Inter-annual controls on oxygen isotopes of precipitation in the Asian Monsoon region

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1. Introduction

The complexity of Asian monsoon region speleothem $\delta^{18}O$ may be introduced from monsoon strength, moisture source region, transport history, local precipitation, cave hydrology and other influences on cave dripwater $\delta^{18}O$. In order to provide a more robust interpretation of speleothem $\delta^{18}O$ data from the broader Asian monsoon region, we utilize existing simulations from the isotope-enabled GCM, IsoGSM (Yoshimura *el al.* 2008), to investigate the climatic controls on precipitation $\delta^{18}O$ ($\delta^{18}O_p$) in four cave locations: Dongge cave, China (25°17′ N, 108°5′ E); Tham Mai cave, Laos (20.75 N, 102.65 E); Mawnluh cave, India (25°15′44″N, 91°52′54″E); and Qunf cave, Oman (17°10′ N, 54°18′ E).

2. Study Sites

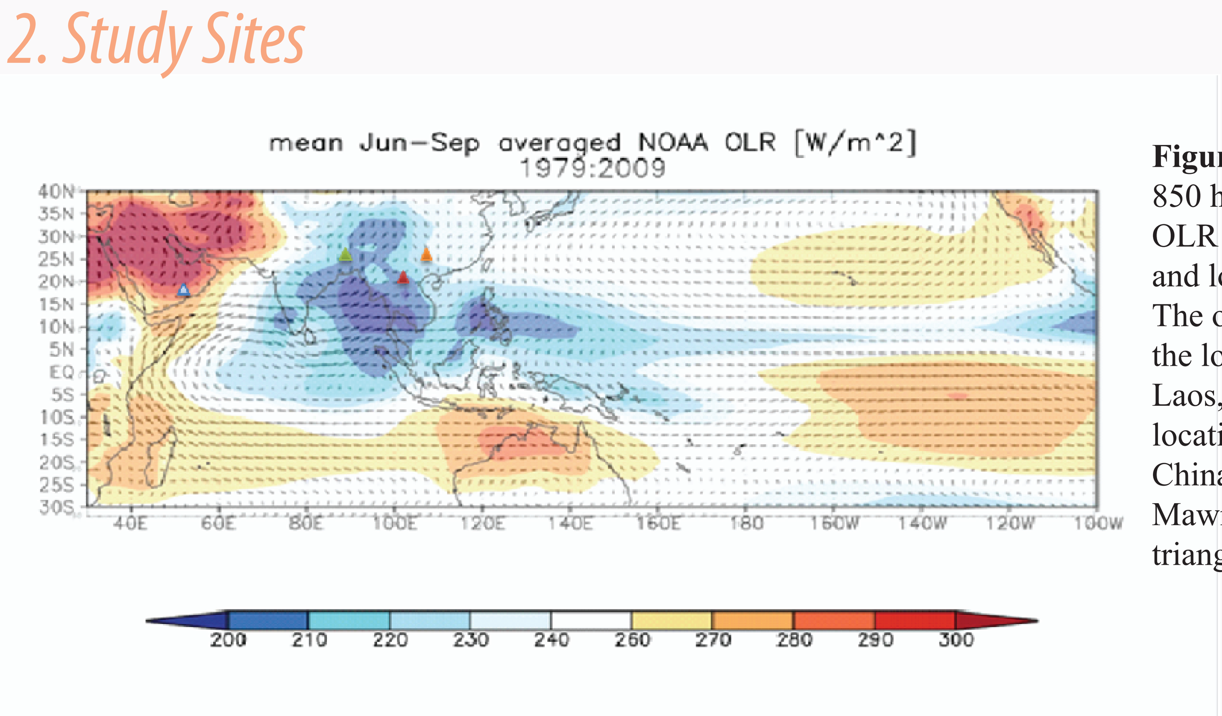

Figure 1. NCEP-NCAR JJAS 850 hPa wind vectors (m/s) and OLR averaged from 1979-2010 and locations of four cave sites. The orange triangle indicates the location of Tham Mai cave, Laos, red triangle is the location of Dongge Cave, China; green triangle is Mawmluh cave, India and blue triangle is Qunf Cave, Oman

