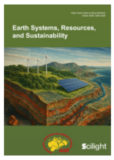
Earth Systems, Resources, and Sustainability, 2026, 1(4), 416–440

Scilight **Earth Systems, Resources, and Sustainability**

Journal Homepage: https://www.sciltp.com/journals/esrs



Article

Quaternary Hydroclimate Evolution of the Indian Subcontinent: A Multi-Archive Framework for Interpreting Monsoon Variability and Proxy-System Behaviour

Monmohan Gogoi* and Diganta Bhuyan

Department of Applied Geology, Dibrugarh University, Dibrugarh 786004, Assam, India

*Correspondence: monmohan017@gmail.com

ABSTRACT

The Indian subcontinent preserves diverse Quaternary palaeoenvironmental archives that record Indian Summer Monsoon (ISM) variability across contrasting climatic and environmental settings. This review synthesizes speleothem, lacustrine, marine, fluvial, aeolian, cryospheric, ecological, and archaeological evidence within a multi-archive framework that explicitly considers proxy sensitivity, archive filtering, chronological uncertainty, and spatial heterogeneity. Multi-archive evidence indicates weakened monsoon circulation during the Last Glacial Maximum, rapid deglacial reorganization including the Younger Dryas, and widespread monsoon intensification during the early Holocene. The subsequent middle-to-late Holocene was characterized by generally declining monsoon strength superimposed by substantial centennial-scale variability. Hydroclimatic instability around 4.2 ka was regionally important but spatially heterogeneous and not uniformly expressed among archives, while the late Holocene and last millennium experienced recurrent drought–wet variability. A central outcome of this synthesis is that apparent disagreement among palaeoclimate records does not necessarily represent contradictory climate histories. Different archives record distinct components of hydroclimate and transform climatic forcing through seasonality, hydrological storage, sediment mixing, ecological response, temporal integration, and other archive-specific processes. Consequently, speleothem, lacustrine, marine, fluvial, and Himalayan records are most informative when interpreted as complementary constraints rather than directly interchangeable climate indicators. Future progress requires process-based and uncertainty-aware integration through proxy-system and isotope-enabled modelling, climate data assimilation, standardized multi-archive networks, and coordinated terrestrial–marine synthesis. This framework portrays the ISM as a spatially heterogeneous and dynamically coupled hydroclimatic system and provides a long-term context for evaluating contemporary hydroclimatic change across South Asia.

ARTICLE INFO

History:

Received 16 May 2026
Revised 11 August 2026
Accepted 16 August 2026
Published: 1 September 2026

Keywords:

Indian Summer Monsoon;
Quaternary palaeoclimate;
hydroclimate;
proxy system model;
Indian subcontinent;
Holocene

Citation:

Gogoi, M.; Bhuyan, D. Quaternary Hydroclimate Evolution of the Indian Subcontinent: A Multi-Archive Framework for Interpreting Monsoon Variability and Proxy-System Behaviour. *Earth Systems, Resources, and Sustainability* **2026**, *1*(4), 416–440. https://doi.org/10.53941/esrs.2026.100024

Research Highlights

- Multi-archive synthesis reveals spatially heterogeneous Quaternary monsoon evolution across India.
- Archive-specific filtering explains major divergences among Indian palaeoclimate records.
- The 4.2 ka hydroclimatic transition was regionally significant but spatially non-uniform.
- Quaternary records reveal a dynamically coupled and non-stationary Indian monsoon system.
- Process-based modelling and data assimilation offer a pathway for future hydroclimate reconstruction.

1. Introduction

The Quaternary Period (2.58 Ma to the present) is characterized by repeated glacial–interglacial cycles, large-amplitude changes in atmospheric circulation, cryospheric extent, sea level, and hydrological regimes that have profoundly influenced terrestrial and marine environments worldwide. Therefore, Quaternary climate variability is fundamental not only to palaeoclimatology, but also to geomorphology, hydrology, archaeology, and future climate-risk assessment. The South Asian monsoon occupies a particularly important position among the world's major climate systems due to its role in redistributing heat and moisture between the tropical oceans and the Asian continent as well as its direct societal significance for the Indian subcontinent [1, 2]. This review synthesizes Quaternary hydroclimate evolution across the Indian subcontinent through a multi-archive framework that explicitly considers how archive-specific sensitivities, filtering processes, and chronological uncertainties influence the reconstruction of monsoon variability.

The Indian Summer Monsoon (ISM) provides most of the annual precipitation across large parts of South Asia and exerts first-order control on river discharge, groundwater recharge, ecosystem functioning, agriculture, and water security for more than a billion people. Instrumental observations demonstrate substantial variability from seasonal to multidecadal timescales, but the observational record is too short to constrain the full range of natural hydroclimatic behaviour, including low-frequency variability, megadrought recurrence, and abrupt monsoon reorganizations. Geological and biological archives are therefore critical for reconstructing long-term monsoon evolution under contrasting climatic boundary conditions [3, 4].

The Indian subcontinent offers one of the world's most diverse Quaternary archive networks because of its strong climatic gradients, tectonic complexity, extensive coastlines, and varied geomorphology. From Himalayan glaciers and Indo-Gangetic fluvial systems to peninsular and southern Indian lakes, northeast Indian karst terrains, the Thar Desert, coastal environments, and adjoining marine basins of the Arabian Sea, Bay of Bengal, and Andaman sector, the region preserves a wide range of palaeoenvironmental records, including speleothems, lake sediments, peat sequences, dune systems, marine sediment cores, glacial deposits, and archaeological stratigraphies [5–8]. Advances in uranium–thorium geochronology, luminescence dating, stable-isotope geochemistry, biomarker analysis, and numerical modelling have substantially improved temporal resolution and regional synthesis during the last two decades. Major Quaternary archive systems and dominant atmospheric circulation pathways relevant to Indian hydroclimate reconstruction are shown in Figure 1.

High-resolution speleothem records from Mawmluh and Sahiya caves provide evidence of Indian monsoon variability during the Younger Dryas, the Holocene, the 4.2 ka interval, and the last millennium [9–11]. Lake records from northwest India have changed the understanding of the hydroclimatic conditions relevant to Indus Civilization landscapes [7, 12]. Arabian Sea and Indus-margin marine archives show strong interlinking with monsoon variability and wider ocean–atmosphere circulation systems [5, 6]. Recent studies indicate the importance of tropical Indo-Pacific teleconnections, Himalayan cryosphere interactions, and abrupt deglacial transitions in defining the evolution of Indian hydroclimate [13–15].

Despite these advances, a major interpretative challenge remains: different archives can produce contrasting reconstructions of the same climatic interval because they record different components of the hydroclimate system, respond over different timescales, and preserve signals through distinct physical and biogeochemical pathways. For example, speleothem $\delta^{18}O$ may integrate changes in rainfall, moisture source, recharge seasonality, and karst hydrology, whereas lacustrine and marine proxies commonly reflect combinations of water balance, sediment routing, runoff, salinity, circulation, and ecological response [16, 17]. Apparent disagreement among records may therefore arise from differences in proxy sensitivity, chronological uncertainty, temporal integration, storage effects, and genuine spatial heterogeneity rather than from mutually incompatible climate histories.

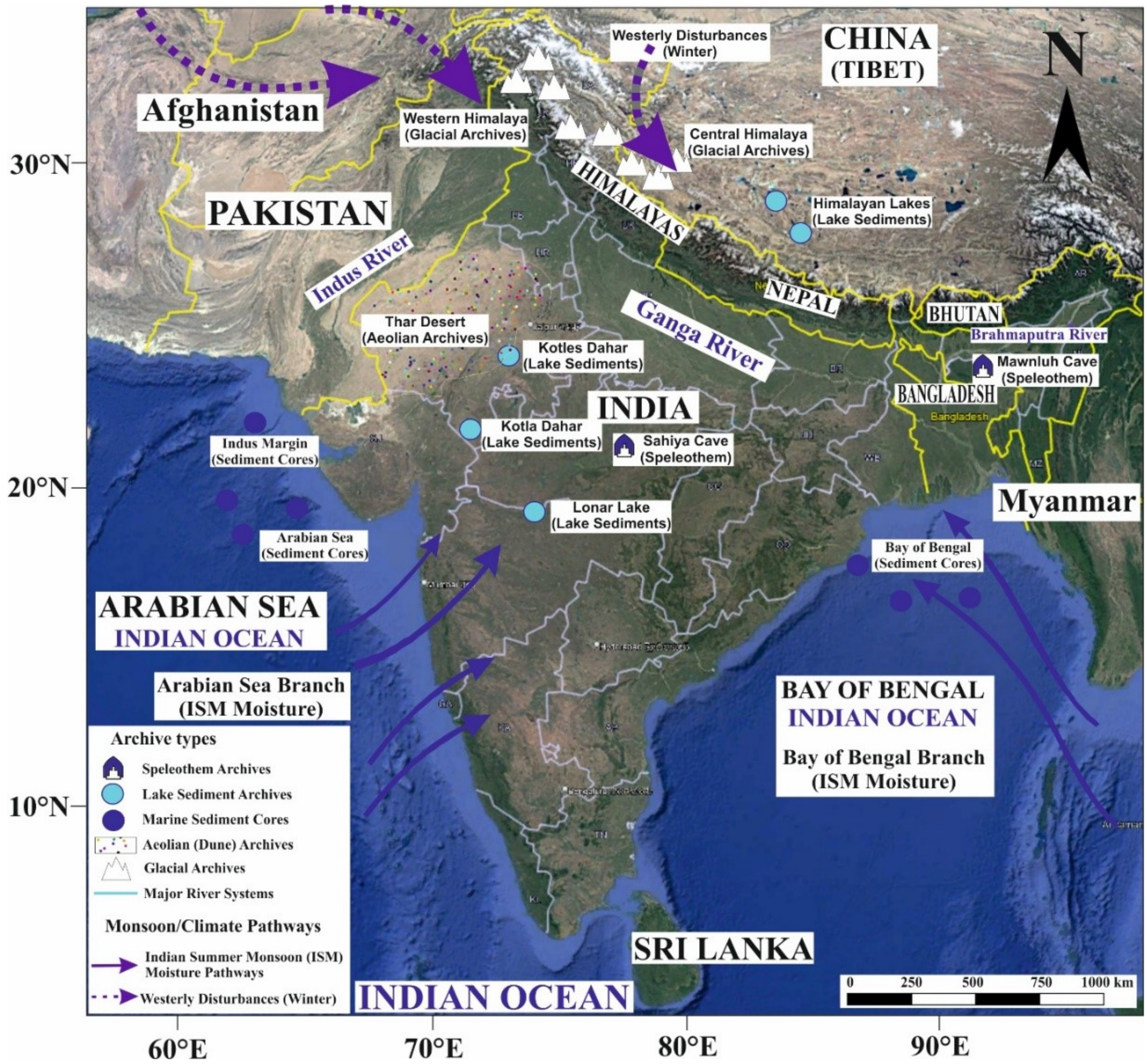


Figure 1. Major Quaternary palaeoenvironmental archives and hydroclimatic pathways across the Indian subcontinent. The figure illustrates the distribution of representative speleothem, lake-sediment, marine, aeolian, and glacial archives with major ISM moisture pathways from the Arabian Sea and Bay of Bengal, winter westerly disturbances affecting the Himalaya, and major river systems including the Indus, Ganga, and Brahmaputra.

Against this background, the review has four specific objectives: (i) to evaluate the principal terrestrial and marine archives used in Indian Quaternary hydroclimate reconstruction; (ii) to synthesize major phases of monsoon and hydroclimate evolution from the Late Pleistocene to the recent period; (iii) to examine why apparently coeval records may diverge by considering archive sensitivity, temporal resolution, chronology, and environmental filtering; and (iv) to assess emerging approaches, including proxy-system modelling, isotope-enabled simulations, and climate data assimilation, for improving multi-archive synthesis. Rather than treating individual archives as competing reconstructions, the review evaluates them as complementary records of different components of a spatially heterogeneous hydroclimate system, with broader implications for interpreting monsoon variability across South Asia.

2. Geological and Climatic Controls on Hydroclimate Variability Across the Indian Subcontinent

The hydroclimate evolution of the Indian subcontinent represents a complex interaction of tectonic architecture, monsoon circulation, cryosphere dynamics, ocean–atmosphere coupling, and regional physiography. Situated between the Indian Ocean and the Himalayan–Tibetan highlands, South Asia receives one of the world's most energetic seasonal circulation systems and is highly sensitive to insolation forcing, sea-surface temperature variability, glacial boundary conditions, and remote climate teleconnections [1, 8]. Therefore, Indian Quaternary archives preserve both regional hydroclimatic variability and broader responses to large-scale climate-system reorganization.

2.1. Tectonic and Physiographic Framework

The modern physiography of the Indian subcontinent largely reflects India's Cenozoic collision with Eurasia and subsequent upliftment of the Himalayan–Tibetan system. The Himalaya acts as both a thermal and mechanical barrier, intensifying orographic precipitation and modulating seasonal pressure gradients crucial for monsoon circulation. Long-term uplift of the Himalayan–Tibetan region is widely considered to play a major role in the evolution of Asian monsoon [18], although the timing, magnitude, and underlying mechanisms of this influence remain debated.

