Proxy-Model Constraints on Holocene Indian Summer Monsoon Variability and Seasonality in Northwest India

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Background & Motivation

- Northwest (NW) India shows strong spatial heterogeneity in paleoclimate records. Specifically, the relative roles of summer vs. winter monsoon in mid-Holocene precipitation remain unclear.
- This region, occupied by Indus Civilization in the past, provides a valuable context for understanding climate-cultural relationships.
- This study compares multi-proxy lake records with PMIP4 simulations to assess seasonal rainfall contributions.

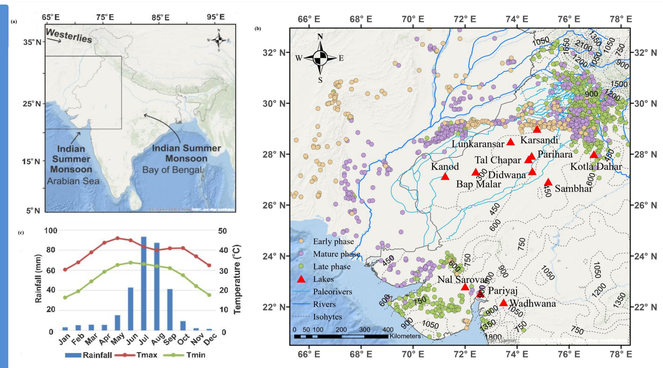


Figure 1: Study area and hydroclimate of South Asia. (a) Study region and moisture sources. (b) Thar Desert map showing Indus settlements, rivers, paleolakes, and isohyets (1995–2024). (c) Monthly rainfall and temperature (Tmax, Tmin) climatology. Thar Desert receives ~267 mm annual rainfall, ~87% during JJAS.

Model Performance Evaluation

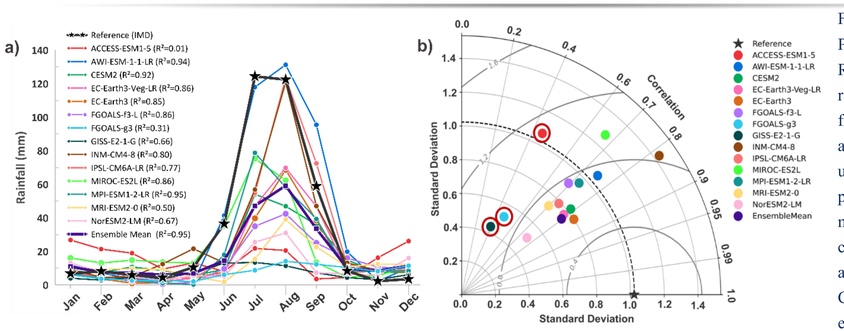


Figure 2: Evaluation of Model Performance in Simulating Seasonal Rainfall over NWI: (a) Monthly rainfall climatology (1901–2014) from IMD, PMIP4–CMIP6 models, and the ensemble mean. Most models underestimate precipitation amounts, particularly during the monsoon peak months. (b) Taylor diagram comparing spatial model performance against IMD gridded data using SD, CC, and RMSE. Circled models are excluded from further analysis.

Spatial distribution of hydroclimate anomalies during the mid-Holocene (MH) relative to the pre-Industrial period (PI)

