Adaptation and human migration, and evidence of agriculture coincident with changes in the Indian summer monsoon during the Holocene

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Human societies have evolved through a complex system of climate and ecological interactions. Known records suggest intimate relationship of adaptations, mitigations and migrations to climate extremes leaving their impacts on human societies. The northwestern part of India provides such an example, where human civilizations flourished in the early Holocene along the major fluvial systems when the Indian summer (southwest) monsoon was much stronger and rainfall was higher over the Indian land mass. Summers were thus wetter, conducive to agriculture and ecodiversity. Changes in the early civilizations in the Indian subcontinent had a close relation to changes in the monsoon climate over the past 10,000 years. The summer monsoon has weakened over the last 7000 years since its peak intensification in the early Holocene (10,000–7000 cal yrs BP). Discrete intervals of dry phases in the summer monsoon are visible in the proxy record of the monsoon winds from the marine sediments of the Arabian Sea, which had significant impact on human settlements in South Asia. The strongest aridity in the Indian subcontinent and extended periods of droughts at ca 5000–4000 cal yrs BP seems to have triggered eastward human migrations towards the Ganga plain. Other times of monsoon weakening during the Holocene are coincident with the initial development of ponds, reservoirs and other rainwater harvesting structures that may have served as an adaptation to climate change.

Keywords: Civilizations, Holocene, human dynamics, rainwater harvesting, SW monsoon.

HUMAN occupations and migrations have been closely linked to climate changes throughout the known records[1–3]. Climate has had distinct impacts on human society and its evolutionary dynamics. For instance, it has been suggested that increased aridity in Africa led to the eventual rise of arid-adapted hominids and their migration to regions with more conducive climate regimes[1]. Human response to climate primarily arises due to changes in regional hydrology, i.e. an assured availability of water. Water availability appears to be the main reason for all the major ancient human civilizations to grow and flourish along major perennial river systems. For instance, civilizations in Egypt, Mesopotamia, and the Indian subcontinent (South Asia) all developed along perennially flowing Nile, Tigris–Euphrates and Indus river systems, respectively. Recent palaeoclimatic, archaeological and historical evidences across regions suggest considerable human adaptations, dispersal, population dislocation, cyclic spatial and demographic reorganization such as abandonment and expansion, and human migrations. For instance, there is evidence for climate-induced human migrations in western and central Europe[4], Germany[5], North American West Coast[6], Alaska[7] and Central Andes[8].

The Holocene was once thought as a climatically stable time interval[9], but well-dated, detailed palaeo records now indicate that the Holocene climate was marked by century to millennial-scale variability both at high[10,11] and low[12,13] latitudes. Cultural responses to these changes in climate are manifested in geoarchaeological records, ranging from adaptation to small changes to migration in cases where the changes were extreme. deMenocal[14] presented four examples of population responses to the late Holocene climate change: the collapse of the Akkadian (~ 4200 cal yrs BP), Classic Maya (~ 1200 cal yrs BP), Mochica (~ 1500 cal yrs BP), and Tiwanaku (~ 1000 cal yrs BP). In all these cases, there was a close interaction between human cultural elements and persistent multi-century shifts in climate.

Studies suggest that the Indian subcontinent experienced widespread climate fluctuations that had significant impact on human population in the region. It is also believed that the rise and fall of various civilizations in the Indian subcontinent were triggered by climate fluctuations dominated by seasonal changes in the monsoons[15,16]. Based on palynological evidence, Singh[15] suggested that

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increases in the monsoon rainfall directly contributed to the rise of the Indus civilization and a decrease in precipitation contributed to its fall.

