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Influence of Oceanic Teleconnections on the Indian Summer Monsoon During the Holocene and Younger Dryas: Insights from Paleo Records and Modeling

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Introduction & Motivation

- The Indian summer monsoon (ISM) displays significant variability across all timescales, ranging from inter-annual to centennial scales.
- Proxy records provide broad insights into the phases of oceanic phenomena over paleo-timescales. However, their limited temporal resolution poses challenges for closely comparing individual and multiple teleconnection pathways and their complex relationships with the ISM.
- By examining teleconnection pathways over extended time scales throughout the respective simulation periods, the study seeks to understand the impact of the AMO and PDO, Tropical-Pacific and Indian Ocean(IO) on ISM variability.
- The study aims to understand the impact of oceanic conditions on the Indian Summer Monsoon across major paleo-epochs, including EH, MH, and YD.

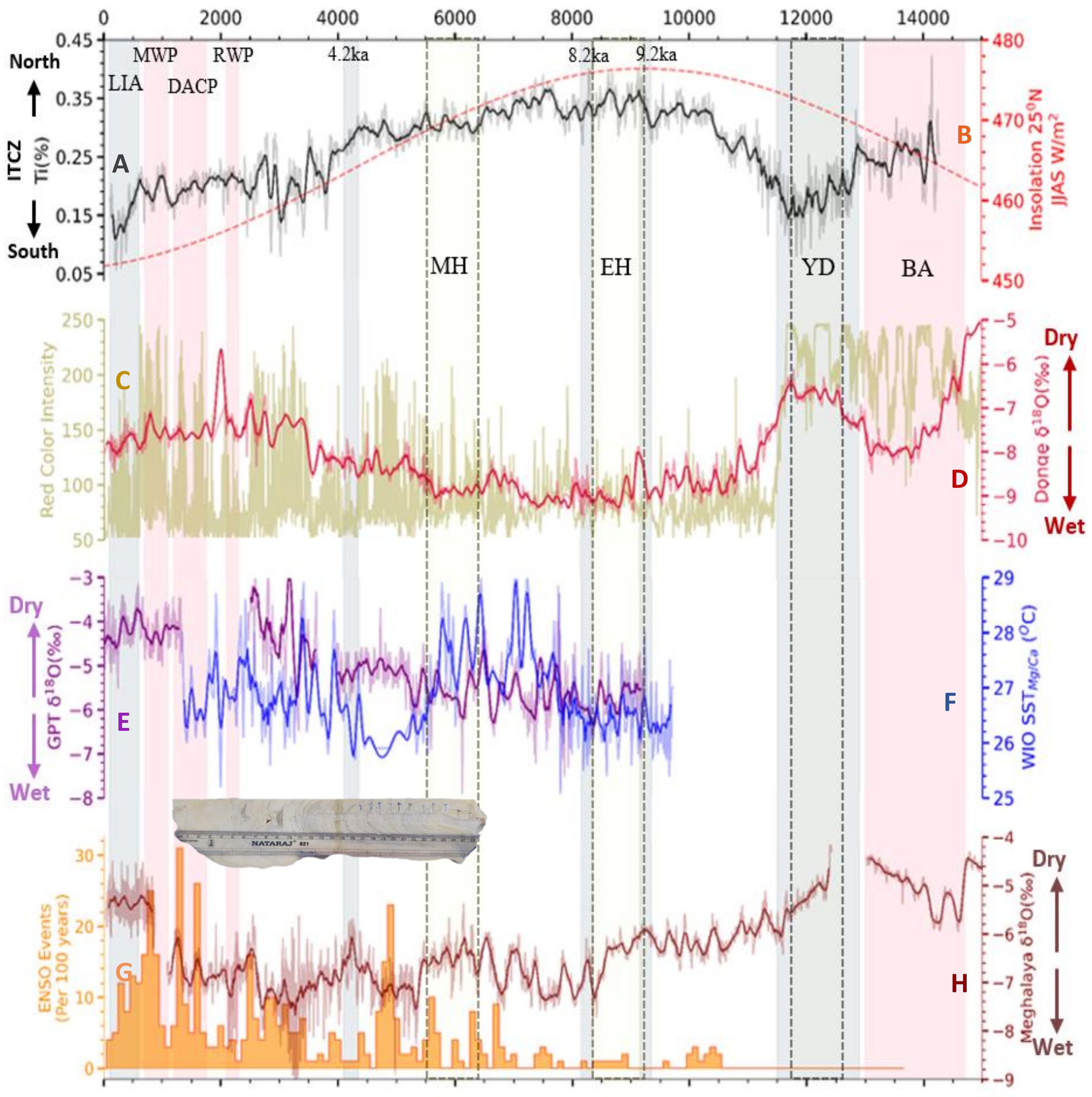

Fig 1: Comparison between MH, EH and YD climate reconstruction records from the Indian Summer Monsoon domain and surrounding regions.(A) Titanium (%) data from the anoxic Cariaco Basin, (B) Solar insolation for the 25 °N latitudes (*Lasker et al., 2004*) (C) Speleothem δ¹⁸O Dongge Cave (Dykoski et al., 2005), (D) Red color intensity from sediment cores in the Laguna Pallcacocha drainage basin (E) Gupteshwar Cave (GPT-5A, unpublished), (F) WIO SST (Mg/Ca) sediment data from the Pemba Channel (G) ENSO event frequency per 100 years, and (H) δ¹⁸O Mawmluh Cave, Cherrapunji Meghalaya.

