Fluvial archives of north and northwestern India as recorders of climatic signatures in the late Quaternary: review and assessment

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The Indian sub-continent is characterized by extremely variable climatic regimes at present, and this strong climatic diversity is also reflected during late Quaternary and Holocene time scales. Fluvial archives across different morpho-climatic zones of India record variable response to monsoonal fluctuations through time as preserved in patterns of sedimentary sequences and characteristic facies. This study has compiled the fluvial records from north and northwestern India to synthesize the palaeoclimatic information available from this broad region and to assess the coherence or otherwise of these records across widely different morpho-climatic regimes. Rivers across different regions of India show widespread floodplain aggradation during Marine Isotope Stage (MIS)-5 but responded quite differently during MIS-4 e.g. degradation in the Ganga plains and aeolian deposition in the western part. Significant discontinuities were developed in the interfluves of the Ganga plains during MIS-3 and 2 whereas the western Indian rivers recorded variable response. The Holocene monsoonal fluctuations are manifested in widespread incision across western India and several events of valley filing in the Ganga plains.

Keywords: Climate of the past, climate change, Indian summer monsoon, river response.

Introduction

THE issue of global climate change and its impact on socio-economic and natural resources has become a major concern in all parts of the world. To understand the recent climate changes more completely, it is useful to study the natural variability in climates of the past at longer (e.g. late Quaternary) as well as shorter (e.g. millennium and century) time scales. Such studies of the climate variability within the late Quaternary are of significance to determine the magnitude, and rate of past climate changes, which may also provide some insights on future climate changes.

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Northern India is drained by two major river systems, the Ganga/Yamuna system in the north and the Indus system in the northwest. Besides, several moderate-sized rivers such as the Luni, Sabarmati, and Mahi drain western India. The rivers of the Indian sub-continent have experienced large fluctuations in discharge and sediment yield related to the variations in the Indian Summer Monsoon (ISM) that deliver more than 85% of total annual precipitation during mid-June through September. Therefore, any changes in the monsoon strength and precipitation, regional distribution and seasonality will impact the entire Indo-Gangetic plains (IGP) and neighbouring regions. Fluvial sedimentary archives from the late Quaternary sequences of northern and northwestern India should, therefore, record a complex history of changes in the ISM that have been documented by detailed analyses of sedimentary facies characteristics, stratigraphy and depositional ages by several workers. The alluvial stratigraphic records primarily represent aggradational and erosional/incisional history of the rivers that are in turn driven by forcing factors such as monsoonal precipitation. Further, a significant rainfall gradient exists in the Indo-Gangetic plains in an east–west transect, which coupled with variable hinterland characteristics has generated a remarkable geomorphic diversity[1]. This also means that the river systems across the IGP may have had ‘differential sensitivity’ to imposed climatic changes resulting in significant spatial variability in fluvial response to climate change at late Quaternary and Holocene time scales. This study attempts to compile the available information on alluvial stratigraphic records across the IGP and neighbouring regions (Figure 1) to develop a regional scale understanding of fluvial responses to climate change.

The southwest monsoon and its variability

One of the first simulations of palaeoclimatic history of the northern hemisphere summer monsoon for the past 150 ka using Global Circulation Models (GCMs)[2] showed four distinct monsoon maxima at 10, 82, 104 and 126 ka that are closely related to solar insolation maxima. In