3. Model validation

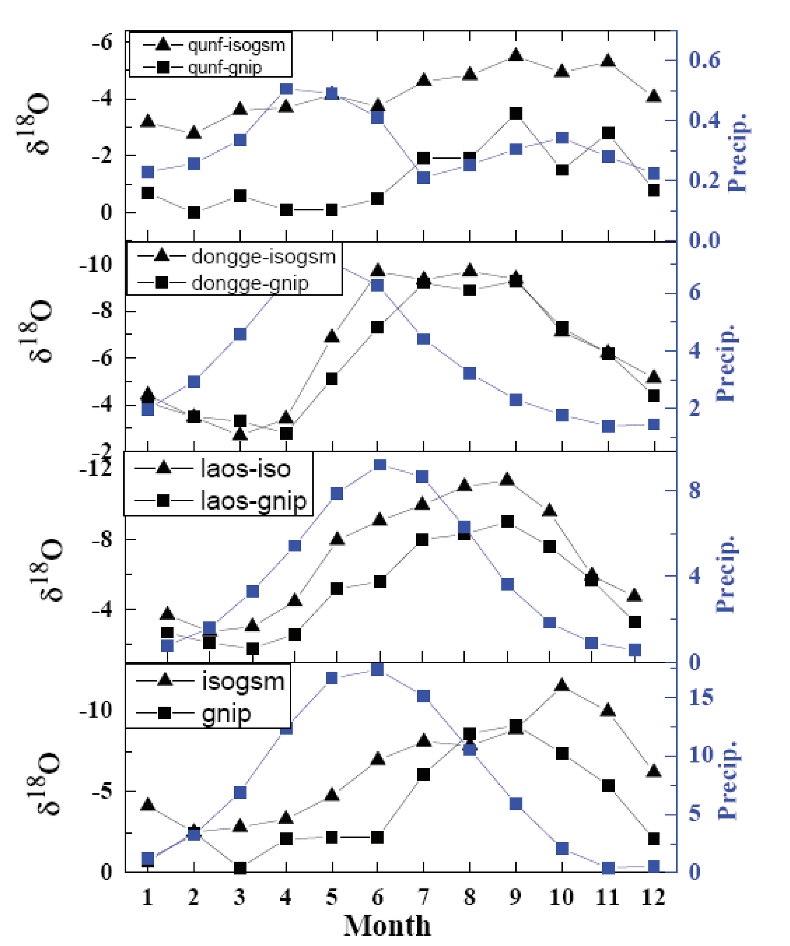

Figure 2. Monthly averages of GPCP precipitation(mm/day), GNIP $\delta^{18}O_p$, and 20th century IsoGSM $\delta^{18}O_p$ for four sites averaged from 1979-2009. a) Qunf Cave, Oman, b) Dongge Cave, China c) Tham Mai cave, Laos d) Mawmluh cave , India.

- Modeled $\delta^{18}O_p$ values match the seasonal cycle observed in GNIP data fairly well, though IsoGSM underestimates monthly $\delta^{18}O_p$ for some sites, especially for Qunf Cave, Oman.
- All four sites 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. Each site shows a significant negative correlation between monthly precipitation amount and $\delta^{18}O_p$ values.
- The maximum monthly precipitation for Tham Mai, Laos and Mawmluh Cave, India both occur during June, while precipitation peaks earlier for Qunf Cave, Oman (~April) and Dongge Cave, China (~May).
- Lowest $\delta^{18}O_p$ values exhibit a lag of about 2-3 months behind maximum precipitation