Data & Methodology

Data

- **Sea Surface Temperature - TraCE-21K-II** Longitude – 3.6º ,Latitude- variable grid 1º to 1.5º
- **Precipitation(3.75º x 3.71º) – TraCE-21K-II**

Methodology

- For paleo-reconstruction, data from the Meghalaya cave Meg-2 (25.25°N, 91.71°E), located near Cherrapunji in North-East (NE) India used.
- The variability of oxygen isotopes (δ¹⁸O) in stalagmite samples, made use for the reconstruction.
- To support our analysis of the South Asian monsoons, we incorporated reconstructed data from Dongge Cave (**Wang et al., 2005**) and Gupteshwar Cave (unpublished data).
- In this study, four ocean basins were selected — the North Pacific, North Atlantic, Tropical Pacific, and North Indian Ocean — based on their potential influence on the Indian Summer Monsoon (ISM).
- The following paleoclimate epochs were chosen for analysis: the Mid-Holocene (6500–5500 years Before Present, BP), Early Holocene (9330–8330 BP), and Younger Dryas (12700–11700 BP).
- The EOF technique used to understand oceanic conditions such as the AMO, PDO, ENSO, and IOD. Additionally, regression and PCMCI+ analysis was performed to gain deeper insights into their teleconnection phases.

Results

Change in Precipitation

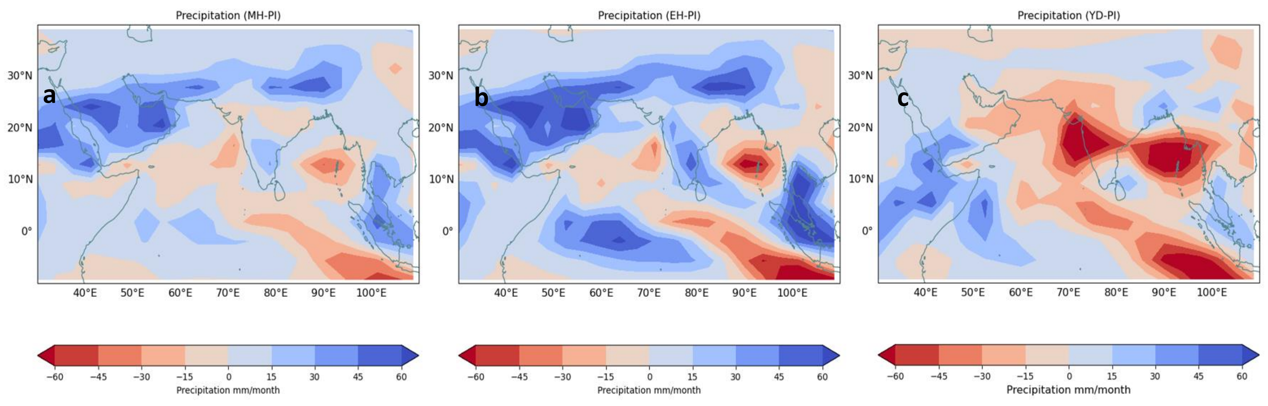

Fig 2: Change in Seasonal (JJAS) mean Precipitation (a) Mid-Holocene, (b) Early-Holocene, and (c) Younger-Dryas with respect to Pre-Industrial condition.