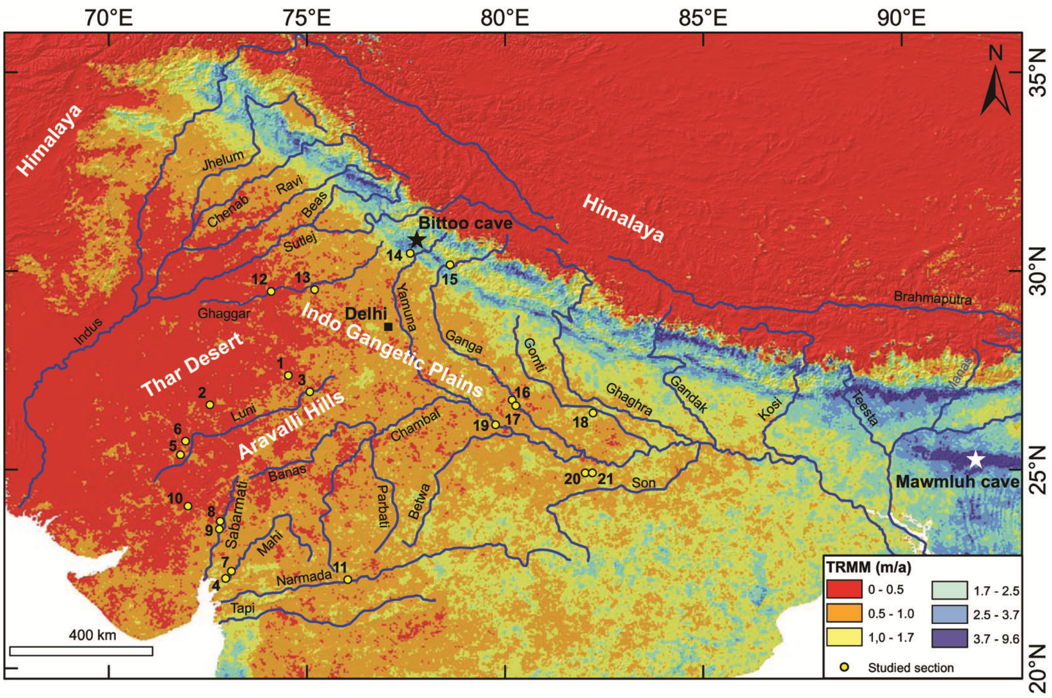

Figure 1. Mean annual rainfall (1998–2009) based on calibrated TRMM 2B31 data, a combined precipitation radar (PR)/TRMM Microwave Imager (TMI) rain-rate product with path-integrated attenuation at 4 km horizontal and 250 m vertical resolutions. Locations of stratigraphic sections and coring sites are: 1, 2, Thar Desert; 3, Sambhar lake; 4, Southern margin of the Thar; 5, 6, Luni plains; 7, Mahi; 8, 9, Sabarmati; 10, Gujarat plains; 11, Narmada-Bhima; 12,13, Ghaggar-Hakra; 14, Frontal Yamuna; 15, Alaknanda; 16, Ganga Plains; 17, Ganga-Yamuna interfluve; 18, Ganga-Gomati interfluve; 19, Yamuna plains; 20, 21, Belan. Locations of Mawmluh cave and Bitto cave are also shown.

contrast, generally weaker monsoon conditions were simulated between 75 and 15 ka during which southern Asia was drier than today but with two monsoon maxima at ~58 and ~32 ka. Based on δ^{18}O variation in an ice core from the Guliya ice cap on the Qinghai–Tibetan Plateau, the interglacial stages (Marine Isotope Stage (MIS)-3 and 5) and the glacial stages (MIS-2 and 4) have been marked[3]. Higher values of δ^{18}O in the Guliya ice core during the early Holocene compared to those in the mid-Holocene were interpreted to represent warm and moist conditions[3]. A more recent record from the Mawmluh cave in Meghalaya shows strengthened ISM during 33.5–32.5 ka, 15–12.9 ka (Bølling–Allerød) and 10–6.5 ka (early Holocene) but a weakened ISM during late-MIS-3 that continued to early MIS-2 (26–23.4 ka)[4]. A high-resolution speleothem oxygen isotope (δ^{18}O) record from Bittoo cave in Uttarakhand, northern India[5] has provided millennial–orbital scale variations in the southwest monsoon dominated by orbital scale (23 ka long) cycles punctuated by millennial-scale strong interstadial events. A compilation of Holocene climate based on lake records across the Indian subcontinent[6] has shown an intensified monsoon between 9 and 5 kyr BP, corresponding to the globally recorded warm and wet period of the Holocene Climate Optima. After 4 kyr BP, a general trend in aridity is recorded throughout India. These results support the previous palaeoclimatic studies[2,7] and suggest that the monsoonal conditions have varied on centennial–millennial time scales within the Holocene.

Fluvial archives from north and NW India: regional correlation and inter-comparisons

Late Quaternary

Late Quaternary alluvial stratigraphy of the eastern and western Ganga plains based on cliff sections and drill cores has been documented and reviewed earlier (Figure 1)[8–12]. Table 1 and Figure 2 summarize the climatic interpretations from studies in the Himalaya, IGP and western India rivers for the late Quaternary period. Stratigraphic sections supported by luminescence ages and radiocarbon dates have indicated that the western Ganga plains were dominated by floodplain aggradation, punctuated by periods of stronger pedogenic activity and local degradation during MIS 5–3 (100–35 ka)[8,11,13,14]. A set of drill cores from the Ganga valley coupled with cliff section stratigraphy[10,11,15] recorded a general weakening of ISM during the transition period from late MIS-5 to 4. This period is represented by channel (74 and 61 ka) and floodplain (at ~89 ka) deposition in the Ganga valley[16]. A more recent

Table 1. Summary of fluvial aggradation and incision in fluvial archive of Indian rivers