The Indian subcontinent contains several contrasting geomorphic and physiographic domains, including the Himalayan mountain belt, Indo-Gangetic foreland basin, Peninsular Indian shield, Thar Desert, northeast Indian karst terrains, coastal plains, and adjoining marine basins of the Arabian Sea and Bay of Bengal. These regions differ substantially in rainfall regime, sediment routing, hydrology, and archive preservation potential. Himalayan environments preserve glaciers, moraines, and high-altitude lake systems sensitive to changes in both precipitation and temperature, whereas the Indo-Gangetic basin records fluvial migration, sediment flux, and floodplain evolution. Peninsular India contains diverse lacustrine, peat, cave, and coastal archives, including records from the Western Ghats and southern India that capture regional variations in southwest and northeast monsoon influence. Marine sediments from the Arabian Sea, Bay of Bengal, and Andaman sector provide complementary records of monsoon-driven changes in circulation, freshwater discharge, productivity, and continental environmental conditions. Representative Quaternary archive systems distributed across the Indian subcontinent and their principal climatic interpretations are summarized in Table 1. The representative records are selected to capture the major geographical sectors and principal terrestrial and marine archive systems relevant to Quaternary hydroclimate reconstruction across the Indian subcontinent and adjoining marine regions. Although palaeoenvironmental and archaeological records from Sri Lanka and the Maldives provide important complementary evidence for South Asian monsoon variability, coastal evolution, and Holocene sea-level change, the present synthesis focuses primarily on the Indian subcontinent and its adjoining marine sectors; these records are therefore considered selectively rather than comprehensively. The compilation is not intended to be exhaustive; priority is given to records with adequate chronological control, clearly established proxy–environment relationships, sufficient temporal coverage or resolution for the climatic interval considered, and demonstrated relevance to regional monsoon or hydroclimatic variability. Geographical representation and diversity of archive type are also considered to facilitate comparison among proxy systems with different sensitivities and response characteristics.

Table 1. Representative Quaternary palaeoclimate archives across the Indian subcontinent and adjoining marine regions, showing their principal proxy systems and hydroclimatic interpretations.

Region	Archive	Approx. Age Range	Key Proxy	Climatic Interpretation	Representative Studies
Northeast India (Meghalaya)	Speleothems (Mawmluh Cave)	Holocene–Recent	δ^{18}O, trace elements, laminae	ISM intensity, abrupt hydroclimatic events, 4.2 ka variability	[3, 9, 10, 19]
Northern India (Uttarakhand)	Speleothems (Sahiya Cave)	Late Holocene–Recent	δ^{18}O	Last-millennium monsoon variability and megadroughts	[4, 11]
Northwest India (Haryana–Rajasthan)	Lake sediments (Kotla Dahar and related basins)	Holocene	Salinity indicators, isotopes, sedimentology	Effective moisture balance and late-Holocene aridification	[7, 12]
Thar Desert	Dune and aeolian deposits	Late Quaternary	Grain size, luminescence ages	Aridity fluctuations and monsoon-margin shifts	[20, 21]
Central Himalaya	Lake and glacial archives	Late Quaternary–Holocene	Sediment flux, isotopes, geomorphology	Monsoon–westerly interaction and hydroclimate variability	[14]

Table 1. *(Continued).*

Region	Archive	Approx. Age Range	Key Proxy	Climatic Interpretation	Representative Studies
Western Himalaya	Glacier and moraine systems	Late Quaternary–Holocene	Glacier extent, cosmogenic dating	Temperature and snowfall variability	[22, 23]
Ganga Plains	Fluvial/alluvial archives	Late Quaternary–Holocene	Sedimentation, palaeochannels	River dynamics and monsoon-driven discharge variability	[18]
Peninsular India (Lonar Lake)	Lake sediments	Holocene	Geochemistry, pollen, isotopes	Holocene monsoon variability and environmental change	[24]
Southern India (Western Ghats)	Lake sediments (Pookode Lake)	∼6.2 ka–Recent	Sediment texture, geochemistry/CWI, phytoliths, pollen, diatoms	SW monsoon variability, lake hydrology, vegetation and catchment response	[25]
Southeastern India	Coastal sediments	Holocene	Sedimentology, geochemistry and multi-proxy indicators	Coastal palaeoenvironmental and hydroclimatic variability	[26]
Arabian Sea	Marine sediment cores	Late Quaternary–Holocene	Upwelling indicators, foraminifera, isotopes	Regional monsoon circulation and wind intensity	[1, 5]
Eastern Arabian Sea	Marine sediment cores	∼200 ka	Pollen, $\delta^{18}O$, organic carbon	Glacial–interglacial monsoon, precipitation, vegetation and surface-ocean hydrographic variability	[27]
Indus Margin/Arabian Sea	Marine sediments	Holocene	Terrigenous flux, isotopes	Hydroclimatic reorganization near 4.2 ka	[6]
Bay of Bengal	Marine sediment cores	Late Quaternary–Holocene	Salinity proxies, runoff indicators	River discharge and monsoon rainfall variability	[28, 29]
Andaman Islands/Bay of Bengal	Marine sediments	Middle–Late Holocene	Planktic foraminifera, pteropods, isotopes, sedimentary/geochemical proxies	Monsoon-related freshwater input, stratification, thermocline and productivity variability	[30, 31]
Central India	Peat and wetland archives	Late Quaternary–Holocene	Pollen, organic matter, charcoal	Vegetation response and hydroclimate variability	[21, 32, 33]

2.2. Monsoon Circulation and Seasonal Hydroclimate

The dominant climatic feature of South Asia is the seasonal reversal of winds associated with the monsoon system. During boreal summer, continental heating generates low pressure over the Asian landmass, drawing moisture inland from the Arabian Sea, Bay of Bengal, and equatorial Indian Ocean. The resulting ISM supplies most annual rainfall across large parts of the subcontinent.

Two principal moisture pathways characterize the summer monsoon: the Arabian Sea branch affecting western and central India, and the Bay of Bengal branch supplying eastern India, northeast India, and the Himalayan foothills. Orographic uplift along the Western Ghats, Khasi Hills, and Himalayan front produces strong spatial rainfall gradients, ranging from hyper-arid conditions in northwest India to some of the world's highest precipitation totals in Meghalaya. The major circulation pathways, seasonal ITCZ migration, and interactions between monsoon branches, westerlies, and topographic barriers are illustrated schematically in Figure 2.

This seasonality has important implications for palaeoclimate interpretation because archives differ in the seasonal and hydrological components they preferentially record. Speleothems may preferentially reflect summer recharge, lakes commonly integrate water balance over longer periods, and Himalayan systems may preserve varying combinations of summer-monsoon and winter-westerly influences [16].

2.3. Orbital Forcing, Glacial Boundary Conditions and Teleconnections

On Quaternary timescales, orbital forcing exerted a first-order control on monsoon intensity through modulation of Northern Hemisphere summer insolation and land–sea thermal contrast. Asian speleothem syntheses indicate strong correspondence between precessional insolation variability and monsoon strength [8]. During glacial intervals, expanded ice sheets, reduced greenhouse-gas concentrations, lower sea-surface temperatures, and reduced atmospheric moisture transport generally weakened monsoon circulation. Warmer ocean conditions do not necessarily produce stronger monsoon circulation. Evidence from the Last Interglacial indicates that elevated Indian Ocean sea-surface temperatures could weaken the South Asian monsoon by reducing the land–sea thermal contrast, illustrating the nonlinear influence of oceanic boundary conditions on monsoon strength [34]. Associated glacial–interglacial sea-level changes modified coastline position, continental-shelf exposure, land–sea geometry, and sediment routing around the subcontinent. These changes are particularly relevant to coastal and marine archives because variations in depositional setting and freshwater–marine connectivity may influence the recorded palaeohydroclimatic signal in addition to atmospheric monsoon forcing.

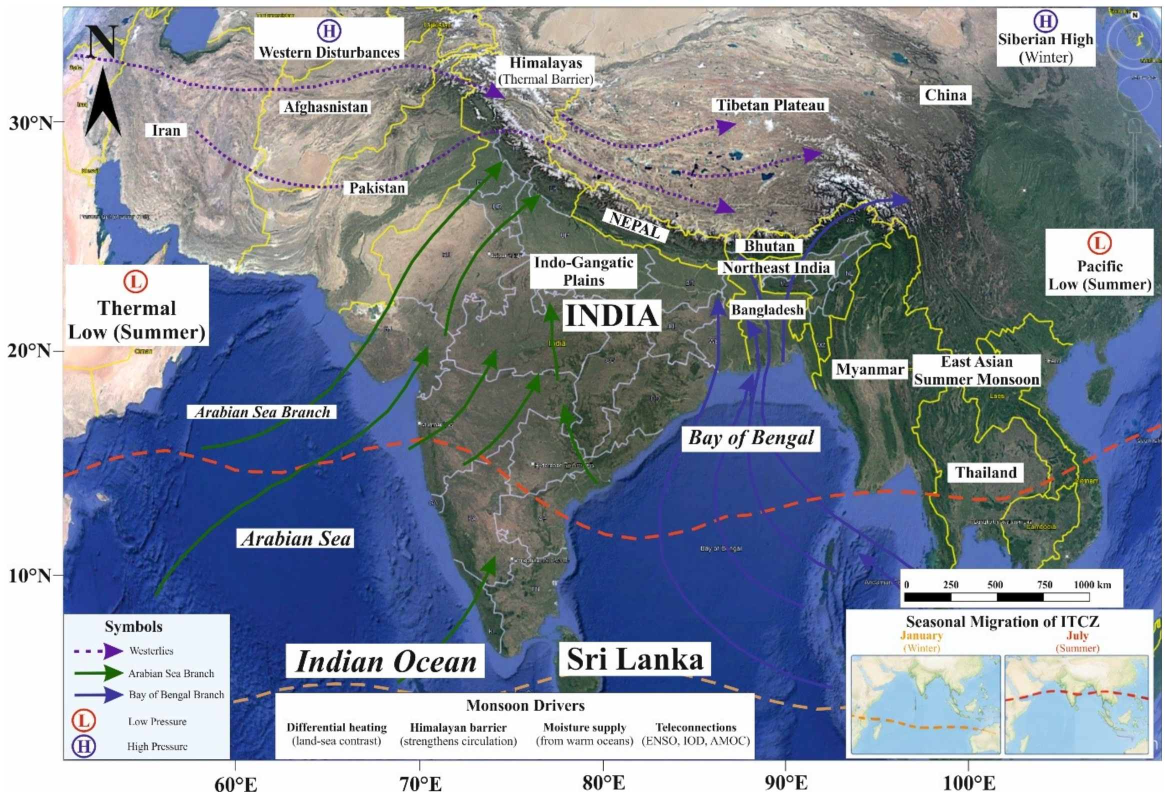


Figure 2. Schematic representation of major atmospheric circulation systems influencing Indian hydroclimate, including the Arabian Sea and Bay of Bengal monsoon branches, seasonal ITCZ migration, western disturbances, and topographic controls exerted by the Himalayan–Tibetan system.

Superimposed on these orbital trends were abrupt reorganizations linked to ocean–atmosphere teleconnections. Millennial-scale North Atlantic events such as Heinrich stadials and the Younger Dryas are recorded in Indian speleothems and marine archives, implying strong coupling between tropical hydroclimate and high-latitude circulation changes [5, 19]. Changes in the Atlantic Meridional Overturning Circulation (AMOC) can alter interhemispheric heat transport and contribute to latitudinal displacement of the Intertropical Convergence Zone (ITCZ), providing a potential mechanism linking North Atlantic cooling with changes in South Asian monsoon hydroclimate. At shorter timescales, El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) influence rainfall distribution, moisture transport, and monsoon persistence, although these relationships appear non-stationary through time [13]. The major climatic forcings, feedbacks, and teleconnections influencing Indian hydroclimate variability across Quaternary timescales are summarized in Table 2.

Table 2. Major climatic forcings, feedbacks, and teleconnections influencing Indian hydroclimate, their principal archive expressions, and associated interpretative uncertainties.

Climate Forcing/Mode	Mechanism	Typical Hydroclimatic Influence	Quaternary Relevance	Principal Archives/Proxy Expressions	Key Uncertainty
ENSO	Alters Walker circulation and tropical Pacific convection	El Niño commonly associated with weaker ISM; La Niña with stronger ISM, although coupling is non-stationary	Centennial-scale Holocene variability and historical droughts [4, 13]	Speleothems, lake sediments, corals/marine records, historical records	Temporal stability and spatial expression of ENSO–ISM coupling
IOD	Zonal Indian Ocean SST gradients modify convection and moisture transport	Positive IOD may enhance rainfall in some sectors and partly offset El Niño effects	Important for late-Holocene regional variability	Marine sediments, corals, speleothems, lacustrine records	Interaction with ENSO and regional rainfall seasonality
AMOC	Changes North Atlantic heat transport and ITCZ position	Weakening generally associated with reduced ISM	Heinrich stadials and Younger Dryas [19]	Speleothems, Arabian Sea sediments, Bay of Bengal records	Transmission pathway, lag and regional response
ITCZ migration	Latitudinal displacement of tropical convergence and rainfall belts	Southward migration generally reduces South Asian summer rainfall	Deglacial and abrupt climatic transitions	Speleothems, marine sediments, lake records	Spatially heterogeneous response among monsoon sectors
Northern Hemisphere summer insolation	Precessional forcing modifies seasonal land–sea thermal contrast	Higher summer insolation generally favours stronger monsoon circulation	First-order orbital-scale monsoon forcing [8]	Speleothems, marine sediments, lacustrine sequences	Relative influence of internal feedbacks and boundary conditions
Westerly disturbances	Mid-latitude circulation delivers winter precipitation to north-ern/western Himalaya	Controls winter snowfall and cold-season hydroclimate	Important for Himalayan glacial and high-altitude archives	Glaciers/moraines, lake sediments, speleothems	Separation of winter-westerly and summer-monsoon signals

Table 2. *(Continued).*

Climate Forcing/Mode	Mechanism	Typical Hydroclimatic Influence	Quaternary Relevance	Principal Archives/Proxy Expressions	Key Uncertainty
Indian Ocean SST variability	Alters evaporation, convection and moisture availability	Modulates land–sea thermal contrast, moisture transport and regional rainfall; anomalously warm Indian Ocean SSTs may weaken monsoon circulation under some boundary conditions [34]	Glacial–interglacial to centennial–millennial monsoon variability, including the Last Interglacial [34]	Marine sediments, corals, speleothems	Nonlinear interaction with ENSO, IOD and circulation
High-latitude cooling	Alters hemispheric thermal gradients and atmospheric circulation	Abrupt cooling generally associated with weaker ISM	Heinrich events and Younger Dryas	Speleothems, marine sediments, Himalayan records	Timing, magnitude and spatial heterogeneity
Sea-level change	Changes coastline position, shelf exposure, land–sea geometry, sediment routing and freshwater–marine interactions	Modifies coastal hydroclimate and the spatial configuration of moisture-source and depositional environments	Especially important across glacial–interglacial and deglacial transitions	Marine and coastal sediments, deltas, estuarine sequences, mangroves, coral/reef records	Separating eustatic effects from climatic, sedimentary and tectonic controls
Land–atmosphere feedbacks	Soil moisture, vegetation and evapotranspiration modify surface–atmosphere exchange	Can amplify regional wet or dry conditions	Relevant to persistence of Holocene hydroclimatic states	Pollen, peat, lake sediments, biomarkers	Quantification and attribution of feedback strength
Anthropogenic greenhouse forcing	Greenhouse warming alters atmospheric moisture, SSTs and circulation	Modifies rainfall variability and hydroclimatic extremes	Primarily relevant to the modern/Anthropocene comparison	Instrumental observations, historical records, recent sediments	Separation from natural variability and regional attribution

2.4. Cryosphere, River Systems and Regional Hydroclimatic Gradients

The Himalayan cryosphere plays an important role in regional hydroclimate through snow cover, glacier mass balance, seasonal meltwater supply, and albedo feedbacks. Major river systems, including the Indus, Ganga, and Brahmaputra respond to climatic and geomorphic change through variations in discharge, sediment flux, channel migration, and groundwater recharge.