4. $\delta^{18}O$ systematics

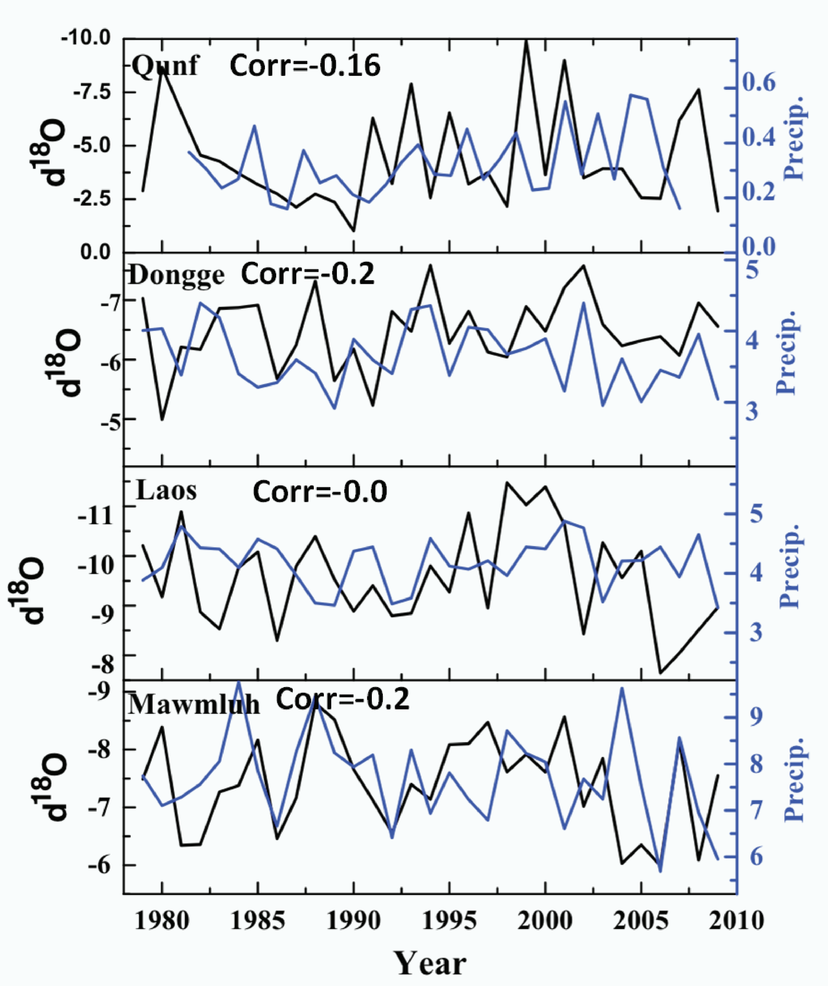

Figure 3. Time series of GPCP precipitation amount(mm/day) and precipitation $\delta^{18}O_p$ from the IsoGSM grid point closest to cave sites in the Asian monsoon region. a) Qunf Cave, Oman ,b)Dongge Cave, China c) Tham Mai cave,Laos d). d)Mawmluh cave , India.

Table 1. Composite averaged $\delta^{18}O_p$ and precipitation amount for El Niño, La Niña, and neutral ENSO years between1979-2010.

	Qunf	Dongge	Laos	Mawmluh
El Niño $\delta^{18}O_p$ ave.	-4.47	-6.26	-9.38	-7.13
La Niña $\delta^{18}O_p$ .ave.	-4.33	-6.77	-9.91	-7.79
Neutral $\delta^{18}O_p$ ave.	-4.56	-6.48	-9.56	-7.41
El Niño precip. ave.	0.26	3.49	3.98	7.30
La Niña precip.ave.	0.33	3.60	4.25	8.18
Neutral precip. ave.	0.32	3.65	4.17	7.69

- The time series indicate for all four cave locations, $\delta^{18}O_p$ has a low correlation (from 0-0.2) with local precipitation amount. This indicates that local precipitaion is not a major controlling factor for interannual $\delta^{18}O_p$ variability.
- Composite average of El Niño and La Niña year $\delta^{18}O_p$ shows that during El Niño years, Dongge, Tham Mai and Mawmluh caves have more negative $\delta^{18}O_p$ compared with La Niña years and neutral ENSO years.
- Composite average of Central Pacific (CP) type El Niño year $\delta^{18}O_p$ at Qunf cave shows that during CP El Niño year, Qunf cave has more positive $\delta^{18}O_p$ (-4.3) compared with neutral average $\delta^{18}O_p$ (-4.7), indicating that a CP El Niño signal in Qunf $\delta^{18}O_p$. Moreover, composite $\delta^{18}O_p$ at Qunf cave for the years following La Niña years (-5.2) is significantly different ($p<0.01$) from neutral year $\delta^{18}O_p$.