Time	14 ka to present (MIS-1)	28–14 ka (MIS-2)	59–28 ka (MIS-3)	74–59 ka (MIS-4)	105–74 ka (Late MIS-5)	Reference
Indo–Gangetic basin						
Frontal Himalaya, Yamuna valley	Aggradation (4–7 ka), (3–2 ka), and (<2 ka) Incision (7–11 ka), (3 ka) and (<2 ka)	Incision (11 ka) Aggradation (12–15 ka)	Incision (24 ka) Aggradation (24–37 ka)	N/a	N/a	48
Alaknanda valley	Valley aggradation (15–8 ka) incision (<11 ka)	Aggradation (11–18 ka)	Aggradation (25–49 ka)	N/a	N/a	44, 45
Ganga valley	Incision followed by rapid aggradation (2.7 ka-present) Aggradation (16–11 ka)	Incision Aggradation (16–11 ka)	Incision Aggradation (30–45 ka)	Episodic aggradation (74 ka, 61 ka) with intermittent incision.		16, 40, 86
Ganga–Yamuna interfluve	Fluvial, humid (6–11 ka) Incision (13–9 ka)	Floodplain, palaeoslos (30–20 ka) Aggradation (30–40)	Floodplain aggradation, palaeoslos with extensive illuviation, humid conditions (40–60 ka)	Relatively drier, palaeosols (75–60 ka)	Humid conditions, palaeosols showing extensive illuviation (90–80 ka)	11, 13, 17, 86
Yamuna valley in plains	N/a	Drier period followed by regional incision, interfluve facies (53–10 ka); extensive gully erosion and ravine development		Channel facies, warmer and wetter conditions (80–54 ka); major aggradation at 62 ka	Floodplain facies, alternate warm-wet and cold conditions (120–100 ka, 82 ka)	13, 18
Belan valley	Fluvial/aeolian deposition, climatic instability 14–7 ka) Incision (8–10 ka)	Continued alluvialtion with intermittent gully erosion (31–21 ka); reduced precipitation Floodplain build ups (16–70ka)			Mixed-load meandering rivers (85–72 ka)	14
	Aggradation (5.5 ka)	Incision (<16 ka) Aggradation (16–39 ka)	Aggradation (45 ± 12 and 58 ± 6)	Aggradation (73 ± 4 ka)	N/a	28, 29
NW India						
Ghaggar–Hakra	Fluvial deposition (7.3–5ka); Foothills-fed river (4.0–7ka); Dune accumulation (9 ka and post 4.5 ka)	Aggradation in incised valley (12–25 ka)	Channel and floodplain setting (30–46ka)	Aggradation braided river (59–70ka)	Aggradation braided river (70–86 ka)	31, 59, 60
	Foothills-fed (<2.9 ka) Aeolian (2–1.7 ka) Fluvial (5.9–2.9 ka)	Aeolian (14–18 ka)	Aggradation (21–28 ka)	N/a	N/a	57, 58

(*Contd*)

Table 1. (*Contd*)

Time	14 ka to present (MIS-1)	28–14 ka (MIS-2)	59–28 ka (MIS-3)	74–59 ka (MIS-4)	105–74 ka (Late MIS-5)	Reference
Western India						
Thar desert	Aeolian activities after Holocene Climatic Optimum between 5 and 3.5 ka, 2 and 0.8 ka	Aeolian (20–11 ka)	Floodplain and Pedogenesis (60–30ka)	Arid (70–60 ka)	Flood plain fines (100–70 ka)	19, 20, 26
Mahi basin	Incision during the early Holocene	Fluvial dormancy and aeolian dunes	Mixed load meandering rivers. Aggradation during 52–44 ka and 37–30 ka. Warmer, wetter		Mud deposits (MIS-5e) followed by gravel bedload braided stream deposits (74 ka); Humid	22, 23
Luni basin	Aeolian; climatically unstable phase (13–8 ka)	N/a	Humid phase with landscape stability (52–30 ka)	N/a	Channel activation (90 ka), sheet flood deposits (~70 ka) Aeolian phase (86 ka)	24, 33
	Diverse lithofacies (14–11 ka); high-frequency, high-amplitude climatic changes Incision (11–9 ka) Aeolian (9 ka and 5 ka) Incision (3–1 ka)	Ephemeral sand-bed streams (30–22 ka) Incision (22–14.6 ka)	Pedogenesis (70–30 ka)		Gravel–palaeosol association (>86 ka)	24
Sabarmati basin	Regional aridity (6–3.5 ka)	Aeolian dunes, dry (22 ka); fluvial aggradation and pedogenesis (18–12 ka); wet climate	Fine sand sheet wash (39 ka) Red sand pedogenesis (58 ka)	N/a	Fluvial aggradation (~90 to 84 ka) and red soil deposition (prior to 63 ka)	25, 36
	Aeolian (~12 ka) Fluvial aggradation (18–12 ka), wet climate	Aeolian (30–14 ka)	Mix load stream and floodplain (30–60 ka)	N/a	N/a	23