Indian monsoon system is characterised by strong spatial heterogeneity. Northwest India lies near the dry limit of monsoon penetration and is therefore highly sensitive to modest circulation shifts. Northeast India receives intense moisture transported from Bay of Bengal and may record changes in moisture pathways rather than all-India rainfall totals. Himalayan regions preserve varying combinations of monsoon and winter-westerly influences, whereas many peninsular basins integrate runoff–evaporation balance and local hydrological storage. Therefore, no single archive can represent the full spatial and seasonal behaviour of the Indian monsoon system.

2.5. Implications for Quaternary Interpretation

The pronounced physiographic and climatic heterogeneity of the Indian subcontinent requires palaeohydroclimatic records to be interpreted within their regional environmental setting. Differences in monsoon exposure, winter-westerly influence, cryospheric contribution, catchment hydrology, and marine connectivity can produce spatially contrasting responses to the same large-scale climatic forcing. The geological and climatic framework outlined above therefore provides the environmental context for evaluating the archive-specific sensitivities and response characteristics discussed in Section 3.

3. Resolving Indian Quaternary Hydroclimate through Contrasting Archive Systems

Indian Quaternary archives frequently produce contrasting expressions of the same climatic interval. For example, an abrupt transition may be sharply resolved in a high-resolution speleothem sequence but appear broader or attenuated in lacustrine or marine sediments. Such differences do not necessarily indicate chronological inconsistency or contradictory climate histories; they may arise because archives record different components of the hydroclimate system and transform climatic forcing through distinct physical, hydrological, ecological, and biogeochemical processes [17]. Interpretation therefore requires consideration of each archive's climatic sensitivity, temporal resolution, spatial integration, filtering behaviour, and chronological uncertainty. These characteristics are compared schematically in Figure 3 and summarized in Table 3.

3.1. Speleothems and Abrupt Hydroclimate Variability

Speleothem records can provide annually to decadally resolved reconstructions of Indian monsoon variability where suitable growth rates, sampling density, and chronological control are available. U–Th dating and, in some cases, annual laminae enable abrupt transitions to be resolved more precisely than in many sedimentary archives, making cave records from Mawmluh and Sahiya particularly valuable for examining the Younger Dryas, the 4.2 ka interval, and late-Holocene drought variability [4, 10, 11]. However, high temporal resolution does not necessarily imply direct climatic fidelity. Speleothem $\delta^{18}O$ may reflect combinations of rainfall amount, moisture source and transport history, recharge seasonality, and cave-specific hydrological processes. Recharge thresholds, karst storage and mixing, prior calcite precipitation, and kinetic isotope effects during calcite formation can further modify the recorded signal. Monitoring studies from Meghalaya indicate that cave drip water may integrate rainfall across multiple seasons, generating hydrological memory within the karst system [35]. Speleothems may therefore preserve event timing at high resolution while modifying its magnitude or seasonal expression, and should be interpreted alongside site-specific hydrological information and complementary regional archives.

ARCHIVE TYPES	**SPELEOTHEM Cave Deposits**	**LAKE SEDIMENTS**	**MARINE SEDIMENTS**	**GLACIER & ICE ARCHIVES**
Temporal Resolution	Annual to sub-annual (1–10 years) **Very High**	Decadal to centennial (10–100 years) **Moderate**	Centennial to millennial (100–1000+ years) **Low to Moderate**	Annual to multi-decadal (<1 to ~50 years) **Moderate to High**
Record Types	Moisture source, Rainfall amount Monsoon intensity, Seasonality Atmospheric circulation	Effective moisture balance, Salinity, Productivity, Vegetation, Fire, Catchment processes	Sea-surface conditions, Monsoon winds, Upwelling, Runoff, Riverine input, Productivity	Precipitation, Temperature, Moisture sources, Atmospheric composition, Monsoon–westerly variability
Proxy Examples	$\delta^{18}O$, $\delta^{13}C$, Trace elements (Mg/Ca, Sr/Ca) Growth rate, Fluid inclusions	Grain size, $\delta^{18}O$ (carbonate), Organic matter, Pollen, Diatoms, Biomarkers, Sr/Ca, C/N	Foraminiferal $\delta^{18}O$, Mg/Ca, Alkenones (Uk'_{37}),Ti/Ca, Ba/Al, Biogenic opal, Grain size	$\delta^{18}O$, Deuterium (δD), Major ions, Dust, Black carbon, Gas isotopes, Layer counting
Filtering / Integration Processes	Karst storage, Drip water mixing, Prior calcite precipitation (PCP), VentilationSeasonal recharge	Catchment buffering, Lake mixing, Evaporation, Bioturbation, Sediment mixing & accumulation	Sediment mixing, Bioturbation, Lateral transport, Winnowing, Dilution by carbonate/terrigenous input	Snow redistribution, Firn diffusion, Melt–refreeze, Wind scouring, Post-depositional alteration
Response to Climate Change	**Rapid (days–years)**	**Moderate (decades–centuries)**	**Slow (centuries–millennia)**	**Variable (years–decades)**
Strengths	High precision & dating accuracy Captures abrupt events Record of past monsoon dynamics Long continuous records	Integrates hydrology & ecology Sensitive to moisture balance Good for regional comparison Long-term continuous records	Archives large-scale circulation, Wide spatial coverage, Well-dated with multiple methods, Links land–ocean processes	High-resolution records Direct atmospheric signal Preserves composition & isotopes Excellent annual chronology
Limitations	Point source Influenced by karst processes Interpretation non-unique Not always rainfall amount	Lower temporal resolution Influenced by local processes Sediment mixing & hiatuses Salinity not always rainfall-driven	Low temporal resolution, Indirect signal of monsoon rainfall, Complex sedimentary mixing, Distance from source areas	Limited to high mountains Seasonal snow bias Melt/redistribution effects Shorter continuous records
Best Suited For	Abrupt events Monsoon intensity changes Moisture source shifts Seasonality reconstructions	Hydrological balance Aridity–humidity changes Vegetation & fire history Regional environmental change	Monsoon circulation Wind variability, Upwelling changes, Riverine input Land–ocean coupling	Atmospheric composition Snowfall variability Temperature proxy Moisture transport pathways

Figure 3. Comparative characteristics of major Quaternary archive systems used for Indian hydroclimate reconstruction, highlighting differences in temporal resolution, climatic sensitivity, filtering behaviour, interpretative strengths, and principal uncertainties.

Table 3. Comparative characteristics, climatic sensitivities, strengths, limitations, and filtering processes of major Quaternary archive systems used in Indian hydroclimate reconstruction. (*Tree-ring records remain relatively limited across much of the Indian monsoon domain compared with speleothem and lake archives. But they are increasingly important in Himalayan hydroclimate reconstruction. Sources summarized from [2, 3, 5, 7, 10, 14, 16–18, 32].)

Archive	Typical Resolution	Main Climate Sensitivity	Primary Strength	Major Limitation	Typical Filtering/Bias
Speleothems	Annual to decadal	Monsoon rainfall, moisture source, circulation change	High chronological precision and abrupt-event detection [10]	Complex isotope controls and karst hydrology	Recharge lag, karst storage, seasonality bias
Lake Sediments	Decadal to centennial	Effective moisture, runoff–evaporation balance	Multi-proxy environmental reconstruction [12]	Chronological uncertainty and sediment mixing	Catchment integration, bioturbation, hydrological smoothing
Marine Sediment Cores	Centennial to millennial	Monsoon winds, upwelling, runoff, SSTs	Regional-scale monsoon reconstruction [5]	Lower temporal resolution and oceanographic overprinting	Bioturbation, sediment averaging, circulation mixing
Fluvial/Alluvial Deposits	Centennial to millennial	River discharge, flood frequency, sediment flux	Direct geomorphic response to hydroclimate	Discontinuous preservation and complex reworking	Reworking, erosion, channel migration
Peat and Wetland Records	Decadal to centennial	Vegetation change, moisture balance, fire activity	Strong ecological sensitivity	Human disturbance and ecological lag	Vegetation persistence, delayed ecosystem response
Pollen Records	Decadal to centennial	Vegetation response to temperature and precipitation	Regional palaeoecological reconstruction	Non-climatic vegetation controls	Ecological lag, transport bias, human land use
Aeolian/Dune Systems	Centennial to millennial	Aridity, vegetation cover, wind intensity	Sensitive indicators of monsoon-margin shifts	Difficult separation of wind and rainfall effects	Sediment reworking, episodic deposition
Glacial/ Cryospheric Archives	Centennial to millennial	Temperature, snowfall, glacier mass balance	High-altitude climate sensitivity	Mixed monsoon–westerly forcing	Glacier response lag, topographic effects
Archaeological/ Historical Records	Annual to centennial	Hydroclimatic stress on societies	Direct evidence of human response and adaptation	Strong socio-political overprint	Settlement continuity, preservation bias
Tree Rings*	Annual	Moisture stress and seasonal temperature	Precisely dated annual variability	Limited spatial distribution in India	Biological growth thresholds, seasonal bias

3.2. Lakes as Integrators of Effective Moisture

Lake archives record an integrated expression of hydroclimate variability through the combined influence of precipitation, runoff, evaporation, groundwater exchange, erosion, sediment delivery, and ecological response. Therefore, lacustrine records are particularly effective for reconstructing effective moisture balance, catchment response, and persistent hydrological stress, although they may be less sensitive to short-lived atmospheric anomalies.

Northwest Indian lakes, most notably Kotla Dahar, have emerged as important archives for defining late-Holocene aridification and its relationship with the Indus Civilization landscape. Their stratigraphic records indicate enhanced salinity and evaporative stress around ~4.1 ka [7, 12]. Complementary evidence from southern India demonstrates how lacustrine systems can also resolve regional monsoon variability through multiple environmental indicators. At Pookode Lake in the Western Ghats, sediment texture, geochemical weathering indices, phytoliths, pollen, and diatoms have been used to reconstruct late-Holocene variations in southwest monsoon conditions, lake hydrology, vegetation, and catchment response [25]. Importantly, these proxies do not respond uniformly: pollen preservation is restricted within parts of the sequence, while geochemical weathering indicators may exhibit a delayed response to climatic forcing. Such behaviour illustrates how preservation thresholds and proxy-specific response times can produce offsets even within a single sedimentary archive. Multi-proxy coastal sediment records from semi-arid southeastern India provide an additional perspective on regional environmental change, demonstrating how sedimentological and geochemical indicators can preserve coupled hydroclimatic and coastal responses [26].

Relative to high-resolution speleothem sequences, lacustrine transitions are commonly broader and smoother because of differences in temporal resolution, chronological uncertainty, sedimentary mixing, and hydrological buffering. This does not necessarily imply lower palaeoclimatic reliability; rather, lakes integrate hydroclimatic conditions over different temporal and spatial scales and may more effectively record the persistence, cumulative hydrological effects, and ecological consequences of environmental change.

3.3. Marine Archives and Regional Monsoon Circulation

Marine sediment cores from the Arabian Sea, Bay of Bengal, and Andaman Sea provide regional perspectives on monsoon variability by integrating changes in wind strength, upwelling, continental runoff, salinity, productivity, and water-column structure. Arabian Sea records are particularly important for establishing links between Indian monsoon variability and large-scale ocean–atmosphere reorganizations, including North Atlantic climate shifts [5]. Longer records from the eastern Arabian Sea further extend this perspective across multiple glacial–interglacial cycles. Pollen, oxygen-isotope, and organic-carbon records extending to ~200 ka document coupled changes in continental vegetation, precipitation, surface-ocean hydrography, and southwest monsoon conditions [27]. Glacial intervals generally indicate reduced precipitation and weaker southwest monsoon influence, whereas interglacial intervals are associated with greater freshwater input and stronger monsoon conditions.