Monsoon has been an integral part of cultural, economic and political dimensions of India. The folklores, rites and festivals are intimately associated with the changing seasons, and the sowing and harvesting of crops. Even in the twenty-first century, the economic planning and the political scenario are largely determined by a good or bad monsoon. High resolution century to millennial-scale records of monsoon change during the Holocene are rare, which may help understand cultural responses to abrupt climate changes in South Asia. To augment this, an Indo-US joint project was initiated, which culminated in the production of a new record of centennial-scale southwest (SW) or summer monsoon variability during the Holocene from rapidly accumulating sediments in the northwestern Arabian Sea[12]. In the present contribution, these results combined with land records from southern Oman and eastern Tibetan Plateau have been used to examine links between changes in monsoon precipitation and population in the Indian subcontinent during the Holocene (Figure 1; Table 1). Understanding the interactions of monsoon and society in a region with more than 1 billion people living on just 2.3% of the global land mass may offer insights on perils and promise of times ahead.

Early Holocene monsoon intensification and beginning of agriculture in the Indian subcontinent (~ 10,000–7000 yrs BP)

Proxy records of monsoon changes from the Arabian Sea[12,17], southern Oman[18], and Tibetan Plateau[13,19] indicate that the early Holocene (~ 10,000–7000 yrs BP) was an interval of warmer and wetter conditions with intensified SW monsoon (Figure 1). Several major rivers, including the Indus were flowing with full vigour during this time[15,20,21]. The Ganga–Brahmaputra river system delivered double its present sediment load to the Bengal basin between 10,000 and 7000 cal yrs BP[22]. The enhanced sediment discharge by Ganga–Brahmaputra rivers[22] and widespread peat formation in Tibet[13] during the early Holocene are indicative of increased precipitation in response to a stronger than present day SW monsoon over the Indian subcontinent[12].

We extend our previous results by analysing the relationship between the winds in the Arabian Sea, and rainfall over southern Asia. The atmospheric General Circulation Model results show that for both changes in summer insolation, and for the combined effect of changes in summer insolation and changes in glacial boundary conditions, precipitation over southern Asia increases as the monsoonal pressure gradient increases (Figure 2), measured in

Table 1. Chronology of events in the Indian subcontinent during the Holocene (for references see text)

Cal yrs BP	Climate in the Indian subcontinent	Agriculture	Population response
AD 1800 onwards	Increased global warming causing high variability in the southwest monsoon	General increase in agriculture production	Widespread floods in the north and northeast and droughts in the west and northwest
AD 1400–1800	Little Ice Age, weak southwest monsoon, widespread droughts	Decreased agricultural production	Great famines in India, widespread population migrations
AD 700–1200	Medieval Warm Period, wet phase in India	Increase in agriculture production	Height of prosperity, increased trade with Europe and Middle East, beginning of invasions by Islamic invaders
1700 onwards	Increasing strength of summer monsoon	General increase in agriculture production	Strengthening of economy, increased trade with Europe and the Middle East
4000–3500	Intensification of dry phase, weakening of southwest monsoon, widespread droughts	Mixed agriculture, both *rabi* (winter) as well as *kharif* (rainy season) crops were grown; *kharif* crops include maze, millet, rice and a variety of lentils	Indus people migrated to the east towards Ganga (Ganges) plain, fall of Indus civilization
7000–4000	Transitional phase with moderate rainfall, southwest monsoon shows step-wise weakening	Wheat and barley were main crops with a shift towards *kharif* crops	Rise of Indus civilization; people start migrating to newer areas; traces of human settlement in Thar deserts as early as ca 4800 cal yrs BP
10,000–7000	Humid phase, strongest southwest monsoon, major rivers like Indus in their full splendour	Winter crops like wheat and barley were main crops grown in Indus region	Traces of first human settlement ca 9000 cal yrs BP in the Indus region near Mehrgarh (now in Pakistan)

the model results as the change in the north-south component of the surface wind speed (regions defined in Prell and Kutzbach[23]). This strengthens our confidence to extend conclusions based on the *Globigerina bulloides* (protozoa) record[12] to the pattern of rainfall in southern Asia.