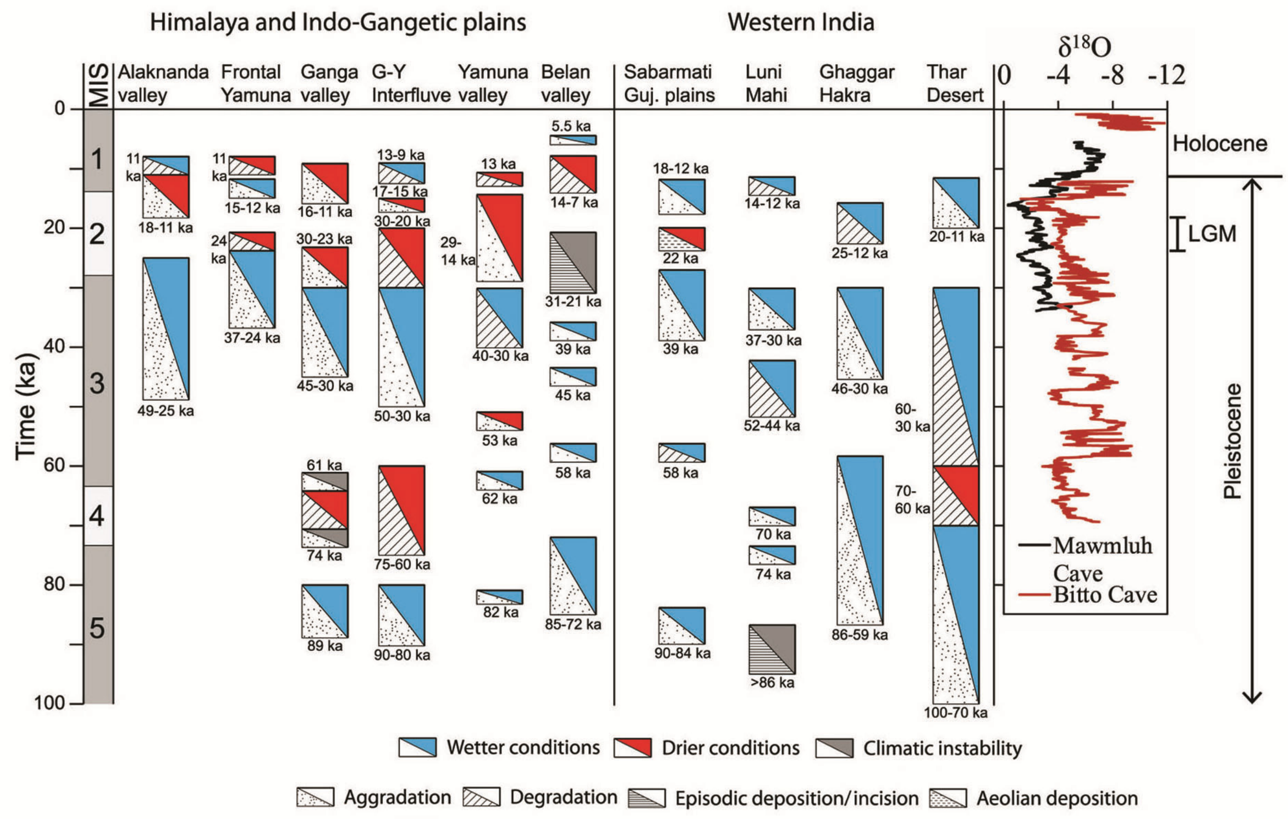

Figure 2. Climatic reconstruction and fluvial response in northern and northwestern India during the late Quaternary period. High-resolution speleothem oxygen isotope ($\delta^{18}O$) record from Mawmluh cave[4] in Meghalaya, northeast India and Bittoo cave in Uttarakhand, northern India[5] are also shown.

work based on micromorphology of the palaeosols in the Ganga–Yamuna (G–Y) interfluve has inferred three major phases of humid conditions spanning 90–80 ka, 50–30 ka and 10 ka with intervening drier phases[17]. These humid phases in the G–Y interfluve were characterized by palaeosols showing extensive illuviation, increased mineral weathering and strong pedogenic activity. In contrast, the dominance of pedogenic carbonates and weak pedogenic development were recorded in the palaeosols developed under relatively drier conditions during 75–60 ka and 30–20 ka in the G–Y interfluve (Table 1). New data from the cliff sections along the Yamuna river has indicated alternate warm–wet and cold conditions during 120–100 ka (MIS-5) represented by floodplain lithofacies followed by warmer and wetter conditions during 80–54 ka (including MIS-4) characterized by channel facies[18]. Further south in the Ganga plains, mixed load river deposits in Belan valley[14] provided dates between 85 and 72 ka (Table 1, Figure 2) suggesting sustained fluvial activity during MIS-5 (ref 14).

In western India, the ISM maxima during late MIS-5 and early MIS-3 is represented by aeolian sand deposition (at ~75 and ~55 ka) due to strengthened monsoonal winds in the Thar Desert[19,20] whereas continued fluvial aggradation (86–64 ka) of multi-storied fining upward sand bodies in the Ghaggar–Hakra palaeochannel[21] in NW India (Table 1) in response to hydrological changes across the transitions from late MIS-5 to early MIS-3 is observed. The MIS-5/4 transition in western India has been documented as gravel bedload aggradation (74 ka) in braided stream deposits in the Mahi river[22,23], sheet flood deposits (~70 ka) in Luni river[24], fluvial aggradation (~90 to 84 ka) and red soil formation (prior to 63 ka) in upper Sabarmati river[25]. Also, the MIS-4 in western India is represented by aridity (60–70 ka) as recorded in calcrete isotope records[26].

The early MIS-3 (>40 ka) has been identified as a period of prolonged floodplain accumulation punctuated by pedogenetic modification and floodplain degradation in the Yamuna valley[13] and Ganga valley[16] as well as in the Mahi basin[22], Sabarmati basin[27] and Luni basin[23] in western India. It has been suggested that such variable response across different regions was related to monsoonal fluctuations manifested as aggradation (higher floods) during wetter and degradation during drier periods[13].

During late MIS-3 and MIS-2, a major change in sedimentation pattern was recorded in terms of discontinuities manifested as gullying in the Yamuna plains (Kalpi section) and Belan valley[14] (13.4 and 12.2 ka), aeolian/lacustrine sedimentation in the Ganga valley (~27 ka, Bithur section[15]), and floodplain degradation in smaller interfluve rivers (13–9 ka, Mawar section[13]). During the post-LGM time, the weakest phase of ISM was during 17 to 15 ka, the Heinrich event H1 that was followed by an increase in ISM strength during the Bølling–Allerød from 15 to 12.9 ka followed by a decrease in strength during Younger Dryas from ~12.8 to 11.7 ka (ref. 4). Records based on drill cores from the Ganga valley showed renewed fluvial activity (~16–11 ka)[16] in the post-LGM period followed by incision, as well as southward migration of the Ganga river after 6 ka (ref. 15). In the Belan valley also, the evidence of localized eolian activity has been documented, interspersed with fluvial activity, during 14–7 ka that coincided with the establishment of Palaeolithic and Mesolithic settlements after the LGM[28,29]. More recent work in the ravines of the marginal Ganga plains places ~14 ka as the cessation of aggradation on these plains and initiation of incision leading to the formation of the ravines[30]. In the Ghaggar valley in NW India, the incision was interpreted based on the inset of younger deposits (~23 ka) into older fluvial deposits[31]. It is inferred that such incision possibly occurred during high precipitation[4] in the late MIS-3.