Complementary records from the Bay of Bengal and Andaman Sea provide an eastern Indian Ocean perspective in which monsoon variability is expressed through freshwater discharge, salinity, stratification, thermocline structure, and productivity [30, 31, 36]. Recent planktic-foraminiferal records from the northeastern Bay of Bengal and Andaman Sea demonstrate that monsoon-related rainfall and river discharge modify upper-ocean stratification and thermocline structure [37, 38]. In the northeastern Bay of Bengal, enhanced freshwater input during stronger monsoon phases can strengthen surface stratification and suppress nutrient supply and productivity, whereas weaker stratification during reduced freshwater input permits greater vertical mixing and productivity [37]. These observations show that eastern marine archives may record the hydrographic consequences of monsoon variability rather than monsoon forcing alone.

Pteropod and foraminiferal records provide an additional perspective on water-column and carbonate-system variability. Pteropod preservation is sensitive to changes in productivity, oxygen-minimum-zone intensity, intermediate-water ventilation, and aragonite saturation, such that abundance and dissolution may reflect preservation conditions as well as biological production [39–41]. In the northern Indian Ocean, monsoon-driven productivity and water-column ventilation can therefore modify carbonate preservation through changes in oxygenation and carbonate chemistry [40]. These processes reinforce the need to interpret marine proxies as products of coupled hydrographic and biogeochemical processes rather than as direct measures of monsoon strength.

Coastal sedimentary records from semi-arid southeastern India provide a complementary land–ocean perspective, in which hydroclimatic variability interacts with local sedimentary and coastal processes [26]. Together, Arabian Sea and Bay of Bengal–Andaman records enable comparison between western and eastern marine sectors characterized by different combinations of monsoon winds, continental runoff, freshwater stratification, productivity, and water-mass processes [27, 30, 31, 36–38].

Spatial integration is a major strength of marine archives. Marine sediments commonly integrate climatic and environmental signals over broader source regions and therefore provide information on basin-scale circulation and land–ocean interactions rather than exclusively local hydrological conditions. Their principal limitations include temporal smoothing associated with sediment accumulation, bioturbation, and sample time-averaging, which can attenuate abrupt or seasonal events. Marine archives are therefore particularly useful for resolving centennial- to millennial-scale variability and long-term hydroclimatic trends, whereas short-lived anomalies and individual seasonal events may be incompletely resolved.

3.4. Himalayan Archives and Mixed Climate Forcing

The Himalayan region increases interpretative complexity because many archives respond simultaneously to summer monsoon precipitation, winter westerlies, snow cover, glacier mass balance, and temperature variations. As a result, moraine chronologies, lake levels, and sediment flux should not be considered as simple monsoon indices. Recent studies from the Central Himalaya highlight strong sensitivity to elevation, catchment geometry, and cryospheric buffering [14]. Therefore, Himalayan archives are crucial for understanding glacier–hydrology interactions and mountain water resources. Attribution of individual Himalayan proxy changes specifically to ISM variability requires careful separation of temperature, snowfall, winter-westerly, topographic, and cryospheric influences. Climatic forcing is transformed into palaeoclimate signals through a hierarchical filtering process integrating external forcing, atmospheric dynamics, hydrology, archive behaviour, and proxy formation (Figure 4).

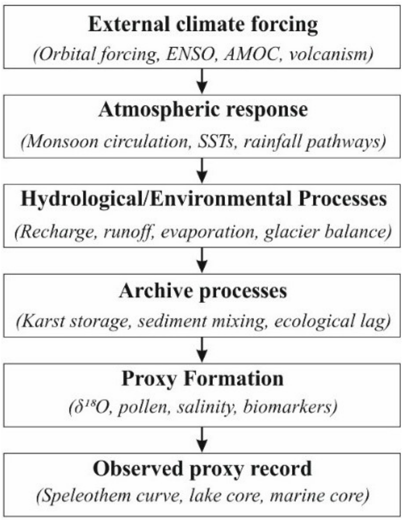


Figure 4. Conceptual framework for transformation of external climatic forcing into observed palaeoclimate proxy records through atmospheric, hydrological, environmental, and archive-system filtering processes.

3.5. Archive Filtering and Proxy-system Behaviour

Archive-specific responses can be represented conceptually as a signal-filtering process in which an underlying climatic or environmental forcing is transformed into an observed proxy signal by the response characteristics of the archive system. Mathematically, it can be defined as shown in Equation (1).

$$P(t) = \int C(\tau)K(t-\tau)d\tau + \epsilon(t) \quad (1)$$

where $P(t)$ is the observed proxy signal, $C(t)$ represents the underlying climatic or environmental forcing, K is an archive-specific response kernel describing processes such as storage, mixing, diffusion, ecological lag, and seasonal weighting, and $\epsilon(t)$ represents unresolved chronological, analytical, and process-related uncertainty. Equation (1) is used here as a conceptual representation rather than as a calibrated quantitative proxy-system model; no response kernel is estimated or inverted in the present synthesis. Its purpose is to illustrate why the same climatic perturbation may be expressed differently among archive systems. For example, an abrupt hydroclimatic change may be sharply resolved in a rapidly responding speleothem sequence, broadened through catchment and lake-water integration, attenuated by sediment mixing and bioturbation in a marine core, or delayed where groundwater storage or ecological response introduces additional memory. Inter-archive disagreement may therefore arise predictably from differences in archive response rather than necessarily indicating contradictory climatic histories.

3.6. Cross-archive Convergence

Despite archive-specific filtering, confidence in regional hydroclimatic interpretation increases where broadly coherent changes recur across independent archive classes with compatible chronological constraints. The temporal evolution of these convergent and divergent signals from the Late Pleistocene through the Holocene is evaluated in Section 4.

4. Quaternary Hydroclimate Evolution of the Indian Subcontinent

Multi-archive evidence documents substantial reorganization of Indian hydroclimate from the Late Pleistocene through the Holocene, expressed across orbital, millennial, centennial, and shorter timescales. The synthesis below evaluates these changes chronologically, with particular emphasis on the extent to which major hydroclimatic phases are supported across independent archive systems and regions. Archive-specific differences are interpreted according to the response characteristics outlined in Section 3 rather than as direct measures of equivalent climatic variables. Major phases, dominant forcings, archive expressions, and levels of interpretative confidence are summarized in Table 4 and Figure 5.

4.1. Late Pleistocene Variability and Glacial Boundary Conditions

During Marine Isotope Stages (MIS) 3 and 2, Indian monsoon intensity fluctuated substantially due to orbital forcing and millennial-scale reorganizations associated with the North Atlantic. Speleothem records from Mawmluh Cave show alternating stronger and weaker circulation, broadly linked to interstadial and Heinrich-like conditions [19]. Arabian Sea marine records preserve parallel variability in upwelling and productivity [5]. Together, these archives show that Indian hydroclimate remained dynamic even during glacial intervals often described as suppressed. However, coherence among records does not imply spatially uniform monsoon responses. Speleothem $\delta^{18}O$ indicates moisture transport pathways, condensation history, and recharge seasonality. Marine productivity records respond more to wind-driven upwelling and surface circulation. Therefore, their coherence likely indicates large-scale weakening of monsoon circulation rather than identical hydrological responses across South Asia.

Table 4. Major climatic phases across Indian Quaternary archives and their characteristic proxy responses. *[Confidence categories reflect the degree of convergence among independent archive classes, geographical replication, chronological agreement, and consistency of hydroclimatic interpretation. High confidence indicates agreement among ≥3 independent archive classes, preferably represented in more than one geographical sector, with broadly consistent timing and hydroclimatic interpretation. Moderate–High confidence indicates agreement among ≥2 independent archive classes, but with some regional, chronological, or proxy-specific uncertainty. Moderate confidence indicates evidence dominated by a single archive class, limited spatial replication, or appreciable disagreement in timing or hydroclimatic interpretation. These categories represent qualitative synthesis confidence rather than formal statistical probabilities. Sources are synthesized from the references cited in individual cells and the manuscript reference base.]

Interval	Approximate Age	Dominant Forcing	Speleothem Response	Terrestrial/ Hydrological Response	Marine Response	Confidence*
Late MIS 3 Interstadials	∼60–30 ka	Orbital precession and millennial-scale North Atlantic variability	Alternating δ^{18}O shifts indicating fluctuating ISM strength [19]	Limited continuous terrestrial coverage; spatially variable moisture response	Monsoon-sensitive productivity variability in Arabian Sea records [5]	Moderate
Heinrich Stadials	Episodic during MIS 3–2	North Atlantic cooling and weakened AMOC	Positive δ^{18}O excursions indicating weakened monsoon circulation [19]	Evidence for increased aridity is regionally variable and chronologically discontinuous	Reduced upwelling and weaker summer-monsoon circulation [5]	Moderate–High
Last Glacial Maximum (LGM)	∼26–19 ka	Expanded ice sheets, low greenhouse gases and cooler tropical SSTs	Enriched δ^{18}O values consistent with weakened ISM [19]	Himalayan glacier expansion and snowline depression indicate major environmental reorganization [22]	Weakened monsoon circulation relative to Holocene conditions [5]	Moderate–High
Bølling–Allerød Interstadial	∼14.7–12.9 ka	Deglacial warming and strengthened land–sea thermal contrast	Rapid δ^{18}O depletion indicating strengthening monsoon conditions [19]	Hydrological recovery associated with deglacial warming, but terrestrial coverage remains spatially uneven	Strengthening monsoon circulation during deglaciation	Moderate
Younger Dryas	∼12.9–11.7 ka	North Atlantic cooling and southward ITCZ displacement	Abrupt positive δ^{18}O excursion indicating weakened ISM [15, 19]	Generally weakened SW-monsoon conditions, although the event is not consistently expressed across southern Indian records [42]	Weakened monsoon circulation during deglacial cooling [5]	Moderate–High

Table 4. *(Continued).*

Interval	Approximate Age	Dominant Forcing	Speleothem Response	Terrestrial/ Hydrological Response	Marine Response	Confidence*
Early Holocene Monsoon Optimum	~11.7–8 ka	High Northern Hemisphere summer insolation	Strongly depleted $\delta^{18}O$ values indicating intensified monsoon conditions [8, 9]	Enhanced effective moisture and stronger early-Holocene monsoon conditions across multiple terrestrial, lacustrine and fluvial records [42]	Abrupt strengthening of monsoon-related terrigenous input and upwelling at ~9.5–9.1 ka, followed by weakening after ~8.5 ka [43]	High
Middle-Holocene Transition	~8–4.5 ka	Declining summer insolation with increasing influence of internal ocean–atmosphere variability	Gradual weakening/ enrichment trend with superimposed centennial-scale variability [8, 10]	Spatially heterogeneous hydrological response, with several records indicating declining SW-monsoon precipitation and episodes of aridity [42]	Reduced precipitation and marine productivity, particularly during the ~6.0–5.5 ka weak-monsoon interval [43]	Moderate–High
4.2 ka Hydroclimatic Transition	~4.3–3.9 ka	Monsoon instability and ocean–atmosphere reorganization	Abrupt positive $\delta^{18}O$ excursions and multi-phase drought structure [9, 10]	Enhanced salinity and evaporative stress in northwest India [7]	Hydroclimatic reorganization in Arabian Sea and Indus-margin records [6]	Moderate–High
Late Holocene Variability	~4–1 ka	Centennial-scale monsoon variability and ocean–atmosphere teleconnections	Repeated drought–wet oscillations recorded by high-resolution speleothems [3, 4, 10]	Regionally contrasting hydrological responses with alternating dry and wet phases [25, 42]	Arabian Sea records indicate monsoon deterioration near ~3.5 ka and subsequent centennial-to-millennial variability [43]	Moderate–High
Last Millennium Drought Episodes	~1 ka–Present	ENSO/IOD variability and internal monsoon dynamics	Multi-decadal drought intervals documented in high-resolution Indian speleothems [3, 4, 11]	South Indian Lake records preserve pronounced hydroclimatic fluctuations associated with Medieval and Little Ice Age intervals [25]	Arabian Sea records document substantial late-Holocene monsoon variability, including changes around ~1.6 and ~1.0 ka [43]	Moderate–High

Table 4. *(Continued).*

Interval	Approximate Age	Dominant Forcing	Speleothem Response	Terrestrial/ Hydrological Response	Marine Response	Confidence*
Anthropocene/ Modern Interval	∼1850 CE–Present	Greenhouse warming, aerosols, irrigation and land-use change	Anthropo-genically influenced isotope variability	Human modification of catchment hydrology, sedimentation and water balance	Warming SSTs and altered ocean–atmosphere circulation	Moderate

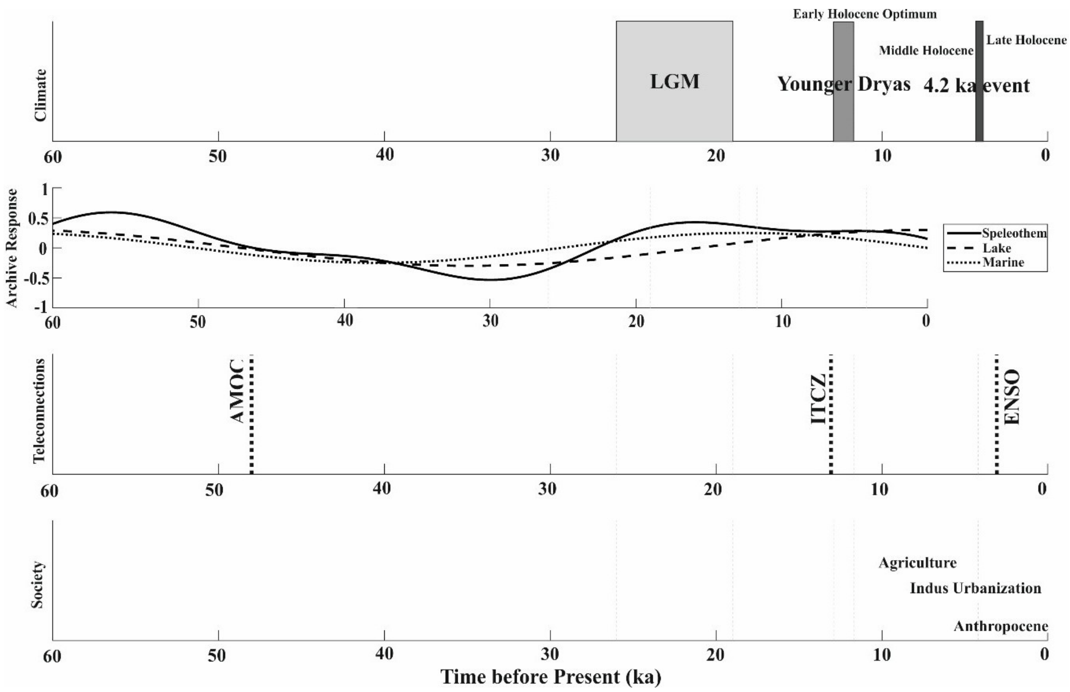


Figure 5. Schematic synthesis of major phases in Indian Quaternary hydroclimate evolution during the last ∼60 ka. This highlights major climatic intervals, contrasting archive responses, dominant teleconnection influences, and selected societal transitions. Archive trajectories are conceptual representations illustrating differing temporal sensitivities and filtering behaviour among speleothem, lacustrine, and marine systems rather than direct quantitative reconstructions.