Documentation of the early Holocene SW monsoon intensification and changes in rainfall and major fluviosedimentary systems begs the question: were rise and fall of human civilizations and beginning of agriculture in the Indian subcontinent climatically mediated? Palynological and archaeological evidences suggest such a link[15,16]. The archaeological evidence of first human occupation in the Indus basin has been found near Mehrgarh (now in Pakistan) and its surrounding areas in the Kachi plain on the bank of the Bolan river (Figure 3). Mehrgarh was suited to be a centre for early civilization and for the transformation from hunting and gathering communities to those with settled agriculture and domesticated animals[16]. The Kachi plain is still considered as the 'bread basket' in Baluchistan. The Bolan valley must have provided a link between mountain valleys of northern Baluchistan and Indus plains, which probably attracted wild animals like deer and sheep moving down to the Indus plains for grazing. Such a scenario with exuberance of vegetation, including wild cereals, presence of wild animals, and water availability might have attracted the earlier man, even before the beginning of agriculture.

The early settlement at Mehrgarh is dated ~ 9000 cal yrs BP[24], which presents the oldest evidence so far for the beginning of agriculture and domestication of animals in the Indus system, coinciding with the peak intensification of the SW monsoon[12,13,17,18]. Mehrgarh provides an important evidence for the change from hunting, gathering and pastoralism to a subsistence economy centred around settled agriculture and domestication of wild animals[16]. Agriculture might have allowed people to become sedentary, establish permanent villages and towns, and develop stratified societies. Evidence from Mehrgarh suggests that the cultivation of wheat along with barley has been from the very beginning of agriculture[25]. The plant remains belong to a variety of fruits, including jujube, stones of date palm

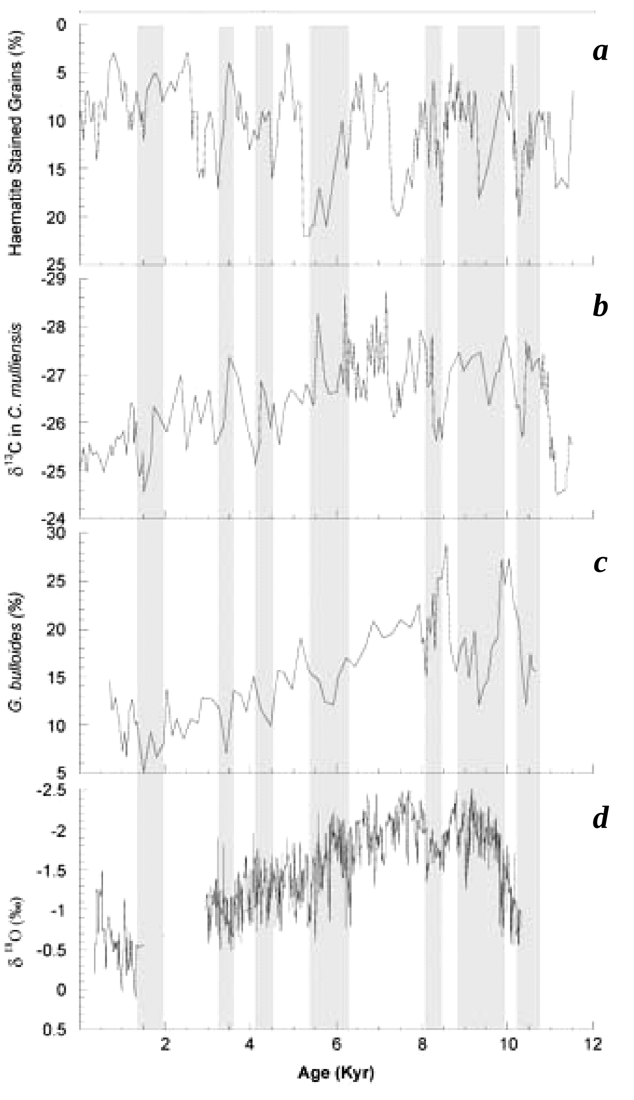

Figure 1. Holocene Indian summer monsoon record from the southern Oman[18] (***d***), Arabian Sea[12] (***c***), and eastern Tibet[13] (***b***). Higher percentages of *Globigerina bulloides* indicate wet periods (***c***) supported by cave deposits (***d***) and peat deposits (***b***) isotope data. Thus summer monsoon was stronger and rainfall was higher during the early Holocene. The intervals of weak southwest monsoon are aligned with cold spells in the North Atlantic[41] (***a***). Superimposed on panels (***a–d***) are population and fluviosedimentary responses to climate events in the Indian subcontinent.