In western India, the late MIS-3 is identified with regional fluvial aggradation as recorded in the Luni basin[33]. This was followed by the weakest phase of ISM from 26 to 23.5 ka identified by ephemeral sand–bed streams in the Luni basin[24]. The post-LGM time is identified as gravel braided and mixed load sediments (12-14 ka) inset within the incised (c. 14 ka) Luni river[24]. However, significant variability in fluvial response to climate change has been recorded in the upland western India that has been attributed to differences in basin area and rainfall[34]. The rivers such as Bhima and Narmada falling in high rainfall zone record massive aggradation during 26–14 ka in contrast to the rivers such as Sindhphana and Vel falling in a semi-arid zone which show a major erosional event around 14 ka. In the North Hill range in Kachchh, a period of non-deposition between 22 and 16 ka corresponding to the LGM period followed by a major fluvial aggradation phase until 10 ka has been reported[35]. This phase was preceded by a bedrock incision event that was driven by the uplift along the Kachchh Mainland Fault (KMF) prior to 24 ka. Sedimentary records from the Gujarat plains[36] suggest strong monsoonal conditions with some fluctuations between 37 and 27 ka followed by a gradual onset of aridity peaking at ~22 ka. Thus, floodplain and channel aggradation occurred respectively in the strong monsoon time during early[37] and late MIS-3 (ref. 4) whereas, pedogenesis and calcrete formation happened in the mid MIS-3 during the time of relatively weak monsoon[5] (50 to 48 ka and 41 to 39 ka).

Holocene

The GCMs show that the climate system in the Indian sub-continent was relatively stable commencing from 11,700 years (ref. 2). Therefore, there has been a very strong focus on the reconstruction of high-resolution records for post-LGM and Holocene periods to understand the forcing parameters, which have governed the monsoonal strength during these periods[7,38,39]. In the Ganga alluvial plains, several Holocene lake records have been extremely useful for the reconstruction of the Holocene climate variability in this region. Based on a compilation of radiocarbon dates across the Indian subcontinent, it has been suggested that the Holocene monsoonal fluctuations have strongly influenced the century to millennium scale variability in fluvial systems albeit with variable regional responses[40].

In central Ganga plains, three major phases of alluviation (13.9–12.3, 11.9–11.2 and 9.8–9.0 cal ka BP) have been suggested before the onset of the Holocene climate optimum phase based on the clustering of the available radiocarbon dates[40]. This has been borne out by several studies based on cliff sections and drill cores in this region by several workers as described next. In the Ganga–Yamuna interfluve, a ~11 m high cliff section at Mawar along the Sengar river reveals floodplain degradation and formation of gully fill channels in the early Holocene (13–9 ka) period (Table 1, Figure 3) and this was interpreted to correspond broadly with a period of increasing precipitation and a probable increase in transport capacity of rivers[13]. In the Ganga–Gomati interfluve, a strong fluvial activity between 13 and 8 ka was followed by minor lacustrine sedimentation and a brief period of aeolian aggradation (post 6 ka) forming alluvial ridges[41]. The presence of lacustrine and aeolian deposits indicates a decline of fluvial activity in mid-Holocene time and reworking of fluvial sand by aeolian processes. Major alluviation phases in late Holocene (3.6–2.8 cal ka; 1.1–0.9 cal ka) have been recorded and it has been suggested that peak monsoon phases during the Holocene generally lacked any clustering of radiocarbon dates as these are generally marked by channel incision[40].

The transition from late Pleistocene to Holocene, marked by the intensification of ISM[2], shows a contrast of limited aggradation with dominant incision (11 and 9.7 ka) north of the frontal thrust with that of continuous aggradation (12–6 ka) to the south[42]. The early Holocene (~9.5 ka) in the Higher Himalaya is characterized by the incision of the valley fills induced by high fluvial discharge attributed to an intensified monsoon as recorded in the Alaknanda valley[43,44]. A major valley aggradation phase has also been documented in the Alaknanda valley[45] during 15–8 ka. In the upstream reaches of the Alaknanda valley, higher incision rates of 4 mm/a and 5 mm/a based on cosmogenic radionuclide (CRN) dating of strath terrace were documented at Srinagar and Nanda Devi respectively in Garhwal Himalaya during the mid-Holocene time[46,47].