The Last Glacial Maximum (LGM, ∼26–19 ka) is a key benchmark for monsoon sensitivity under cold-climate boundary conditions. Expanded Northern Hemisphere ice sheets, reduced greenhouse gases, cooler tropical seas, and weaker moisture transport reduced land-sea thermal contrast, thereby suppressing monsoon circulation. Marine records indicate reduced upwelling intensity and productivity, while speleothems show substantially weaker monsoon conditions than in the Holocene [5, 19]. In the Himalaya, glacier expansion and snowline depression suggest major environmental reorganization, with regionally varied relative roles of temperature and precipitation.

Glacial hydroclimate was neither spatially uniform nor persistently arid. Marginal regions may exhibit amplified sensitivity to circulation shifts, whereas humid regions may retain comparatively stable moisture availability because of topographic and oceanic buffering. This heterogeneity highlights the need to distinguish large-scale circulation weakening from local hydroclimatic expression.

4.2. Deglaciation and the Younger Dryas

Deglaciation involved rapid hydroclimatic reorganization rather than gradual warming. Between ∼14.7 and 12.9 ka, monsoon circulation strengthened as ice sheets retreated, greenhouse gases rose, and tropical oceans warmed. This trend was interrupted by the Younger Dryas (∼12.9–11.7 ka), with its renewed North Atlantic cooling and southward displacement of tropical rainfall belts. Speleothem records from Mawmluh Cave show an abrupt isotopic weakening of monsoon circulation, followed by rapid recovery [19]. Comparable signals across Asian speleothem networks indicate large-scale hydroclimatic reorganization [15]. Marine archives also record weakened winds and reduced upwelling.

The Younger Dryas demonstrates the sensitivity of Indian hydroclimate to high-latitude climatic perturbations despite the region's tropical setting. Its expression nevertheless varies among archive systems and regions, with differences in apparent abruptness and magnitude reflecting both spatial hydroclimatic heterogeneity and the archive-response characteristics discussed in Section 3. The broad recurrence of weakened monsoon conditions across independent records supports a large-scale hydroclimatic response, while differences in timing and expression caution against assuming a spatially uniform event. A multi-archive synthesis of Holocene monsoon evolution, including speleothem, lacustrine, marine, and pollen records, is shown in Figure 6.

4.3. Early Holocene Monsoon Intensification

After Younger Dryas, many archives record intensified monsoon conditions during the early Holocene, coinciding with peak Northern Hemisphere summer insolation associated with orbital precession. Speleothem records from northeast India show depleted $\delta^{18}O$ values indicating enhanced monsoon strength and increased moisture transport [5, 9]. Arabian Sea records indicate intensified monsoon circulation and associated changes in upwelling, productivity, and freshwater influence during the early Holocene [5, 27]. Lake system records show increased effective moisture and hydrological expansion. However, hydrological responses vary significantly depending upon basin geometry, groundwater exchange, evaporation sensitivity, and local runoff processes. Therefore, the early-Holocene interval of generally intensified monsoon circulation should be interpreted as a period with enhanced hydroclimatic connectivity across much of South Asia due to strengthened summer circulation.

All Indian archives do not record the early Holocene as uniformly humid. Some Himalayan and semi-arid records show substantial local variability associated with snowmelt contribution, groundwater storage, and catchment-specific hydrology. Therefore, intensified monsoon circulation does not confirm spatially uniform effective moisture. Regions near the dry monsoon margin may preserve large hydrological responses, while humid sectors may record weaker relative change even with higher absolute rainfall totals.

4.4. Middle-Holocene Transition

Following the early-Holocene interval of intensified monsoon circulation, many archives record a general reduction in monsoon strength associated with declining Northern Hemisphere summer insolation. This transition was neither monotonic nor spatially uniform, and centennial-scale hydroclimatic oscillations remained superimposed on the long-term trend. As orbital forcing weakened, internal climate variability and ocean–atmosphere teleconnections became increasingly important in modulating regional rainfall distribution and moisture transport. ENSO-related variability may have contributed to this enhanced hydroclimatic variability during the middle-to-late Holocene [13]; however, the ENSO–ISM relationship should not be regarded as temporally stationary. Its strength and regional expression can vary with the background state of the tropical Pacific and Indian oceans and with broader changes in monsoon circulation. Therefore, evidence for changing ENSO activity does not necessarily imply a constant relationship between individual ENSO events and Indian rainfall through time. Pollen-based evidence from western Odisha further records mid-to-late Holocene oscillations in vegetation and moisture conditions, illustrating the ecological expression of regional hydroclimatic variability [33]. The middle-Holocene transition is therefore better characterized as a spatially heterogeneous shift toward generally weaker but increasingly variable monsoon conditions rather than as a simple progressive drying trend.

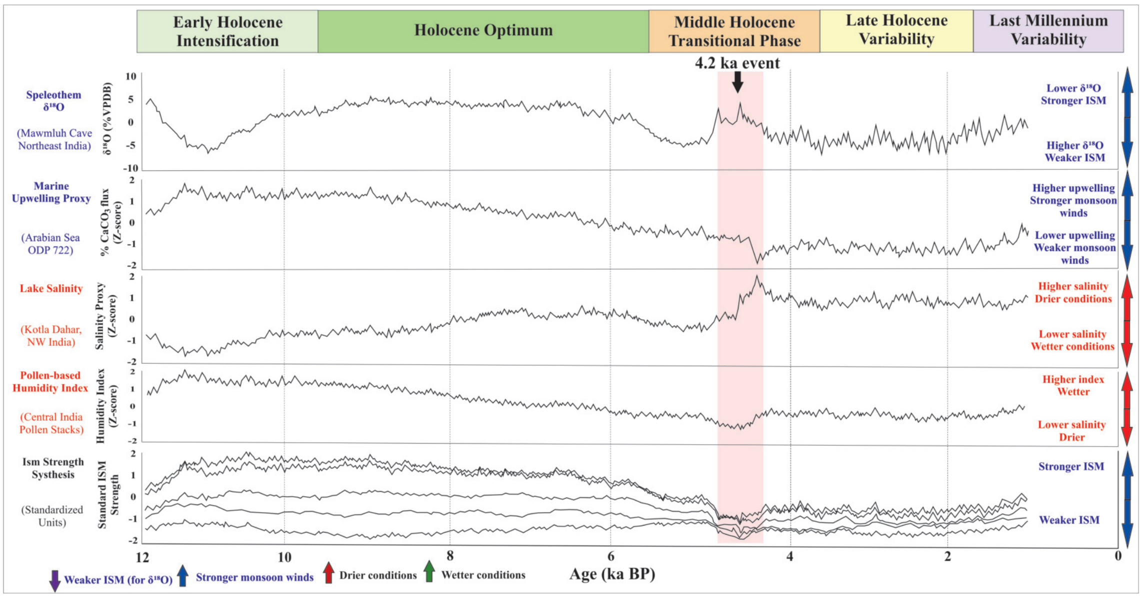


Figure 6. Schematic representation of Holocene Indian monsoon evolution with representative archive indicators.

4.5. The 4.2 ka Hydroclimatic Transition

The hydroclimatic interval centred broadly around 4.2 ka is among the most debated episodes in Indian Quaternary research because of its apparent correspondence with major environmental and societal transformations across parts of South Asia. Multi-archive evidence indicates pronounced hydroclimatic instability during approximately 4.3–3.9 ka; however, the timing, duration, magnitude, and internal structure of this transition vary among archives and regions. The available evidence therefore does not necessarily indicate a single, spatially uniform drought occurring synchronously across the Indian subcontinent. Instead, differences among records may reflect chronological uncertainty, regional rainfall seasonality, hydrological storage, archive-specific sensitivity, and genuine spatial heterogeneity. The term “4.2 ka hydroclimatic transition” is consequently used here to describe a broader interval of monsoon reorganization rather than a single instantaneous climatic event.

High-resolution speleothem records from Mawmluh Cave show marked δ^{18}O enrichment near ∼4.0 ka, indicating weakened monsoon conditions [9], while annually resolved evidence indicates multiple drought episodes embedded within a broader phase of hydroclimatic instability [10]. Northwest Indian lake records independently indicate enhanced salinity and evaporative stress around ∼4.1 ka [7], whereas Indus-margin marine archives document broader regional hydroclimatic reorganization [6]. Together, these records support a period of substantial hydroclimatic instability, but their differences in timing and expression suggest spatially variable changes in monsoon circulation, rainfall seasonality, effective moisture, and hydrological storage rather than uniform rainfall reduction across the entire region. The relationship between this hydroclimatic transition and societal change is examined separately in Section 5.

4.6. Late Holocene Variability and the Last Millennium

Indian hydroclimate after ∼4.2 ka was characterized by substantial centennial- to multidecadal-scale variability. High-resolution speleothem records document repeated drought and wet intervals during the late Holocene and last millennium [3, 4], while lacustrine and marine archives record corresponding changes in effective moisture, runoff, and regional circulation [25, 28–31, 43]. Late-Holocene hydroclimatic variability has been associated with changes in tropical ocean–atmosphere teleconnections, including ENSO and Indian Ocean variability, although the strength and spatial expression of these relationships were not stationary through time. Changes in tropical Pacific variability, Indian Ocean SST gradients, and land–atmosphere interactions may therefore have contributed to repeated shifts in monsoon circulation, rainfall distribution, and drought occurrence without producing uniform responses across the subcontinent.

Regional hydroclimatic sensitivity also varied substantially. Northwest India, situated near the dry margin of monsoon penetration, was particularly sensitive to relatively modest circulation changes, whereas more humid regions could respond differently because of greater moisture availability and hydrological buffering. Some late-Holocene droughts nevertheless appear to have generated regionally extensive hydrological stress beyond the range represented by the short instrumental record [4]. Their environmental and societal consequences depended not only on rainfall deficits but also on river connectivity, groundwater availability, floodplain storage, land use, and adaptive capacity.

4.7. Anthropocene Hydroclimate and the Quaternary Baseline

Modern Indian hydroclimate reflects the superposition of natural monsoon variability and increasingly important anthropogenic forcing. Greenhouse-gas-driven warming, anthropogenic aerosols, irrigation, land-use change, groundwater extraction, urbanization, and Indian Ocean warming can modify atmospheric moisture availability, land–sea thermal gradients, surface-energy exchange, runoff, and regional circulation. Anthropogenic forcing differs from the dominant natural forcings represented in Quaternary archives not simply in its origin, but also in its rapid rate of change and in the simultaneous modification of atmospheric, oceanic, and terrestrial components of the hydroclimate system.

Quaternary records provide an essential baseline for evaluating these emerging changes because they document the magnitude, persistence, and spatial structure of monsoon variability under contrasting natural boundary conditions. They demonstrate that the monsoon system is intrinsically variable and capable of abrupt and prolonged hydroclimatic reorganizations. However, natural variability recorded during the Quaternary should not be conflated with externally forced changes during the industrial era. Anthropogenic warming can alter the background climatic state upon which internal modes such as ENSO and the IOD operate, while irrigation, groundwater extraction, urbanization, and land-cover modification can additionally alter the terrestrial expression of rainfall variability. The palaeoclimate record therefore provides a context for distinguishing the range of natural monsoon behaviour from hydroclimatic changes emerging under increasingly anthropogenic boundary conditions.

5. Human–Environment Interactions and Hydroclimatic Risk Across the Indian Subcontinent

The Indian subcontinent provides an important setting for examining human–environment interactions because monsoon variability influences agriculture, river discharge, groundwater recharge, ecosystems, and settlement geography. However, societal responses to hydroclimatic stress are mediated by hydrological setting, mobility, infrastructure, technology, governance, trade networks, and adaptive capacity. Human modification of land and water systems can, in turn, alter environmental responses to climate. The archaeological and palaeoclimate records therefore provide a basis for examining these coupled climate–environment–society interactions across multiple timescales.