Time-series of Precipitation & SST for 22Ky BP

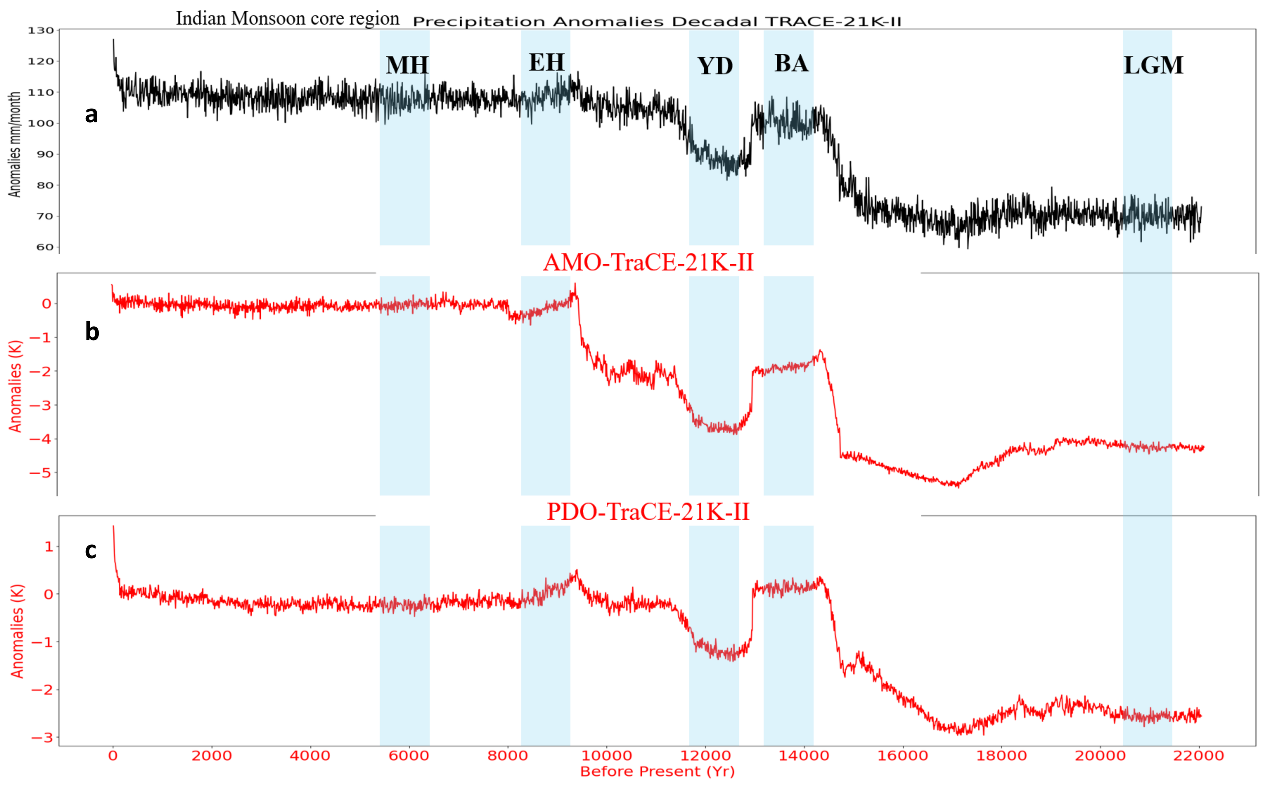

Fig 3: Time-series of 10 years running mean of seasonal (JJAS) anomalies (a) precipitation over Indian Monsoon core region, (b) AMO Index, and (C) PDO Index.