The frontal region in the Yamuna valley[48] has three Holocene aggradation phases (Table 1) recorded between 7 and 4 ka; 3 and 2 ka and <2 ka preceded by three

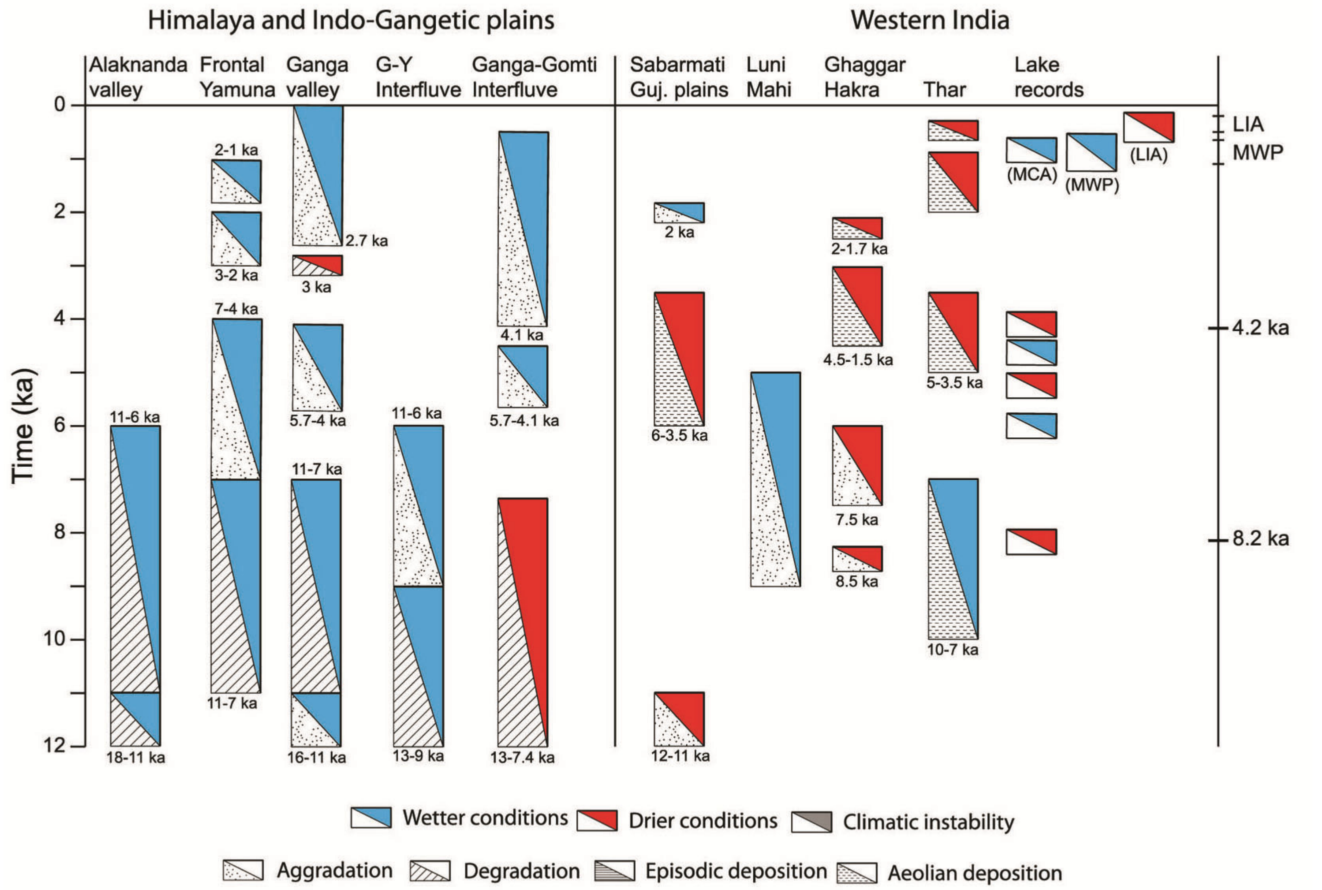

Figure 3. Climatic reconstruction and fluvial response in northern and northwestern India during the Holocene period.

incision events during 11–7 ka, 4–3 ka and <2 ka. Peat-lake sediments in the Chandra valley in NW Himalaya[49] show elevated δ^{13}C values and low TOC values, suggesting a weakening of monsoon between 12.8 and 11.6 ka corresponding to Younger Dryas event followed by intensification of ISM during 11.6 and 8.8 ka. Based on geochemical and pollen data, this study recorded three major cold-dry events, namely (a) ~8810 to 8117 cal year BP (~8.2 ka cold event), (b) ~4808 to 4327 cal year BP (preceding 4.2 ka cold-arid period), and (c) ~1303 to 1609 cal AD (equivalent to the LIA event).

Using clay minerals and soil micromorphology as proxies for climate change and pedo-sedimentary environments in the Central Ganga plains[50,51], three distinct phases have been interpreted in Holocene, namely (i) 12,920–7390 cal year BP: arid climate, (ii) 5730 and 4150 cal year BP: warm and wet climate and (iii) post-4150 cal year BP: arid to sub-humid phase. In the Sharda–Gandak interfluve area, two terrace surfaces in the Ghaghra–Rapti interfluve were dated as 11.5 ka and 5.5 ka, suggesting a fluvial history influenced by rapid deposition and avulsion.

Lake records in the Ganga plains have provided a better-resolved palaeoclimatic data for the Holocene period (Figure 3). The early Holocene is marked by a cool and dry climate (14–12.5 ka and 11.5–10.5 ka), and the monsoonal intensification between 12.5 and 8.7 ka brought in warm and humid climate[52,53]. The warm and moderately humid condition continued during 8.5–6.4 ka and got wetter during 6.4–3.1 ka as inferred from the pollen data and stable isotope analysis of gastropod shells from the ox-bow lakes in the central Ganga plains[54,55]. This was followed by a weakening of monsoon and reduced rainfall between 3.1 and 1.1 ka marked by the dominance of open grasslands particularly after 1100 yrs cal BP[54,55].