5.1. Late Pleistocene Environmental Variability and Early Human Occupation

Late Pleistocene hydroclimatic oscillations altered vegetation, freshwater availability, river systems, and habitat connectivity across South Asia [19]. Wetter intervals may have expanded freshwater and ecological resources, whereas arid phases promoted environmental fragmentation, particularly in water-limited regions. Direct correlation with changes in human occupation remains difficult because archaeological and palaeoclimate records differ substantially in temporal resolution and chronological precision. Monsoon variability should therefore be considered part of the environmental context within which human populations responded through mobility, resource selection, and adaptation, rather than as a deterministic control on population change.

5.2. Early Holocene Hydroclimate and Agriculture

Intensified early-Holocene monsoon circulation increased effective moisture and freshwater availability across many parts of the subcontinent, potentially increasing ecological productivity and reducing environmental constraints on subsistence and agricultural experimentation. However, regional differences in crop adoption, settlement development, and mobility indicate that favourable hydroclimate alone did not determine agricultural expansion. In the northwestern subcontinent, changing monsoon conditions and river dynamics formed part of the environmental setting within which later Indus settlements developed, alongside technological, economic, and social factors.

5.3. The Indus Civilization and Hydroclimatic Stress

The transformation of the Indus Civilization occurred during a period of substantial hydroclimatic instability. Kotla Dahar records indicate increasing aridity and evaporative stress near ~4.1 ka [7, 12], while Indus-margin marine [6] and Mawmluh Cave speleothem records [10] document broader monsoon reorganization. Recent palaeoclimate–hydrological modelling further suggests that this stress was not confined to a single 4.2 ka event: Recent study identified persistent river droughts between ~4.4 and 3.4 ka that progressively constrained freshwater availability across parts of the Indus domain [44].

Archaeological evidence nevertheless indicates prolonged and spatially heterogeneous transformation involving settlement redistribution, deurbanization, changing subsistence, and mobility rather than a synchronous climate-driven collapse. Hydroclimatic deterioration therefore acted as a stressor whose societal consequences depended on water availability, settlement geography, economic organization, and adaptive capacity. These interactions are summarized in Figure 7, which conceptualizes societal responses as both consequences of hydroclimatic stress and adaptive feedbacks capable of modifying vulnerability and local environmental conditions.

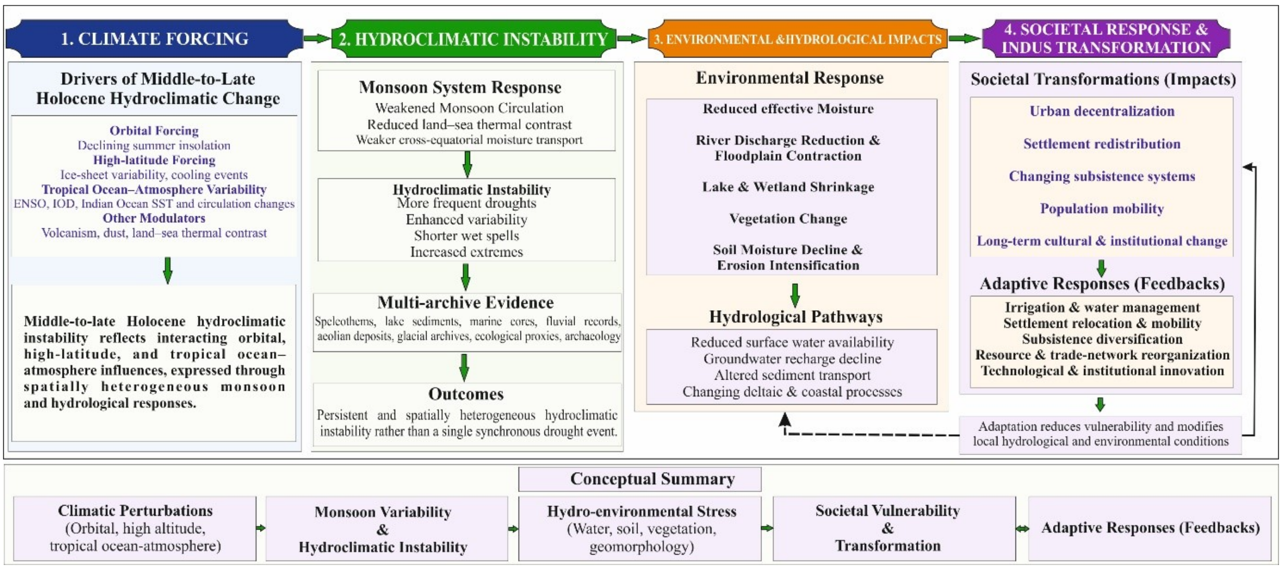


Figure 7. Conceptual framework linking hydroclimatic forcing, hydrological and environmental stress, societal vulnerability, and adaptive responses during the middle-to-late Holocene, with particular relevance to the Indus Civilization. Adaptive responses include settlement redistribution, mobility, irrigation and water management, subsistence adjustment, and resource-network reorganization, with feedbacks to local environmental and hydrological conditions.

5.4. Rivers, Water Security and Settlement Geography

Most settlement systems depended heavily on river dynamics. Channel migration, avulsion, floodplain aggradation, seasonal discharge variability, and groundwater recharge were crucial parameter for agricultural production and long-term settlement. The Ghaggar-Hakra palaeochannel system is the best example of this relationship where settlement distribution intersects monsoon variability, river migration, and tectonic forcing. Similar interactions occur across the Gangatic Plains, peninsular basins, and deltaic systems. Constrained monsoon circulation limits discharge, while intensified circulation increases flood frequency, channel instability, and sediment redistribution. Therefore, palaeoclimate interpretation often accommodate rainfall proxies along with fluvial geomorphology, hydrological and groundwater dynamics. This relationship shows that hydroclimatic risk in the subcontinent is not only dependent on rainfall variability, but also on coupled river–groundwater systems. Regions with similar monsoon pattern may undergo very different societal impacts depending on coupled river–groundwater interaction. Therefore, spatial heterogeneity complicates direct interlinking of palaeoclimate records and archaeological evolution.

5.5. Late Holocene Societies and Monsoon Instability

Late Holocene Indian hydroclimate shows centennial and multidecadal variability. High-resolution speleothem records highlight multiple drought episodes during the late Holocene and last millennium. Some drought episodes were regionally extensive and capable of producing severe hydrological stress beyond present day records [3, 4, 11]. But their societal consequences vary substantially across regions and systems. Some droughts possibly generating severe agricultural and demographic stress, while others being compensated with irrigation systems, groundwater access, reservoir construction, or administrative adaptation. Historical evidence from medieval and colonial South Asia suggests strongly conditioned vulnerability through infrastructure, governance, and resource distribution. Therefore, the late-Holocene record can be the evidence for coupled socio-hydrological interaction under repeated monsoon instability.

5.6. Anthropogenic Landscape Modification and Proxy Interpretation

Human populations became active agents of environmental change by the late Holocene. Anthropogenic activities like deforestation, cultivation, terracing, irrigation, and urbanization drastically changed vegetation cover, erosion rates, sediment influx, and local hydrology. Younger environmental archives tend to preserve overlapping climatic and anthropogenic signals due to these anthropogenic interventions, creating a major interpretative challenge. For example, agriculture-driven erosion may enhance sedimentation just like intensified runoff. Pollen assemblages may indicate land clearance just like rainfall variability. Similarly, both nutrient and climatic change can cause lake eutrophication. Therefore, late-Holocene environmental reconstruction requires adequate integration of archaeological, ecological, geomorphological, and hydrological evidence.

5.7. Lessons for Contemporary Hydroclimatic Risk

Quaternary and historical records demonstrate that monsoon variability can exceed the range captured by the short instrumental record, while its societal consequences depend on interactions among rainfall, rivers, groundwater, infrastructure, and adaptive capacity. These lessons are increasingly relevant where anthropogenic forcing interacts with groundwater depletion, urbanization, land-use change, and heavily modified hydrological systems. Palaeoclimate records therefore provide not direct analogues for future conditions, but a long-term context for evaluating hydroclimatic variability, environmental sensitivity, and societal vulnerability.

6. Interpreting Divergent Proxy Records

Indian palaeoclimate records representing the same interval may differ in timing, magnitude, duration, or inferred hydroclimatic response. Such divergence can reflect genuine spatial heterogeneity or arise from differences in chronology, temporal resolution, seasonality, archive filtering, and proxy sensitivity. Distinguishing between these sources of disagreement is therefore essential for multi-archive synthesis. The principal mechanisms producing divergent proxy responses are summarized in Figure 8 and Table 5.

Therefore, the exact cause of their divergence is the scientific problem. Some divergence reflects genuine spatial heterogeneity within the Indian monsoon system. Some other differences arise due to archives transforming common climatic forcing through contrasting physical, hydrological, and ecological processes. Robust reconstruction of Indian hydroclimate evolution requires distinction of these possibilities. The principal mechanisms responsible for divergence among Indian palaeoclimate records are summarized in Table 5.

6.1. Chronological Uncertainty as a First-order Limitation

Apparent leads, lags, or synchronicity among records must first be evaluated against age-model uncertainty. U–Th-dated speleothems can provide high chronological precision, whereas lake and marine records may be affected by radiocarbon calibration, reservoir effects, sediment reworking, and interpolation between dated horizons; luminescence-dated fluvial and aeolian records commonly have broader uncertainty envelopes. Consequently, apparent offsets among archives may remain statistically compatible within their respective age uncertainties, particularly when evaluating short-lived events such as the 4.2 ka transition.

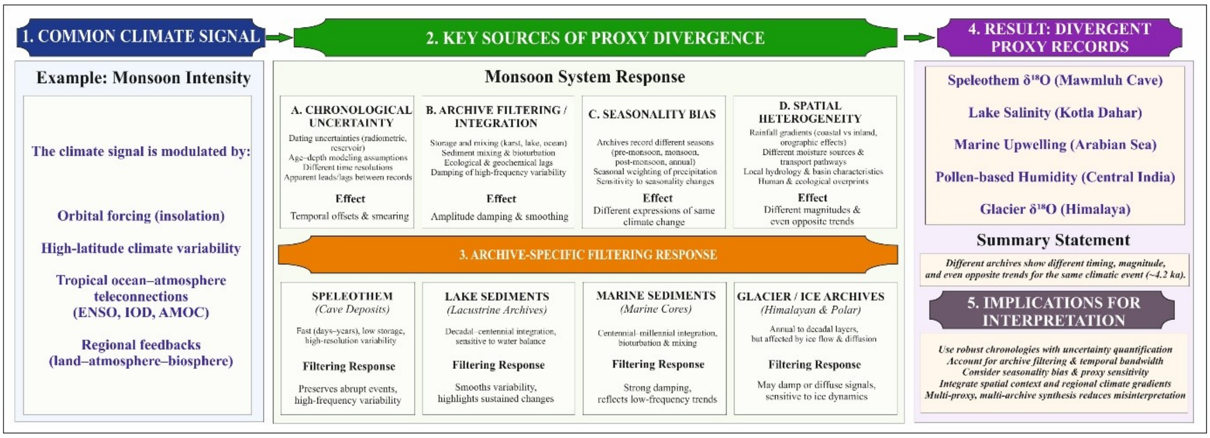


Figure 8. Principal mechanisms producing divergence among Indian palaeoclimate records, including chronological uncertainty, archive filtering, seasonality, spatial heterogeneity, anthropogenic overprinting, and archive-specific responses.

Table 5. Principal causes of divergence among Indian palaeoclimate archives (sources synthesized from [5, 10, 12, 14, 17, 35–41, 45, 46]).

Source of Divergence	Mechanism	Most Affected Archives	Interpretative Consequence	Example
Chronological uncertainty	Age-model uncertainty, reservoir effects, sparse dating	Lakes, marine, fluvial	Apparent leads/lags may be artificial	Variable apparent timing of the 4.2 ka transition
Temporal resolution	Sampling density and accumulation-rate differences	Marine, lakes, fluvial	Abrupt events may appear attenuated or prolonged	Sharper Younger Dryas expression in high-resolution records
Hydrological buffering	Groundwater, karst or catchment storage	Speleothems, lakes, wetlands	Damped or lagged response	Karst storage modifying Mawmluh Cave signals
Seasonality bias	Preferential sensitivity to particular seasons	Speleothems, tree rings, glaciers	Different components of hydroclimate are recorded	Summer recharge versus annual effective moisture
Spatial heterogeneity	Regional rainfall and moisture-pathway differences	All archives	Genuine regional responses may appear contradictory	Northwest India versus Meghalaya
Proxy nonlinearity	Threshold-dependent proxy response	Speleothems, pollen, lakes	Similar forcing produces unequal responses	Isotopic shift without equivalent lake-level change
Sediment mixing/bioturbation	Post-depositional mixing	Marine, lakes	Short events become smoothed	Attenuated abrupt drought signals
Ecological lag	Delayed biological response	Pollen, peat	Proxy response follows climate change	Gradual vegetation transition
Human modification	Land use, cultivation, irrigation, burning	Lakes, pollen, fluvial	Anthropogenic change may mimic climate	Cultivation-driven erosion versus enhanced runoff
Mixed climatic forcing	Monsoon, westerlies and temperature interactions	Himalayan archives	Attribution to individual forcing is difficult	Glacier response to snowfall and temperature

6.2. Temporal Filtering and Archive Response Behaviour

Even records with robust chronologies may differ because archive systems integrate climate over different temporal scales. As conceptualized in Equation (1) and Section 3.5, storage, mixing, bioturbation, ecological response, and sampling resolution can attenuate or broaden short-lived signals. Therefore, an abrupt hydroclimatic anomaly may be sharply expressed in one archive but appear prolonged or subdued in another. Such differences should be evaluated as potential archive-response effects before being interpreted as climatic disagreement.