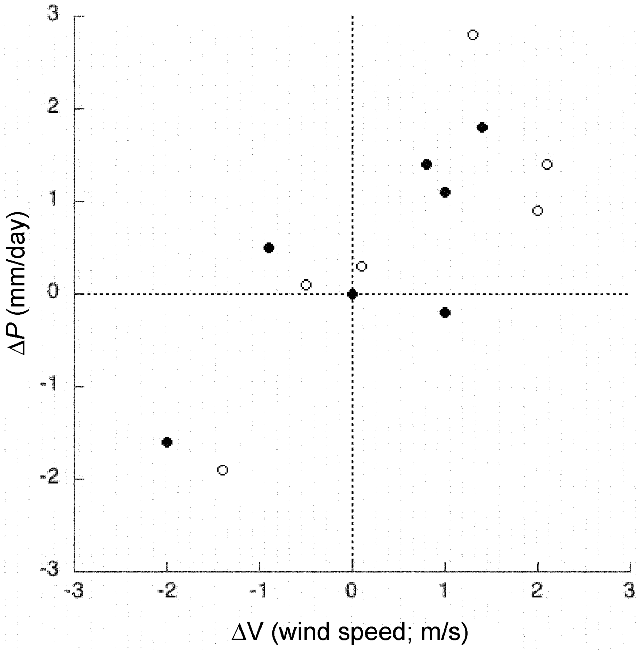

Figure 2. Correlation between increased wind speed in the Arabian Sea and increased rainfall over southern Asia, for atmospheric General Circulation Model experiments with a range of summer insolation (open circles) and combined insolation plus glacial boundary condition (filled circle) changes[23].