5. Statistical Analysis

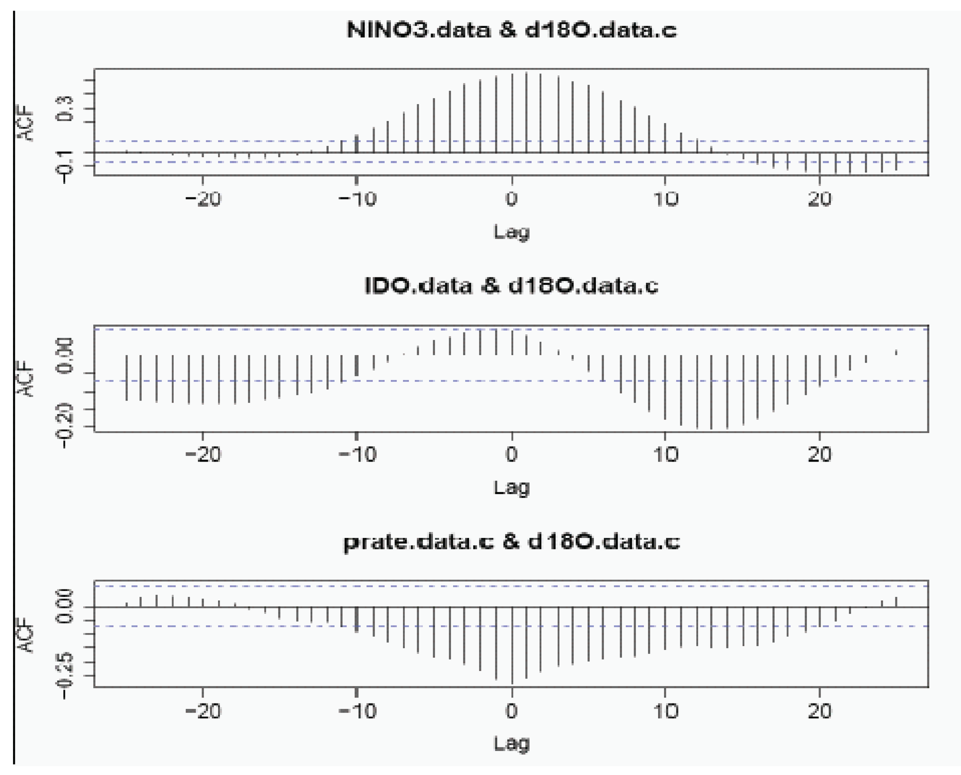

Figure 4. Cross correlation between annual cycle detrended NINO3.4 index(HadISST), IOD index(HadISST), local precipitation anomaly with long term trend removed (20th centery Iso GSM) and $\delta^{18}O$ anomaly with long term trend removed (20th centery Iso GSM) at our site from 1948-2009.

- Statistical analysis of the 20th century reanalysis nudged IsoGSM model was conducted to further investigate the controls on precipitation $\delta^{18}O_p$ at case site Laos Results show:
  - cross correlation between precipitaion and $\delta^{18}O_p$ anomaly from 1948-2009 is about -0.25
  - $\delta^{18}O_p$ anomaly of Laos is moderately correlated with the NINO3.4 index ($r = 0.53$) and with the IOD index at a lag of 1 year ($r = -0.35$)
  - Results indicate that the interannual to decadal scale variability may reflect coupled ocean-atmosphere modes that influence the precipitation $\delta^{18}O_p$, but not necessarily the amount of local precipitation.