6.3. Seasonality Bias in Indian Proxy Systems

Indian palaeoclimate archives may preferentially record different seasonal components of hydroclimate. Speleothem signals can be weighted toward recharge seasons, lakes integrate precipitation–evaporation balance, marine records may emphasize monsoon runoff or circulation, and Himalayan archives can incorporate both summer-monsoon and winter-westerly influences [16]. Therefore, apparently divergent records may represent different seasonal or hydrological variables rather than contradictory climate histories.

6.4. Spatial Heterogeneity of the Indian Monsoon System

Genuine spatial heterogeneity provides another source of inter-record divergence. Northwest India lies near the dry margin of monsoon penetration, northeast India receives strong Bay of Bengal moisture, peninsular basins integrate variable precipitation–evaporation balances, and Himalayan records additionally reflect elevation and westerly influences. A common circulation anomaly may therefore produce contrasting hydrological responses among regions. Divergence should consequently be evaluated against hydroclimatic geography before being attributed solely to chronological or proxy-system uncertainty.

6.5. Anthropogenic Overprinting

During the late Holocene, increasing land use and water management introduced an additional source of proxy divergence. As discussed in Section 5.6, changes in sedimentation, vegetation, erosion, and nutrient cycling may reflect climatic forcing, anthropogenic modification, or both. Younger records therefore require explicit consideration of archaeological and palaeoecological evidence when attributing environmental change.

6.6. From Contradiction to Complementarity

Inter-record divergence can itself provide process information. A sharp speleothem anomaly accompanied by a muted lake response may indicate a short-lived rainfall perturbation insufficient to reorganize catchment hydrology, whereas prolonged lacustrine drying with a weaker speleothem response may reflect sustained effective-moisture decline. Similarly, a marine circulation anomaly without a corresponding terrestrial response may indicate atmospheric or oceanographic reorganization with limited inland hydrological expression. Divergent records should therefore be treated as complementary constraints on different components of the hydroclimate system rather than automatically as conflicting reconstructions. Multi-archive comparisons should account explicitly for chronological uncertainty, temporal resolution, spatial context, and the climatic variable represented by each proxy rather than treating different proxy signals as directly interchangeable.

7. Emerging Frontiers

Despite major advances in chronology and archive coverage, several questions remain unresolved in Indian Quaternary hydroclimate research, particularly the regional structure of the 4.2 ka transition, non-stationarity of ENSO–ISM coupling, separation of monsoon and westerly influences in Himalayan records, and limited high-resolution coverage across parts of central, eastern, and southern India. Addressing these problems requires moving beyond visual comparison of proxy records toward process-based, uncertainty-aware reconstruction. Four priorities are particularly important: (i) proxy-system and isotope-enabled modelling, (ii) climate data assimilation and probabilistic reconstruction, (iii) expansion and standardization of multi-archive networks, and (iv) integrated land–sea and human–environment synthesis (Figure 9; Table 6).

Traditional Indian palaeoclimate synthesis often compare proxy records visually without explicitly integrating archive-system behaviour, chronological uncertainty, climate dynamics, or temporal filtering. However, monsoon rainfall amount, circulation intensity, runoff generation, groundwater recharge, effective moisture balance, and isotopic composition are not interchangeable climatic parameters. Therefore, future reconstruction requires transition from descriptive proxy comparison toward process-based hydroclimate reconstruction constrained by physically interpretable proxy-system relationships. This transition highlights a broader conceptual shift in palaeoclimatology where archives are not just isolated climatic indicators, but observations constraining probabilistic climate states. Such approaches are particularly important in South Asia because the Indian monsoon system shows strong seasonality, nonlinear responses, pronounced hydroclimatic anomalies, and sensitivity to both tropical and high-latitude climatic forcing. Major emerging analytical approaches currently reshaping Indian Quaternary science are summarized in Table 6.

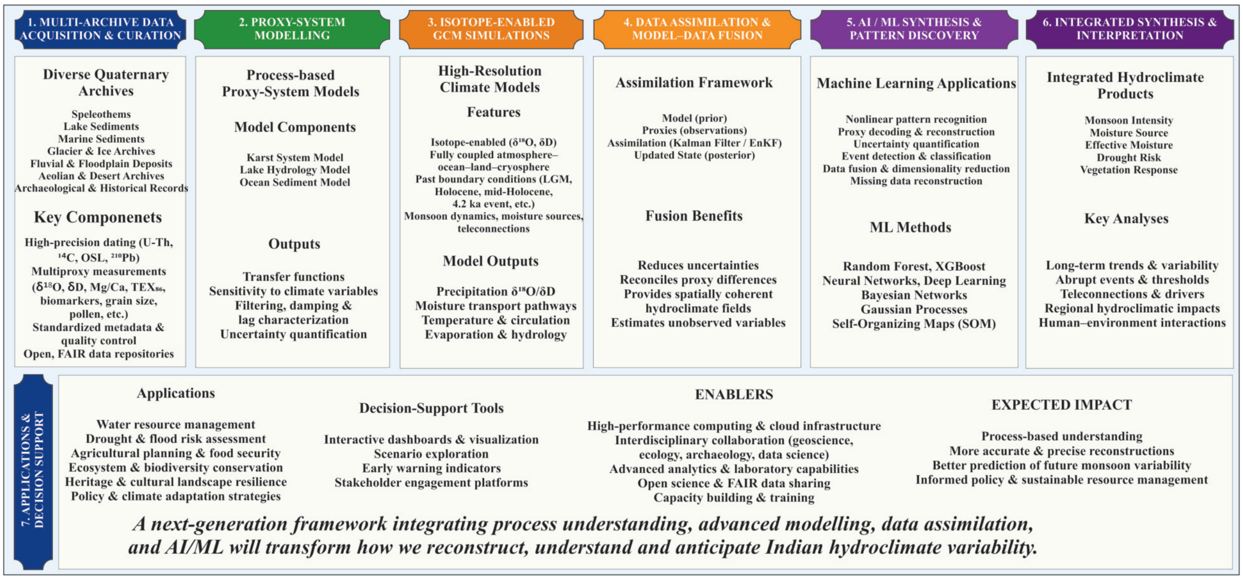


Figure 9. Proposed next-generation analytical framework for Indian Quaternary hydroclimate reconstruction integrating proxy-system modelling, isotope-enabled climate simulations, climate data assimilation, AI/ML synthesis, and multi-archive interpretation.

Table 6. Priority research directions for Indian Quaternary hydroclimate reconstruction [14, 16, 17, 35, 46, 47].

Priority	Principal Challenge Addressed	Required Approach	Expected Contribution
Proxy-system and isotope-enabled modelling	Archive-specific filtering and ambiguous interpretation of isotopic proxies	Forward proxy models coupled with isotope-enabled climate simulations	Mechanistic separation of climatic forcing from archive response
Climate data assimilation and uncertainty quantification	Chronological uncertainty, spatial heterogeneity, and inconsistent proxy resolution	Assimilation of proxy ensembles with climate-model priors	Probabilistic reconstruction of monsoon fields, droughts, and teleconnections
Expanded and standardized multi-archive networks	Sparse coverage across central, eastern, and southern India and inconsistent metadata	New high-resolution records, harmonized chronologies, open proxy databases	Improved spatial representation and reproducible regional synthesis
Integrated land–sea and Himalayan reconstruction	Disconnection among terrestrial, marine, monsoon, and westerly signals	Cross-domain synthesis and regional climate–hydrological modelling	Better attribution of regional circulation and hydrological responses
Palaeoclimate–archaeological integration	Difficulty separating climatic stress from anthropogenic modification and societal response	Multiproxy environmental records integrated with archaeological chronology	Stronger attribution of climate–environment–society interactions

7.1. Proxy-System and Isotope-Enabled Modelling

Process-based modelling provides a means of separating climatic forcing from archive-specific controls on proxy formation. At Mawmluh Cave, integration of trace-element observations with forward modelling demonstrated that speleothem Mg/Ca variability can be particularly sensitive to dry-season infiltration, with cave ventilation and prior carbonate precipitation further modifying the recorded signal [45]. Use of an advection–reaction model demonstrated that variations in speleothem initial $^{234}U/^{238}U$ cannot always be attributed directly to rainfall, because changes in seepage-water routing, weathering and host-rock characteristics may substantially influence the proxy response [48]. These studies illustrate how forward modelling can identify non-climatic and seasonally dependent processes that complicate direct proxy–climate relationships.

At broader spatial scales, isotope-enabled climate modelling provides a complementary framework for interpreting stable-isotope records. Monsoon-region speleothem δ^{18}O reflects interacting effects of precipitation, atmospheric circulation and moisture-source conditions rather than a universally applicable rainfall signal [49]. Transient simulations demonstrated that coherent Asian monsoon δ^{18}O variability may accompany spatially contrasting rainfall responses [50], highlighting the importance of large-scale circulation and hydroclimatic dynamics. Greater integration of such proxy-system and isotope-enabled modelling with Indian palaeoclimate records would therefore improve mechanistic interpretation and provide more defensible quantitative reconstructions of past hydroclimate variability.

7.2. Climate Data Assimilation and Probabilistic Reconstruction

Climate data assimilation offers a framework for combining proxy observations, their uncertainties, and climate-model dynamics to reconstruct spatially coherent past climate states. For Indian hydroclimate, such approaches could test whether the 4.2 ka transition represented synchronous or regionally asynchronous change, reconstruct the spatial extent and recurrence of last-millennium droughts, and evaluate temporal changes in ENSO–ISM coupling. Their application requires harmonized chronologies, explicit proxy uncertainties, standardized metadata, and sufficient spatial archive coverage; otherwise, archive biases may propagate into the reconstructed climate fields.

7.3. Expanding and Standardizing Multi-archive Networks

Spatially uneven archive coverage remains a fundamental limitation, particularly across parts of central, eastern, and southern India. Future work should prioritize high-resolution records from underrepresented hydroclimatic sectors while harmonizing age models, proxy metadata, calibration information, and uncertainty estimates across existing records. Open, standardized multi-archive databases would improve reproducibility and provide the infrastructure required for quantitative synthesis, data assimilation, and computational analysis. AI/ML approaches may assist pattern recognition and nonlinear analysis within such networks, but their palaeoclimatic value will depend on data quality, interpretability, and explicit treatment of uncertainty.

7.4. Integrated Regional Synthesis

Future synthesis should explicitly connect terrestrial and marine records while distinguishing regional monsoon, westerly, temperature, and hydrological influences. This is particularly important for resolving whether the 4.2 ka transition was regionally synchronous, evaluating non-stationary ENSO–ISM coupling, and separating monsoon-driven from temperature- and westerly-driven changes in Himalayan archives. Regional climate, hydrological, and glacier models constrained by multi-archive observations provide a pathway for testing these mechanisms rather than relying solely on visual proxy correspondence. Integration with archaeological records can further distinguish climatic forcing, anthropogenic landscape modification, and societal adaptation during the late Holocene.

Collectively, these priorities would shift Indian Quaternary research from comparison of individual proxy trajectories toward probabilistic reconstruction of hydroclimatic states constrained by archive processes, climate dynamics, and quantified uncertainty. Such integration is necessary to resolve persistent palaeoclimate debates and to place contemporary hydroclimatic risk within a robust long-term context.

8. Conclusions

Multi-archive evidence demonstrates that Quaternary hydroclimate across the Indian subcontinent evolved through interactions among orbital forcing, glacial boundary conditions, high-latitude climate perturbations, tropical ocean–atmosphere variability, and regional physiographic controls. Weakened monsoon circulation during the Last Glacial Maximum was followed by rapid deglacial reorganization, including monsoon weakening during the Younger Dryas and widespread intensification during the early Holocene. Subsequent middle-to-late Holocene evolution was characterized by generally declining monsoon strength superimposed by substantial centennial-scale variability. The hydroclimatic transition around 4.2 ka was regionally important but neither spatially uniform nor necessarily synchronous across archive systems, while the late Holocene and last millennium were marked by recurrent drought–wet variability.

A principal outcome of this synthesis is that apparent disagreement among palaeoclimate records should not automatically be interpreted as conflicting climate histories. Speleothems, lakes, marine sediments, fluvial systems, and Himalayan archives record different components of hydroclimate and integrate climatic forcing over different temporal and spatial scales. Chronological uncertainty, seasonality, hydrological storage, sediment mixing, ecological response, and spatial heterogeneity can therefore generate contrasting expressions of the same climatic perturbation. Cross-archive convergence provides stronger evidence for regional change, whereas divergence can itself reveal differences in hydrological response, circulation, or environmental buffering.

Future progress requires a transition from descriptive comparison of proxy trajectories toward process-based and uncertainty-aware reconstruction. Proxy-system and isotope-enabled modelling, climate data assimilation, harmonized multi-archive networks, and integrated terrestrial–marine and archaeological synthesis provide the strongest pathways for resolving the spatial structure of abrupt events, non-stationary ENSO–ISM relationships, Himalayan monsoon–westerly interactions, and climatic versus anthropogenic signals. The Quaternary record therefore portrays the ISM not as a uniformly responding system, but as a spatially heterogeneous and dynamically coupled hydroclimatic system whose regional expression depends on both climatic forcing and environmental mediation. This perspective provides a more robust long-term context for evaluating contemporary hydroclimatic change and risk across South Asia.

Author Contributions

M.G.: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing—original draft, Writing—review & editing. D.B.: Supervision, writing—review and editing.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new empirical datasets were generated in this study. All data discussed in this review are available in the cited published literature.

Ethical Statement

This article is a review and synthesis of previously published studies and does not involve human participants, animals, or newly collected field samples.