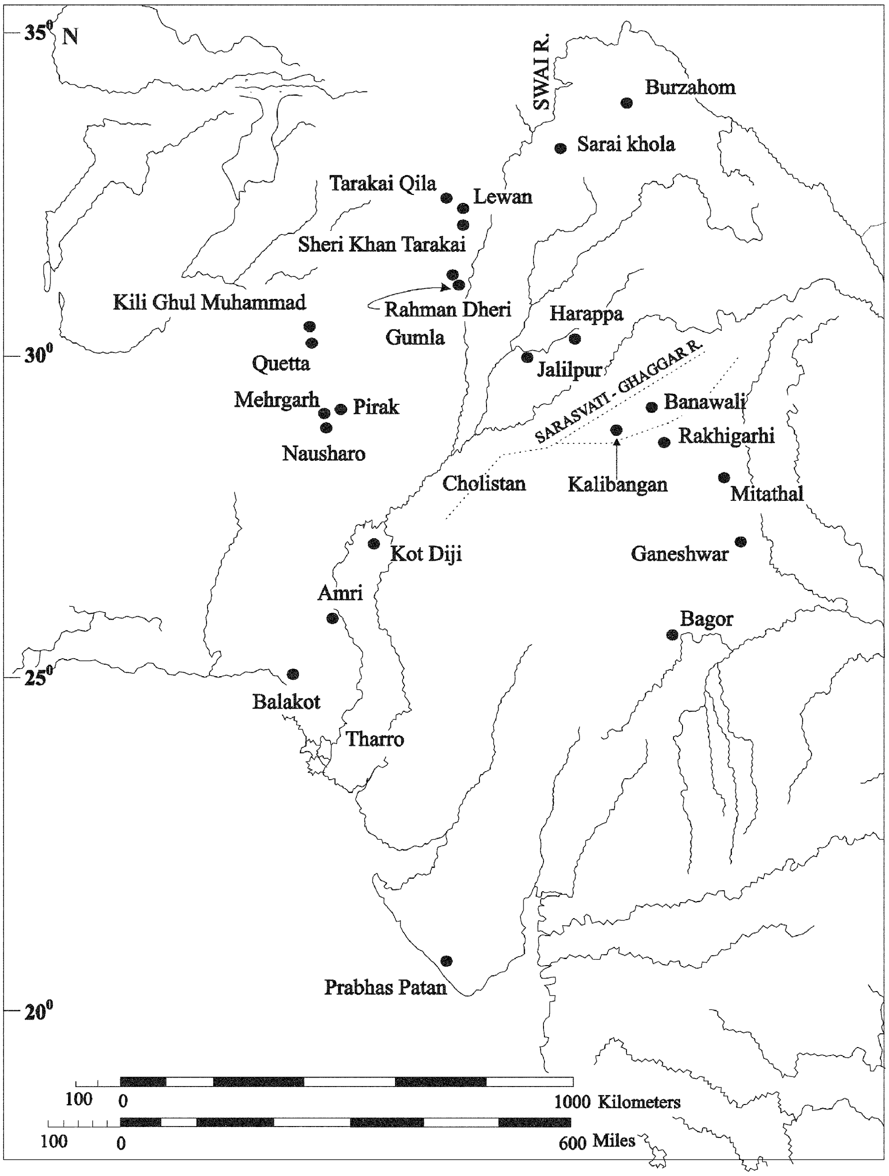

Figure 3. Archaeological sites showing presence of human occupation in northwestern part of Indian subcontinent during ca. 9000–7000 cal yrs BP (modified from Allchin and Allchin[16]; courtesy F. R. and B. Allchin).

and grape seeds. In the subsequent period (~ 7000–6000 cal yrs BP), archaeological evidence suggests that the production of grains, particularly wheat, and the construction of mud-brick storehouses increased steadily in Mehrgarh area[16]. The spread of agriculture thus was essentially the expansion of the highly successful pattern of wheat and barley production, and domestication of cattle, sheep and goat that emerged at Mehrgarh area. The increase in rainfall throughout the Indus basin must have created conditions conducive for an expansion of agriculture to the other areas as well. Thus the early Holocene interval (10,000–7000 cal yrs BP) was marked by a subsistence economy based on the cultivation of wheat and barley and urban civilization. This process of agricultural expansion probably led to the rise of Harappan civilization in the Indus valley about 5500–5000 cal yrs BP. The evidence that ca. 10,000 to 7000 cal yrs BP there was a general increase in rainfall in South Asia[12,13,15,20,22], adds credence to the hypothesis that proliferation of early civilizations and beginning of agriculture in northwestern India were closely linked to the strength of the SW monsoon.

In recent years, the study of monsoon seasonality has become a topic of great interest, and it has been found that the seasonal duration had varied in the past[26]. It is also likely that the summer monsoon season was longer in the early Holocene with excess moisture content than what was required for food production. This might have provided enough moisture for the winter monsoon rains needed for winter crops. Since both wheat and barley are winter (*rabi*) crops, it seems probable that grain production would initially have depended mainly upon winter rains or people had developed methods of irrigation and rainwater harvesting as an adaptation to monsoon variability[27]. Excess rain and/or longer summer monsoon season in the early Holocene might have caused widespread floods and that probably did not allow early farmers of the Indus region to grow *kharif* (rainy season) crops like maize, millet (jawar, bajra) and a variety of lentils. These crops were probably introduced later with the beginning of arid phase ca. 5000 cal yrs BP, as discussed in the next section. In summary, the strong monsoon of the early Holocene appears to have been wet enough for agriculture during the winter season, while the late Holocene (5000 cal yrs BP) was drier, and coincided with the appearance of rainy-season crops.