Oceanic conditions during MH, EH & YD

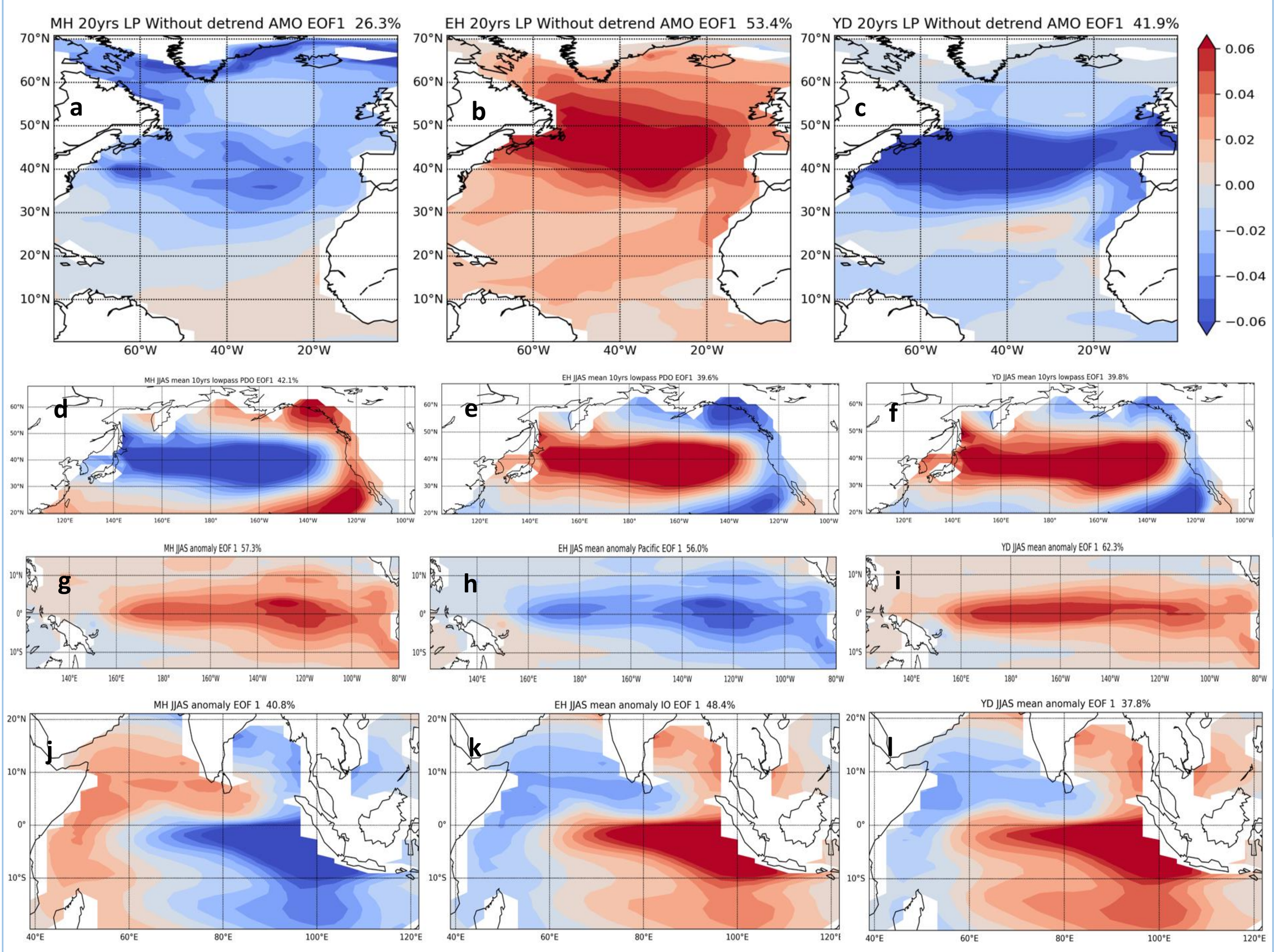

Fig 4: First mode of EOF: (a-c) AMO, (d-f) PDO, (g-i) Tropical-Pacific, and (j-l) for North Indian Ocean. left (a, d, g, j) for MH, centre (b, e, h, g) for EH, and right (c, f, i, l) for YD period.