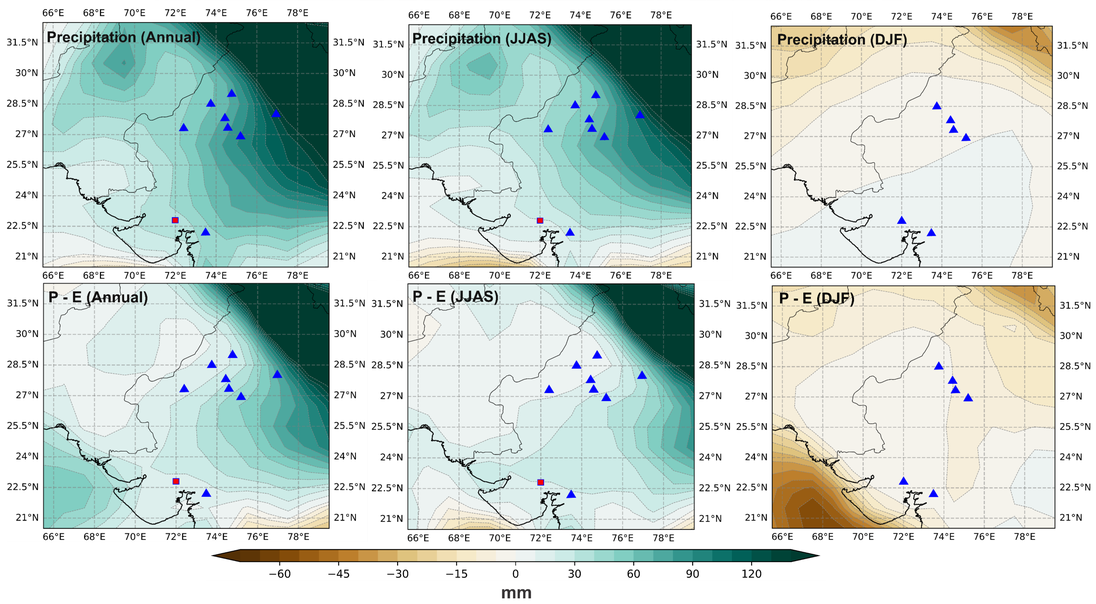


Figure 3: PMIP4 ensemble-mean anomalies of precipitation and P–E (MH vs. PI) compared with paleorecords. Symbols denote wet (blue triangles), dry (red inverted triangles), and mixed conditions (blue-red squares). Both indicate wetter annual conditions in the MH, with higher lake levels driven mainly by enhanced JJAS monsoon rainfall. Proxies and models also suggest a secondary winter (DJF) contribution in the southern Thar but weaker/declining trend in the north, highlighting spatial heterogeneity.

Seasonality in mid-Holocene precipitation

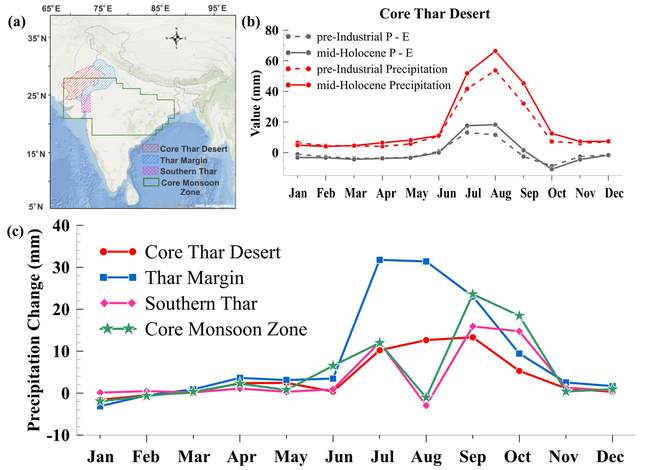


Figure 4: Monthly precipitation and P–E anomalies (MH vs. PI) show strongest JJAS increases in the Thar and margins, with rising pre/post-monsoon rainfall. Winter rainfall mostly declines, except for a slight increase in the southern Thar, indicating spatial heterogeneity.