Increased aridity since ~ 5000–4000 cal yrs BP: shifting of population to the east towards Ganga plain

There are several views about the beginning of the arid phase in India. Phadtare[28] reports the beginning of aridity ca 4000–3500 cal yrs BP based on pollen data from the Higher Garhwal Himalayas, whereas in western peninsular India the reduction in humidity starts ca. 4500 cal yrs BP and intensifies at around 3500 cal yrs BP[29]. In yet another study from Kumaon Himalayas, the arid phase was observed beginning around 3500 cal yrs BP[30]. In Rajasthan, northwestern India, the vegetational history documents a shift towards arid phase since 4200 cal yrs BP[20]. Marine record from the northwestern Arabian Sea suggests beginning of aridity at 4200 cal yrs BP[31] and 4800 cal yrs BP[12], whereas in the northeast Arabian Sea this event has been observed during 4000–3500 cal yrs BP[32]. In the Bay of Bengal, the aridification event has been documented between 5000 and 4300 cal yrs BP[33]. More recently, the Arabian Sea record[12] shows a stepwise weakening trend since ~ 7000 cal yrs BP until 1700 cal yrs BP. Superimposed on this weakening trend were several centennial-scale events. In the Ganga (Ganges) plain, there is an indication of increased aridity beginning at 5000 cal yrs BP[34]; in Southeast Asia, the Cambodian lake record[35] shows a dry phase beginning at ca. 5000 cal yrs BP. It appears to us thus that the arid phase in the Indian subcontinent started ca 5000–4000 cal yrs BP coinciding with a stepwise weakening of the SW monsoon[12], desiccation of river channels in the Ganga plain and a drop in the Cambodian lake levels[35]. The arid phase might have intensified ca 4000–3500 cal yrs BP as has been in the Himalayas[28,30], western peninsula[29] and northwestern India[36], and ended ca 1700 cal yrs BP, when the SW monsoon was the driest[12,34]. While more records are needed to determine the timing of these events, there is little doubt that the climate across India became drier following the maximum 10,000–7000 cal yrs BP. The dry phase has also been observed in regions adjoining South Asia. For example, a shift towards reduced precipitation has been observed at 4200 cal yrs BP in Egypt[37] and in eastern Turkey[38], and at 5000 cal yrs BP in northwest Africa.

The increased aridity since ~ 5000 cal yrs BP influenced population and agriculture production in the Indus region. A gross decline in rainfall in the northwest and failure of agriculture necessitated adaptations[27] and migration of people to the east towards Ganga plain[16]. This is borne out by an increased number of archaeological sites in the Ganga–Yamuna doab (interfluve) and all across the Ganga Valley (Figure 4). People also migrated towards south to Kachchh region around 5000 cal yrs BP[39]. Shifts in climate are likely to cause movements of the people when the conditions become extreme. The dry spell probably forced many farmers in drier regions of Indus as well as Ganga plains to adopt new farming strategies. This would perhaps explain the use of millet, lentils, horse gram, green gram, field peas, chickpeas, etc. in later agricultural practices[16]. Excavations at Hulas, Saharanpur district, northern India provide the earliest evidence for cultivation of rice in the Ganga plain in the second millennium BC[40]. Since precipitation increases steadily eastwards, the alluvial plains of the Ganga Valley have been, since the earliest settlements, the basis for highly productive agriculture. In the low-rainfall areas of the northwest predominantly wheat, barley and millet are grown and to the east, the proportion of rice steadily increases as the rainfall increases. In the Ganga–Yamuna interfluve, as reported at Hulas, people started utilizing cereal crops of wheat, barley, rice and millet since the second millennium BC. This had enabled farmers to maximize the yield in differing rainfall and climatic conditions, and obtain both winter and summer crops from the same land. It is interesting to observe that people living in the present-day doab region of north and northwest India still have similar dietary habits as their ancestors had in the second millennium BC[16].