Regression Analysis

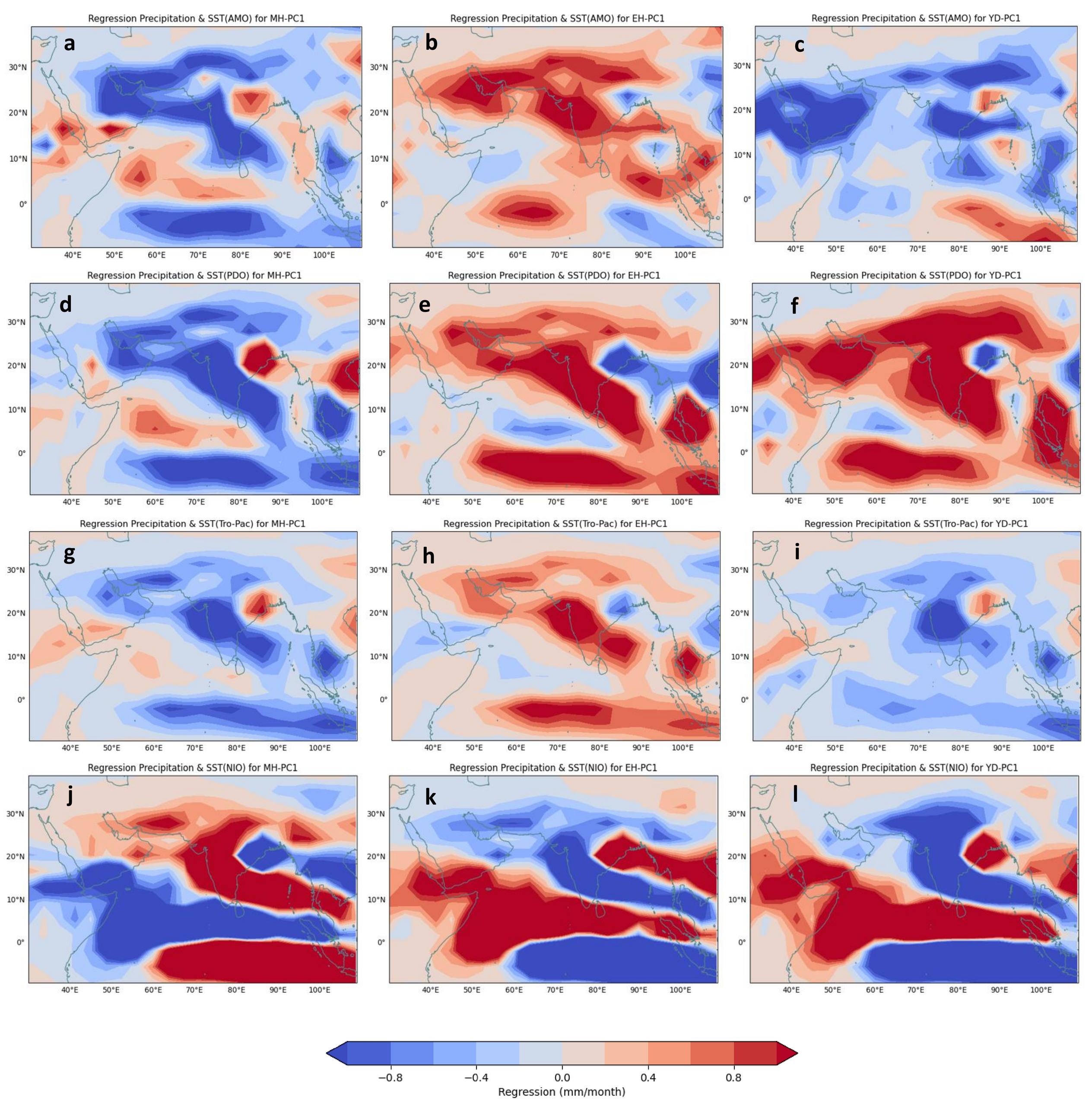

Fig 5: Regression between Precipitation and leading principle component of (a-c) AMO, (d-f) PDO, (g-i) Tropical Pacific. (j-l) Indian Ocean Dipole Mode Index (DMI). Column left (a, d, g, j) for MH, centre (b, e, h, g) for EH, and right (c, f, i, l) for YD period.