Model-proxy comparison at lake locations

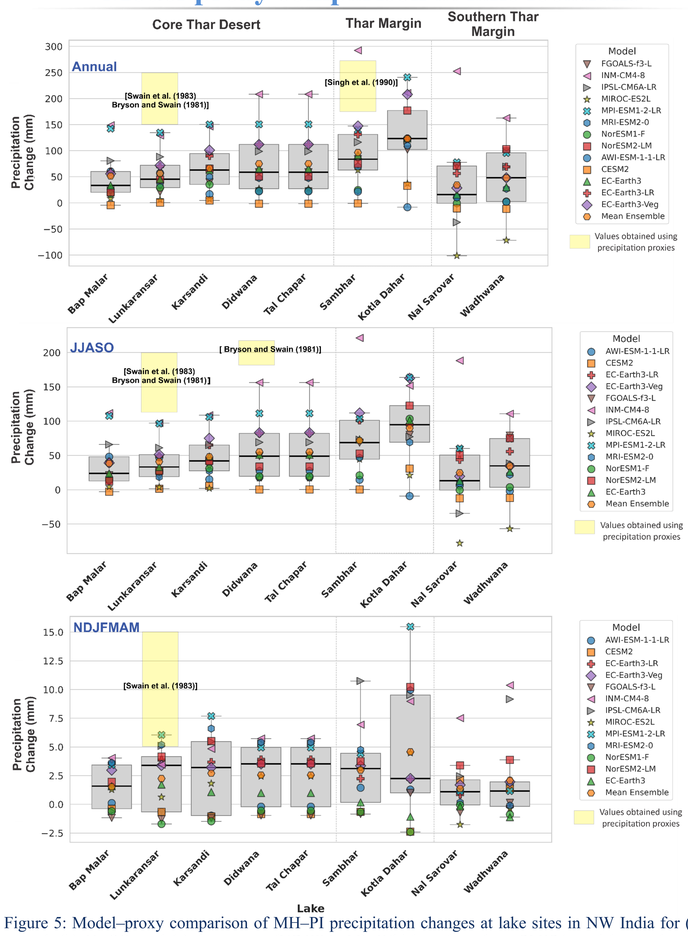


Figure 5: Model–proxy comparison of MH–PI precipitation changes at lake sites in NW India for (a) annual, (b) JJASO, and (c) dry season (NDJFMAM). Whisker plots show PMIP4 model spread, with proxy-based estimates plotted for comparison. Both indicate wetter MH conditions with stronger monsoon increases with a clear north-south contrast. Models capture the direction of change but underestimate magnitude relative to pollen-based estimates.

Seasonal moisture source analysis

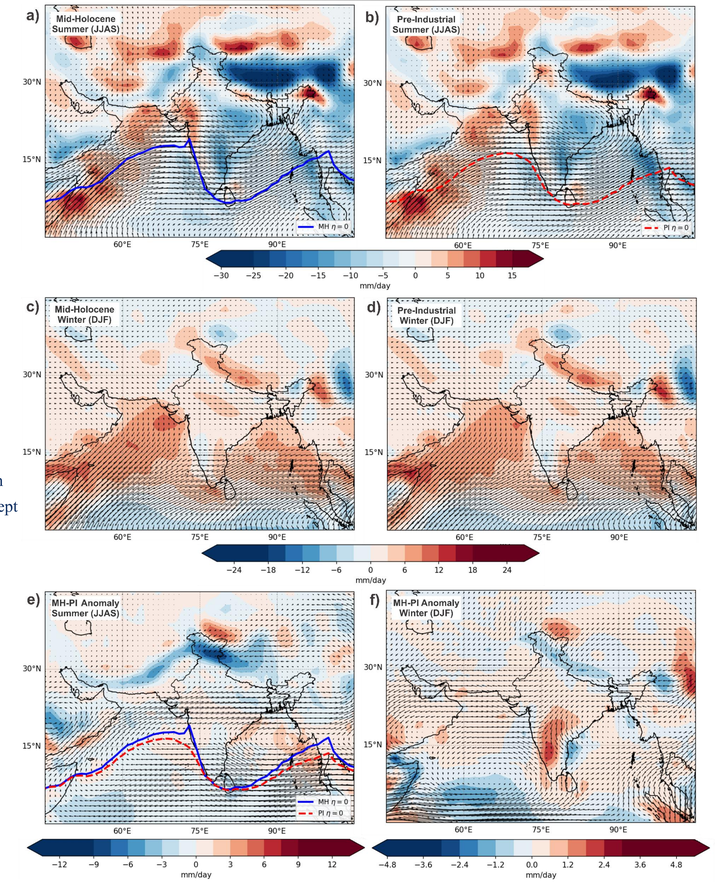


Figure 6: Spatial patterns of moisture flux convergence (DivQ) and IVT (PMIP4 ensemble mean) for MH vs. PI, with ISM low-level jet (LLJ) position (η = 0) shown for MH (blue) and PI (red). A northward shift of the ITCZ/LLJ strengthened Arabian Sea moisture transport, enhancing JJAS rainfall, highlighting strong northward advection and spatial heterogeneity. Westerlies weakened compared to PI.

Conclusion & Future Work

- PMIP4 model results show strong agreement with proxy data on strengthened summer monsoon across the Thar Desert during mid-Holocene, with north receiving double the effective precipitation than south.
- Mid-Holocene hydroclimate was driven by a stronger ISM, northward-shifted ITCZ and LLJ enhancing Arabian Sea moisture transport, combined with seasonal redistribution of rainfall and weakened westerlies, producing spatially heterogeneous moisture patterns across the Thar.
- Spatial and seasonal differences likey influenced settlement patterns and distinct cropping strategies across zones in NW India.
- Future work will use high-resolution proxy records to help develop paleo-constrained hydroclimate projections.

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Abstract

Feedback

Please feel free to share your thoughts or questions.