The modern landscape of the Ganga plain shows evidence of human impact. In the pre-human habitation period, the area must have been full of dense forests, and initially there must have been a need for large-scale clearance and deforestation. Dense forests and non-availability of stones might have restricted the settlement of early civilizations in the Ganga Valley before the iron age 3500 cal yr BP, as the clearance of forests needs iron/stone tools. Though the anthropogenic activity is evident since ca 5000 cal yrs BP, the past 2500 years have undergone large-scale inhabitation with intense agricultural practices in most of the areas in the Ganga plain, coincidental with the increased strength of the SW monsoon. Continuing population pressure in the Ganga plain has led to almost complete extinction of forests. However, as we travel across the present-day Ganga plain, we still see some old trees scattered throughout, which survived the onslaught of deforestation,

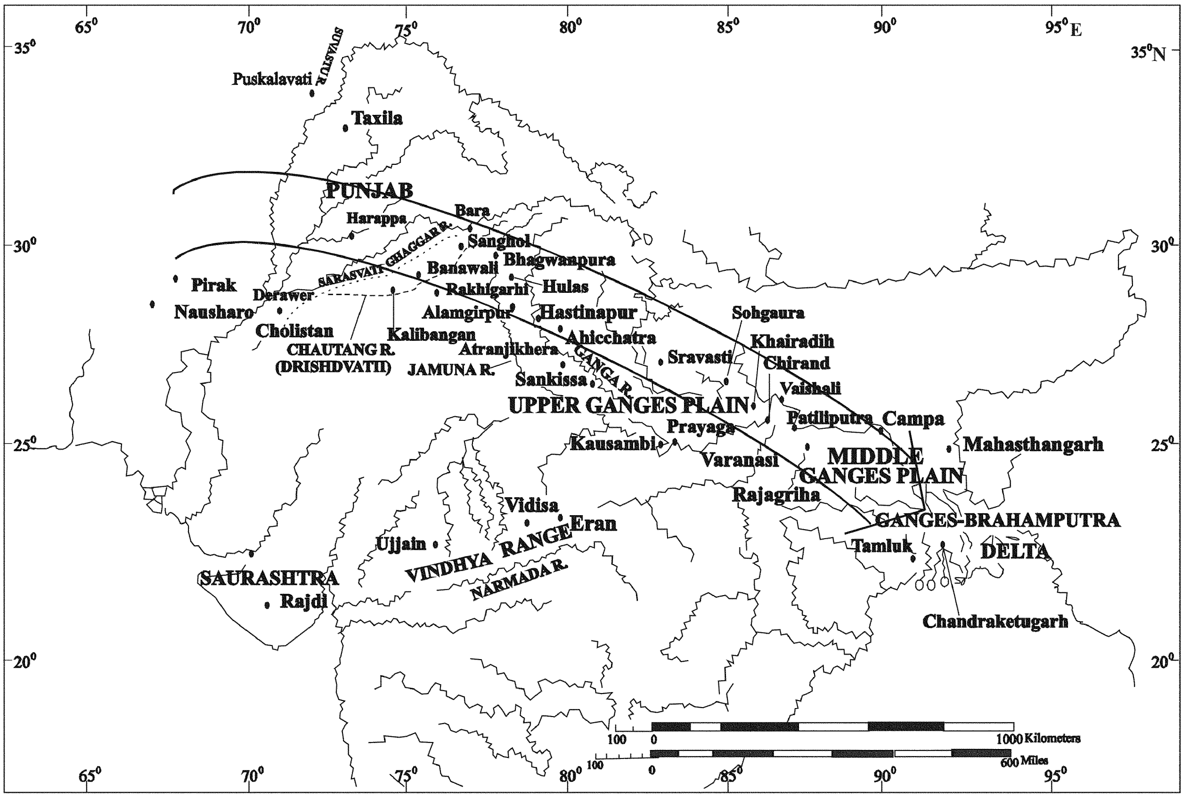

Figure 4. Shifting of population to the east towards Ganga plain is evidenced by the presence of more archaeological sites in the eastern part of the Indian subcontinent since ca. 5000 cal yrs BP (modified from Allchin and Allchin[16]; courtesy F.R. and B. Allchin).

reminding us of the existence of a vast forest land once upon a time.