Inference from Causal analysis

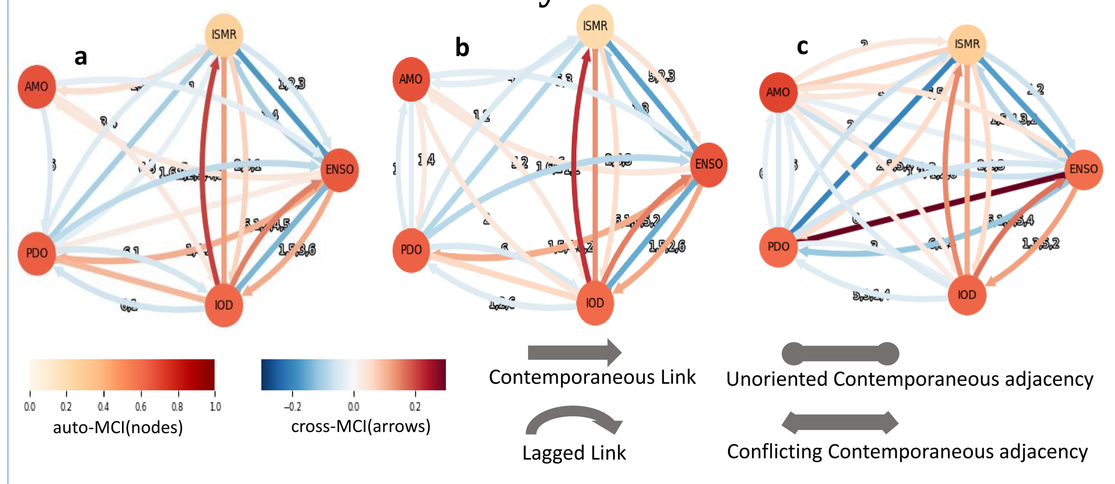

Fig 6: Causal links between the ISMR, AMO(NA), PDO, ENSO(Nino) and IOD on seasonal time-scales based on monthly anomalies of the indices for MJJASO season during the period, (a) MH, (b) EH and (c) YD obtained using the multivariate causal framework at 95% alpha level using the PCMCI+ causal inference algorithm.

Conclusion

The Indian monsoon was strong during the EH and moderately strong during the MH. In contrast, it weakened during the YD, as evidenced by δ¹⁸O proxy data and model analysis.

Following the dry phase of the YD, the Indian monsoon recovered. However, after the EH, monsoon rainfall decreased before recovering in the Late Holocene (Fig. 3a). The SST patterns of the AMO and PDO indices exhibit respective phases, indicating that long-term mean oceanic conditions are in phase in modulating the observed and simulated rainfall variability (Figs. 3b & c).

The dominant mode from the EOF analysis (Fig. 4) reveals that during the MH, conditions featured a cool or negative AMO, a positive PDO, and an El Niño-like state. These conditions may not have been favourable for ISMR, though a positive IOD might have provided some support. Conversely, during the EH, an opposite pattern emerged, with favourable conditions from the AMO, PDO, and Tropical Pacific, though the Indian Ocean was less supportive. Notably, only during the YD did the PDO exhibit a negative phase, potentially favourable for ISMR, even though other oceanic influences were less supportive.

Regression analysis further indicates that oceanic conditions during the MH were generally unfavourable for ISMR, except for the Indian Ocean (see Figs. 5a, d, g, j). In the EH, favourable conditions spanned most oceanic regions except the Indian Ocean (see Figs. 5b, e, h, k). In contrast, in the YD, favourable conditions were mainly limited to the North Pacific Ocean (Figs. 5c, f, i, l).

From the causal analysis, it is evident that the IOD positively influences ISMR, while ENSO and PDO have a negative impact across all three events. However, AMO does not show a clear causal link with ISMR during the MH and EH, although it generally drives ISMR positively.

Acknowledgment & References

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