the isotopically light moisture from the western Indian Ocean. The opposite patterns are observed during La Niña events. Additional support is provided by time series analysis results, which reveal a significant correlation between δ¹⁸O_p at Tham Mai Cave with the Nino 3.4 index from 1949 to 2009. While we see some evidence for a variable influence of CP versus EP type ENSO and IOD on δ¹⁸O_p in this region, additional research is needed to fully assess this. Nevertheless, recent studies which invoke ENSO to explain δ¹⁸O data variations in speleothems [Myers et al., 2015] and tree-ring cellulose [Xu et al., 2011; Sano et al., 2012] are supported by our findings. Unlike monsoon intensity, however, ENSO and IOD variations appear less likely to lead to coherent δ¹⁸O_p variability across the broad Asian monsoon region, and the most robust ENSO records from the AM region are likely those from northern India and Southeast Asia.
Our results indicate that interannual-scale $\delta^{18}$O variation in proxy records, such as speleothems or tree rings, can provide valuable records of past changes in Asian monsoon intensity. Convective precipitation over the tropical Indo-Pacific region, and coupled climate modes such as ENSO and IOD, need to be investigated interannually. Accurate interpretation of proxy data must be careful to take into account the processes through which the $\delta^{18}$O signal is modified during the formation process of speleothem calcite or tree-ring cellulose. For instance, only fast-growing speleothems fed by relatively direct transport pathways through the epikarst are likely to record interannual-scale signals, whereas tree-ring cellulose is likely to record an annual signal, but with a seasonal bias and additional influence from biologic or environmental factors. We find that the largest signals should be observed in Southeast Asia and northern India, especially when weak ISM years occur together with El Niño and positive IOD conditions. While our analysis primarily investigates interannual-scale processes, similar mechanisms could also potentially be invoked to explain lower frequency variations observed in the proxy record. For example, decadal-scale climate modes, such as the IOD, or changes in the mean state of the tropical Pacific, toward a more El Niño-like or La Niña-like state, could lead to decadal or longer term $\delta^{18}$O variations in the proxy record through mechanisms similar to those invoked here.

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