6. Spatial correlations between modeled $\delta^{18}O_p$ and climate

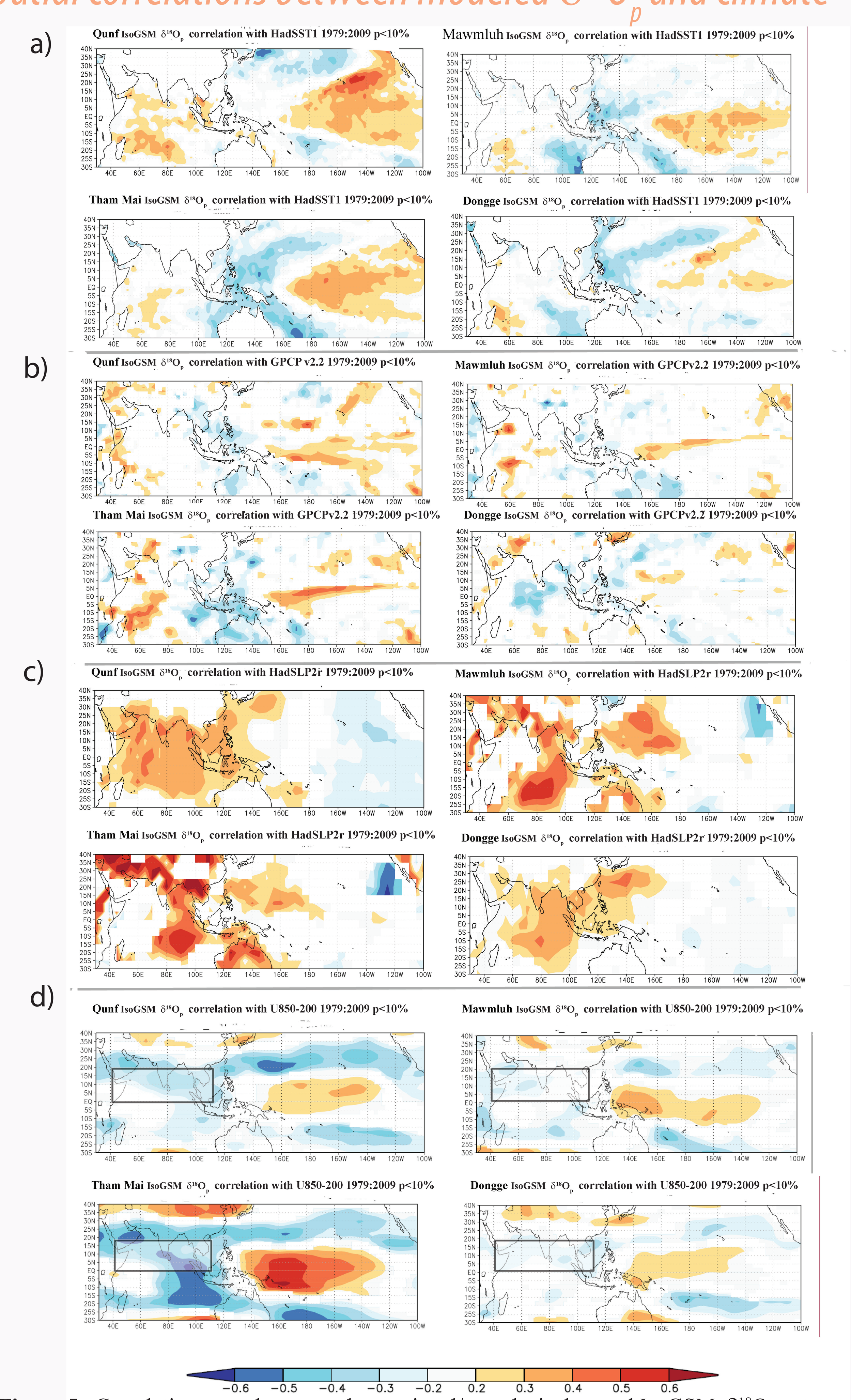

Figure 5. Correlation maps between observational/reanalysis data and IsoGSM $\delta^{18}O_p$ extracted from grid point closest to four cave sites in the Asian Monsoon and tropical Indo-Pacific region and four potential isotopic influential climatic factors for the period 1979-2010. Colors represent significant r value at the 90% level. a) correlation of HadSST1 with $\delta^{18}O_p$; b) correlation of GPCP with $\delta^{18}O_p$; c) correltaion of HadSLP2r with $\delta^{18}O_p$; d) correlation of NOAA u850_200 wind shear with $\delta^{18}O_p$. Box shown in part d is the region used for the Webster-Yang monsoon index (0-20N, 40-110 E).

- $\delta^{18}O_p$ extracted from the grid point closest to four cave sites shows very low correlation between $\delta^{18}O_p$ and local precipitation. $\delta^{18}O_p$ of Dongge cave reveals a negative correlation (0.4 to 0.5) with precipitation in the Bay of Bengal, which indicates $\delta^{18}O_p$ from East Asian monsoon area is affected by an integration of all precipitation amount through Indian-Asian monsoonal area and/or upstream distillation. Laos $\delta^{18}O_p$ exhibits a negative correlation with precipitation over the broad Indo-Pacific warm pool region, indicating increased convection over leads to more negative $\delta^{18}O_p$ over SE Asia. None of the cave sites show a significant correlation between local precipitation and $\delta^{18}O_p$, indicating that $\delta^{18}O_p$ is affected more by regional climatic factors than by local precipitation amount.
- $\delta^{18}O_p$ from IsoGSM at all fours sites, especially Qunf, Mawnluh, and Tham Mai cave, show a positive correlation with Pacific SSTs over the Nino 3.4 region and in the western and northern Indian Ocean, suggesting that the $\delta^{18}O_p$ of annual rainfall may be influenced by ENSO and IOD. Specifically, $\delta^{18}O_p$ of Qunf cave has a positive correlation with broad central Pacific and Indian ocean SST, indicating a central pacific type El Niño signal. Kao and Yu 2009 showed that CP El Niño is more likely to generate warming in Indian Ocean. Correlation between $\delta^{18}O_p$ of Mawmluh cave and SST shows a pure traditional Eastern Pacific (EP) El Niño signal. $\delta^{18}O_p$ of Tham Mai cave is associated with both EP El Niño and influence from northwestern Pacific subtropical high. Correlation between $\delta^{18}O_p$ of Dongge cave and SST indicates a weaker ENSO signal but more influence from northwestern subtropical high and local SST.
- $\delta^{18}O_p$ of all four sites have strong (corr >0.5) correlation with West Pacific and Indian ocean sea level pressure, indicating influence of sinking branch of Walker Circulation on $\delta^{18}O_p$ of four cave sites.