Acknowledgments

The authors acknowledge the researchers whose published datasets and interpretations formed the basis of this synthesis. The authors also acknowledge the broader palaeoclimate research community for developing openly accessible datasets and methodological frameworks that informed this synthesis. The authors also acknowledge DST-FST (SR/FST/ESI-107/2010) for providing the research infrastructure at the Department of Applied Geology, Dibrugarh University.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-assisted Technologies

During the preparation of this work, the authors have used Chat GPT and Grammarly for language improvement. After using the tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Wang, P.; Clemens, S.; Beaufort, L.; et al. Evolution and variability of the Asian monsoon system: State of the art and outstanding issues. *Quat. Sci. Rev.* **2005**, *24*, 595–629. https://doi.org/10.1016/j.quascirev.2004.10.002
2. Sinha, A.; Berkelhammer, M.; Stott, L.; et al. The leading mode of Indian Summer Monsoon precipitation variability during the last millennium. *Geophys. Res. Lett.* **2011**, *38*, L15703. https://doi.org/10.1029/2011gl047713
3. Kathayat, G.; Sinha, A.; Breitenbach, S.F.M.; et al. Protracted Indian monsoon droughts of the past millennium and their societal impacts. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2207487119. https://doi.org/10.1073/pnas.2207487119
4. Sinha, A.; Steiger, N.J.; Tan, L.; et al. On Indian summer monsoon droughts and teleconnections over the past millennium. *Innov. Geosci.* **2025**, *3*, 100108. https://doi.org/10.59717/j.xinn-geo.2024.100108
5. Gupta, A.K.; Anderson, D.M.; Overpeck, J.T. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature* **2003**, *421*, 354–357. https://doi.org/10.1038/nature01340
6. Staubwasser, M.; Sirocko, F.; Grootes, P.M.; et al. Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophys. Res. Lett.* **2003**, *30*, 1425. https://doi.org/10.1029/2002gl016822
7. Dixit, Y.; Hodell, D.A.; Petrie, C.A. Abrupt weakening of the summer monsoon in northwest India 4100 yr ago. *Geology* **2014**, *42*, 339–342. https://doi.org/10.1130/g35236.1
8. Cheng, H.; Edwards, R.L.; Sinha, A.; et al. The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* **2016**, *534*, 640–646. https://doi.org/10.1038/nature18591
9. Berkelhammer, M.; Sinha, A.; Stott, L.; et al. An abrupt shift in the Indian monsoon 4000 years ago. *Clim. Landsc. Civiliz.* **2013**, *198*, 75–88. https://doi.org/10.1029/2012gm001207
10. Kathayat, G.; Cheng, H.; Sinha, A.; et al. Evaluating the timing and structure of the 4.2 ka event in the Indian summer monsoon domain from an annually resolved speleothem record from Northeast India. *Clim. Past* **2018**, *14*, 1869–1879. https://doi.org/10.5194/cp-14-1869-2018
11. Kathayat, G.; Cheng, H.; Sinha, A.; et al. Indian monsoon variability on millennial-orbital timescales. *Sci. Rep.* **2016**, *6*, 24374. https://doi.org/10.1038/srep24374
12. Dixit, Y.; Hodell, D.A.; Giesche, A.; et al. Intensified summer monsoon and the urbanization of Indus Civilization in northwest India. *Sci. Rep.* **2018**, *8*, 4225. https://doi.org/10.1038/s41598-018-22504-5
13. Sun, H.; Liu, X.; Mao, X.; et al. Centennial-scale variability of the Indian Summer Monsoon during the middle to late Holocene and its links with ENSO activity. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2023**, *612*, 111380. https://doi.org/10.1016/j.palaeo.2022.111380
14. Arora, P.; Nawaz Ali, S.; Singh, P.; et al. An assessment of the correlations and causations of palaeo-hydroclimatic variability in India's monsoon-dominated Central Himalaya. *Holocene* **2024**, *34*, 1386–1407. https://doi.org/10.1177/09596836241254480
15. Jacobson, M.J.; Chawchai, S.; Scholz, D.; et al. Speleothem records from western Thailand indicate an early rapid shift of the Indian summer monsoon during the Younger Dryas termination. *Quat. Sci. Rev.* **2024**, *330*, 108597. https://doi.org/10.1016/j.quascirev.2024.108597
16. Lachniet, M.S. Climatic and environmental controls on speleothem oxygen-isotope values. *Quat. Sci. Rev.* **2009**, *28*, 412–432. https://doi.org/10.1016/j.quascirev.2008.10.021

17. Evans, M.N.; Tolwinski-Ward, S.E.; Thompson, D.M.; et al. Applications of proxy system modeling in high resolution paleoclimatology. *Quat. Sci. Rev.* **2013**, *76*, 16–28. https://doi.org/10.1016/j.quascirev.2013.05.024
18. Clift, P.D.; Hodges, K.V.; Heslop, D.; et al. Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nat. Geosci.* **2008**, *1*, 875–880. https://doi.org/10.1038/ngeo351
19. Dutt, S.; Gupta, A.K.; Clemens, S.C.; et al. Abrupt changes in Indian summer monsoon strength during 33,800 to 5500 years B.P. *Geophys. Res. Lett.* **2015**, *42*, 5526–5532. https://doi.org/10.1002/2015gl064015
20. Singhvi, A.K.; Kar, A. The aeolian sedimentation record of the Thar desert. *J. Earth Syst. Sci.* **2004**, *113*, 371–401. https://doi.org/10.1007/bf02716733
21. Laskar, A.H.; Bohra, A. Impact of Indian Summer Monsoon change on Ancient Indian Civilizations during the Holocene. *Front. Earth Sci.* **2021**, *9*, 709455. https://doi.org/10.3389/feart.2021.709455
22. Owen, L.A.; Finkel, R.C.; Caffee, M.W. A note on the extent of glaciation throughout the Himalaya during the global last glacial maximum. *Quat. Sci. Rev.* **2002**, *21*, 147–157. https://doi.org/10.1016/s0277-3791(01)00104-4
23. Dortch, J.M.; Owen, L.A.; Caffee, M.W. Timing and climatic drivers for glaciation across semi-arid western Himalayan–Tibetan orogen. *Quat. Sci. Rev.* **2013**, *78*, 188–208. https://doi.org/10.1016/j.quascirev.2013.07.025
24. Sarkar, S.; Prasad, S.; Wilkes, H.; et al. Monsoon source shifts during the drying mid-Holocene: Biomarker isotope based evidence from the core 'monsoon zone' (CMZ) of India. *Quat. Sci. Rev.* **2015**, *123*, 144–157. https://doi.org/10.1016/j.quascirev.2015.06.020
25. Veena, M.P.; Achyuthan, H.; Eastoe, C.; et al. A multi-proxy reconstruction of monsoon variability in the late Holocene, South India. *Quat. Int.* **2014**, *325*, 63–73. https://doi.org/10.1016/j.quaint.2013.10.026
26. Vidyasakar, A.; Sant'Ovaia, H.; Alappat, L.; et al. Paleoclimatic registers from semi-arid costal sediments of Southeastern India: A multi proxy approach. In *Water Resources in Arid Areas: The Way Forward*; Springer: Cham, Switzerland, 2017; pp. 3–30. https://doi.org/10.1007/978-3-319-51856-5_1
27. Prabhu, C.; Shankar, R.; Anupama, K.; et al. A 200-ka pollen and oxygen-isotopic record from two sediment cores from the eastern Arabian Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2004**, *214*, 309–321. https://doi.org/10.1016/j.palaeo.2004.07.027
28. Rashid, H.; England, E.; Thompson, L.; et al. Late glacial to holocene Indian summer monsoon variability based upon sediment records taken from the bay of Bengal. *Terr. Atmos. Ocean. Sci.* **2011**, *22*, 215–228. https://doi.org/10.3319/tao.2010.09.17.02(tibxs)
29. Contreras-Rosales, L.A.; Jennerjahn, T.; Tharammal, T.; et al. Evolution of the Indian Summer Monsoon and terrestrial vegetation in the Bengal region during the past 18 ka. *Quat. Sci. Rev.* **2014**, *102*, 133–148. https://doi.org/10.1016/j.quascirev.2014.08.010
30. Achyuthan, H.; Nagasundaram, M.; Gourlan, A.T.; et al. Mid-Holocene Indian Summer Monsoon variability off the Andaman Islands, Bay of Bengal. *Quat. Int.* **2014**, *349*, 232–244. https://doi.org/10.1016/j.quaint.2014.07.041
31. Nagasundaram, M.; Achyuthan, H.; Ahmad, S.M. Monsoonal changes inferred from the Middle to late Holocene sediments off Landfall Island, North Andaman. *Arab. J. Geosci.* **2013**, *7*, 3513–3523. https://doi.org/10.1007/s12517-013-1010-6
32. Chauhan, T.; Devanand, A.; Roxy, M.K.; et al. River interlinking alters land-atmosphere feedback and changes the Indian summer monsoon. *Nat. Commun.* **2023**, *14*, 5928. https://doi.org/10.1038/s41467-023-41668-x
33. Tripathi, S.; Basumatary, S.K.; Singh, V.K.; et al. Palaeovegetation and climate oscillation of western Odisha, India: A pollen data-based synthesis for the Mid-Late Holocene. *Quat. Int.* **2014**, *325*, 83–92. https://doi.org/10.1016/j.quaint.2013.12.005
34. Wang, Y.V.; Larsen, T.; Lauterbach, S.; et al. Higher sea surface temperature in the Indian Ocean during the Last Interglacial weakened the South Asian monsoon. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2107720119. https://doi.org/10.1073/pnas.2107720119
35. Fairchild, I.J.; Baker, A.; *Speleothem Science: From Process to Past Environments*; Wiley-Blackwell: Chichester, UK, 2012.
36. Fathima, R.; Saraswat, R. A synthesis of paleomonsoon and associated processes from the unique depocenter, Andaman Sea. *Geo-Mar. Lett.* **2023**, *43*, 15. https://doi.org/10.1007/s00367-023-00756-z
37. Gayathri, N.M.; Sreevidya, E.; Sijinkumar, A.V.; et al. Last 15 ka record of water column changes associated with Indian summer monsoon variability from the northeastern Bay of Bengal. *Quat. Int.* **2025**, *723*, 109713. https://doi.org/10.1016/j.quaint.2025.109713
38. Nayak, P.K.; Singh, A.K.; Mallick, K.R.; et al. Indian monsoon modes and their linkage with precipitation in the Andaman Sea region late Quaternary planktic foraminiferal records. *J. Palaeontol. Soc. India* **2025**, *70*, 249–265. https://doi.org/10.1177/05529360251345236
39. Sreevidya, E.; Sijinkumar, A.V.; Nath, B.N. Palaeoceanographic significance of aragonitic pteropods in the Indian Ocean – A review. *Boreas* **2022**, *51*, 1–19. https://doi.org/10.1111/bor.12540
40. Sreevidya, E.; Sijinkumar, A.V.; Nath, B.N.; et al. A ∼50 kyr record of carbonate (pteropods) preservation from the Laccadive Sea, Northern Indian Ocean. *Mar. Geol.* **2023**, *455*, 106958. https://doi.org/10.1016/j.margeo.2022.106958
41. Sijinkumar, A.V.; Nath, B.N.; Prabhakar, S. Late Quaternary carbonate preservation in the Andaman Sea versus the Central Indian Basin: A test of dissolution under diverse oceanographic settings in the Indian Ocean. *Quat. Int.* **2022**, *642*, 103–115. https://doi.org/10.1016/j.quaint.2021.06.014
42. Resmi, M.R.; Achyuthan, H.; Deopa, H. Holocene monsoonal variations over Southern India: Looking into its antecedents. *Front. Earth Sci.* **2022**, *9*, 717420. https://doi.org/10.3389/feart.2021.717420
43. Thamban, M.; Kawahata, H.; Rao, V.P. Indian summer monsoon variability during the holocene as recorded in sediments of the Arabian Sea: Timing and implications. *J. Oceanogr.* **2007**, *63*, 1009–1020. https://doi.org/10.1007/s10872-007-0084-8
44. Solanki, H.; Jain, V.; Thirumalai, K.; et al. River drought forcing of the Harappan metamorphosis. *Commun. Earth Environ.* **2025**, *6*, 926. https://doi.org/10.1038/s43247-025-02901-1
45. Ronay, E.R.; Breitenbach, S.F.M.; Oster, J.L. Sensitivity of speleothem records in the Indian Summer Monsoon region to dry season infiltration. *Sci. Rep.* **2019**, *9*, 5091. https://doi.org/10.1038/s41598-019-41630-2
46. Desamsetti, S.; Dasari, H.P.; Langodan, S.; et al. Enhanced simulation of the Indian summer monsoon rainfall using regional climate modeling and continuous data assimilation. *Front. Clim.* **2022**, *4*, 817076. https://doi.org/10.3389/fclim.2022.817076
47. Zhou, J.; Chen, F.; Zhu, Y.; et al. Reconstruction of temperature, precipitation, and identification of extreme climate events in high mountain Asia over 500 years using multi-method EnKF. *Sci. Rep.* **2026**, *16*, 5610. https://doi.org/10.1038/s43247-025-02901-1
48. Oster, J.L.; Ronay, E.R.; Sharp, W.D.; et al. Controls on speleothem initial $^{234}U/^{238}U$ ratios in a monsoon climate. *Geochem. Geophys. Geosyst.* **2023**, *24*, e2023GC010899. https://doi.org/10.1029/2023gc010899
49. Parker, S.E.; Harrison, S.P.; Comas-Bru, L.; et al. A data–model approach to interpreting speleothem oxygen isotope records from monsoon regions. *Clim. Past* **2021**, *17*, 1119–1138. https://doi.org/10.5194/cp-17-1119-2021
50. He, C.; Liu, Z.; Otto-Bliesner, B.L.; et al. Hydroclimate footprint of pan-Asian monsoon water isotope during the last deglaciation. *Sci. Adv.* **2021**, *7*, eabe2611. https://doi.org/10.1126/sciadv.abe2611