In NW India, major fluvial activity ceased owing to the avulsion of the large river from the Ghaggar–Hakra palaeochannel[31] around ~8 ka and the palaeo-Yamuna River[56] much before that (possibly prior to 41 ka). Therefore, the Holocene period is represented by fine-grained sediment of ephemeral streams (7.1–4.0 ka) along with aeolian sediments. Similarly, fine-grained fluvial deposition between 6 and 4.3 ka has been reported in the upstream in the Ghaggar–Hakra[57,58] followed by a decline in fluvial activity at 3.4 ka in late Holocene; while in the downstream, major fluvial activity (~7.3 ka and ca. 5 ka) ceased in the Ghaggar basin[59,60] (Table 1) with the start of dune accumulation after 4.5 ka and before 1.4 ka. The early Holocene in Sutlej is identified by periodic but progressive incision between 10 ka and 8.7 ka pre-dating the Harappan settlements[60]. In contrast, both fluvial and aeolian deposition is reported from the Ghaggar-Hakra interfluve[61] with fluvial deposition during early to mid-Holocene (8.5 to 3 ka) with more intense fluvial processes prior to 5 ka, whereas aeolian accumulations were identified at 9 ka, and between ~7.1–5.7 ka and ~2–1.7 ka. Aeolian activity and dune building in the Thar Desert during early Holocene (10.14 ± 0.69 ka) continued until 6.86 ± 0.49 ka with mid- and late Holocene activity at ~5 ka and ~3.5 ka coinciding with periods of lower precipitation[62].

In western India, the early Holocene period of relatively stronger and intense monsoon is represented by erosional events, e.g. incision in Sabarmati basin[63] at ~12 ka followed by fluctuating climatic conditions with frequent arid events including the 4.2 ka cold event[35,36,40,64]. Based on the clustering of the radiocarbon dates, major alluviation phases in the Deccan peninsula[40] during the Holocene have been identified as 12.8–11.2, 10.8–8.9, 8.1–6.7 and 5.1–3.9 cal ka. Variable fluvial responses are manifested as fluvial and aeolian deposition (9–5 ka) in Luni, Mahi and Sabarmati rivers[23,27,65]. Aggradation in both Narmada and Godavari rivers in western India has been documented[34] in the early Holocene but an erosion in the Bhima basin highlights differential fluvial response to climate change. In the Northern Hill Region (NHR) in Kachchh[35], the period 10–8 ka lacks any sediment accumulation but a major aggradation phase was recorded between 8 and 4 ka. In Gujarat plains, the monsoon strengthened gradually after the LGM (18–12 ka) with a short reversal around 12–11 ka that has been attributed to the Younger Dryas cooling event[36]. The regional aridity in this region between 6 and 3.5 ka was recorded as indicated by the aeolian sand sheet followed by a short-lived humid phase after ~2 ka that includes the Medieval Warm Period (MWP)[36]. High-resolution lake records from south of Narmada, particularly from Lonar, have provided some interesting data from the core monsoon zone of central India. An increased detrital flux at Lonar[66,67] in response to intensified monsoon from ~10 ka lasted up to ~6 ka followed by two short arid phases from 4.6 to 3.9 ka and 2 to 0.5 ka.

High-resolution lake records from the Thar and Thar margin have shown that the monsoon was strengthened between 9.4 and 8.3 ka as manifested in high lake levels and salinity variations during this period[64,68,69]. A more recent regional synthesis of lake records from the Indian sub-continent[6] shows a peak in monsoon strength between 9 and 5 ka corresponding to the global Holocene climate optima. An abrupt dying out of Riwasa[70] has been recorded at 8.2 ka followed by wetter monsoon conditions and highest lake levels at ~6 ka in Didwana[71]; Nal Sarovar[72]; Lunkaransar[68]. An abrupt phase of desiccation at ~4.1 ka has been documented at Kotla Dhar[70] and then complete desiccation of several lakes between 4 and 3 ka has been noted[32,68,71] followed by a general aridity trend throughout India.

Last millennium

High-resolution records, particularly from fluvial archives, documenting the climatic events in the Indian subcontinent during the last millennium are very few. However, some fluvial cut off lakes and palaeoflood records in northern and NW India have been compiled here to summarize the climatic history of this region. Recent compilations of lake records and other archives from different geomorphic and climatic regions across India[6,73] suggest that the last millennium witnessed warm and wet phase between 1.05 and 0.7 ka year BP in the Central Ganga Plains as manifested in reduced $\delta^{18}O_{carb}$ (‰) values in sediments from the Ropan Chappra lake[74], roughly corresponding to the Medieval Climate Anomaly (MCA). Pollen records from peat-lake deposits in Chandra valley in NW Himalaya show moderate expansion of broad-leaved, non-arboreal pollens (NAP) and ferns between ~1158 and 647 cal year BP (792–1303 cal AD) and this coupled with increased TOC and LOI content in sediments suggest climatic amelioration during this period that roughly corresponds to the Medieval Warm Period (MWP)[49].

Lake records from the Higher and Lesser Himalaya for the Little Ice Age (LIA) period (0.7–0.1 ka BP) reveal a cold and dry phase[6] along with a weakened ISM. This is exemplified by a decline in broad-leaved taxa and meadow vegetation during 647–341 cal year BP in the peat-lake deposits in Chandra valley suggesting cold–dry and weaker ISM[49]. While it is generally agreed that the ISM was strong during the MCA and relatively weak during LIA, it has been suggested that the region influenced by the Westerlies experienced increased precipitation during LIA linked with the intensified western disturbance over NW India during this period[73].

In NW India, late Holocene dune accumulation (1.92 ± 0.16 ka and 1.07 ± 0.09 ka) in the Thar desert[62] links with the gradual drying of the fluvial channels in this region; recent dune activity (between 600 and 200 years ago) in the area coincides with reduced rainfall 600–200 years ago[75].

An important archive for reconstructing the last millennium palaeoclimatic record is the palaeoflood events identified by the slackwater deposits. A palaeoflood record from the Alaknanda valley suggests a wetter climate 200–300 years ago while an older flood event at 1.2 ka was interpreted as a local sediment mobilization during a relatively drier climate[43]. Several palaeoflood records are available from western India and some of the best-preserved deposits have been found in the Narmada[76–78], Tapi[79], Luni[80] and Mahi[81,82] basins. A recent compilation of palaeoflood records[83] shows that there is a general absence of large floods during MWP in the peninsular as well as Himalayan rivers. Several rivers in Gujarat such as Mahi[82,84], Sabarmati[54] and Narmada[78] recorded high magnitude floods during weak monsoon periods (e.g. 0.5 and 1.7 ka), possibly due to time lag in response to ISM variations[65,85]. This observation seems to be corroborated by the analysis of historical floods as well[76]. A clustering of floods during the LIA has been reported[83] and this has been linked to the intra-seasonal monsoonal variability dominated by 'active' and 'break' spells in the core monsoon zone[86,87]. A 2000-year record of palaeofloods from Narmada[78] suggests that exceptionally high floods occurred during 400–1000 AD and post 1950 AD whereas the period 1400–1950 AD was characterized by lower magnitude floods. The palaeoflood record from Tapi[88] suggests 6–9 high floods in the post-1950 period; the highest being of the order of 4000 m^3/s.

Concluding remarks and future perspectives

Our compilation of climatic reconstructions for northern and northwestern India indicates significant variability in fluvial response to climate change during the late Quaternary. Records in the Himalaya and the IGP generally show a first-order coherence in terms of aggradation and degradation events (Figure 2). Our synthesis shows that the wetter condition during MIS-5 was characterized by widespread floodplain aggradation in rivers across the Indian subcontinent. A general weakening of ISM during the MIS-5/4 transition is marked by channel and floodplain deposition in Ganga valley and gravel deposition in several western Indian rivers. The MIS-4 across India is represented by aridity as recorded in the aeolian deposition and calcrete records in western India and degradation of river floodplains and non-fluvial deposition in the Ganga plains. The early MIS-3 records a prolonged floodplain accumulation punctuated by pedogenic modification in the Ganga valley as well as in the western Indian rivers. A major change in the depositional environment was recorded in terms of discontinuities manifested as gullying and/or aeolian/lacustrine sedimentation in the Ganga plains during late MIS-3 and 2 whereas the river basins in western India record a mixed response (aggradation or degradation) depending upon their rainfall regime along a gradient. The Holocene monsoonal fluctuations are manifested as several periods of aggradation in the Ganga plains, cessation of major fluvial activity in NW India, and strong erosional events in western India. While most workers have documented the cessation of large scale fluvial activity in NW India in early Holocene[21,31,58–60], thereby refuting the sustenance of the Harappan civilization by a large river, a recent work[89] suggests 'reactivation' of a large river between 9 and 4.5 ka that facilitated the development of Harappan settlements along its banks. High-resolution lake records from the Thar region as well as the Ganga plains show high lake levels during early Holocene and then a decline in summer monsoon strength is manifested in drying up of these lakes.

It is also important to note that the fluvial response in terms of aggradation or degradation primarily depends upon the sediment to water ratio and therefore aggradation may occur during wet as well as dry climate and this explains, in some cases, the differential responses of river systems across the different climatic regimes. Further, while sediment production in the hinterland is controlled by tectonic processes, its mobilization into the alluvial plains depends upon the water fluxes which is a function of climate. In western India, several river systems lie on the Thar desert margin and they are extremely sensitive to climate change during the late Quaternary period. This is reflected in frequent switching between the fluvial and aeolian modes of deposition as well as tectonic changes in fluvial styles at several sites.

Further, fluvial systems are inherently discontinuous in terms of their depositional records and preservation potential as manifested in the occurrence of major or minor discontinuities. It is often difficult to establish regional coherence across wide regions based on fluvial records and this is attributable to the region-specific river behaviour as having resulted from the combined effect of the existing climatic condition as well as geomorphic setting.

At shorter time scales, high-resolution records from fluvial cut off lakes and palaeoflood deposits remain potentially significant for palaeoclimatic reconstruction for the last millennium. Some recent studies[90] have demonstrated that the coupling of such proxy records with model simulations can significantly improve our understanding of short term climatic variability. It should, therefore, be a priority to augment this database on palaeofloods and palaeo discharge estimation for obtaining a better process-based understanding of river response to climate change, particularly over the past few millennia.

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