Abrupt century-to-millennial scale events in the monsoon

While the low frequency trend in the monsoon can be explained by changes in summer and winter insolation driven by the precession of the earth axis of rotation (23,000 year periodicity), detailed studies indicate significant changes in the monsoon winds from one century to the next[12]. These abrupt climate events are manifest as irregular oscillations between stronger and weaker monsoon winds in the Arabian Sea. Most events last several centuries, and the amplitude reaches 30% of the change due to precession. The interval between 5800 and 1700 cal yrs BP was punctuated by four of these weak monsoon events (5800, 4400, 3400 and 1700 cal yrs BP). Gupta *et al.*[12] point out that throughout the Holocene, weak monsoon events coincide with cool periods in the North Atlantic when ice rafting was more extensive[41], supporting the hypothesis that changes in the circum-North Atlantic have a downstream influence on the Indian monsoon (Figure 1). Conversely, the millennial-scale events may originate in the tropics[42]. Whether they are driven by changes in the tropics[42] or higher latitudes[41] remains unresolved. Despite their origin, one might expect these large abrupt, weak monsoon events to pose significant challenges to societies already experiencing the driest conditions in thousands of years.

Indian monsoon versus African monsoon during the Holocene

We compared the Indian monsoon records with the African monsoon to understand if the two monsoon systems had any similarity, thus controlled by a same mechanism during the Holocene. An abrupt onset and termination of the humid phase is seen in Africa. Like vegetational change in the Indian subcontinent is linked to the Indian monsoon, the early Holocene greening of North Africa has been associated to an intensification of the African monsoon due to increased summer insolation in the northern hemisphere[1]. The summer insolation in the northern hemisphere was 8% greater during 11,000–9000 cal yrs BP than today[43]. Solar insolation has also been suggested as a possible driver for the Indian southwest monsoon variability during the Holocene[12,18,44,45].

In Africa, the humid conditions initially began ~ 14,500 cal yrs BP[45] and a peak humid phase occurred between ca 9000 and 6000 yrs BP[46]. deMenocal *et al.*[1] bracketed the

African humid phase between 14,800 and 5500 cal yrs BP. Geological evidence suggests that the African humid period shifted toward more arid conditions at 6000–5000 cal yrs BP, associated with the gradual decline in summer insolation[44,47,48]. A high-resolution, multiproxy palaeolimnological record from the Manga Grasslands, northeastern Nigeria suggests that desert-dust deposition began to increase at 4700 cal yrs BP and rainfall during the summer monsoon season declined permanently after 4100 cal yrs BP[45]. This caused a change in lake levels[48], vegetation[50] and a replacement in human living style from sedentary, lacustrine tradition to mobile pastoralism[51]. Indeed, the regional studies establish clear links between climate and cultural responses. For instance, increased climatic aridity and problems of soil exhaustion in western Uganda may have driven a subsequent change in the pattern of settlement, towards the beginning of the AD 1500s. Shortfalls in agricultural output and consequent food insecurity among large, sedentary populations, towards the end of a dry period during the late AD 1600s and early 1700s, explain the decline of nucleated settlements[52]. Likewise, changes in water availability have been suggested to drive population migrations in and out of the Sahara–Sahel. Perhaps, short-term dry events provided trigger to inventive adaptations, but severe aridity in the Sahara at 5–4.5 ka coincides with the fall of the classical Neolithic civilization as well as the settlement of new cultures[53].

Intensification of the southwest monsoon over the past four centuries and current global warming with future implications

The monsoon circulation in South Asia during the Holocene has varied with floods in some areas and droughts in other areas[54,55]. A recent study[56] suggests that the SW monsoon has gained strength during the past four centuries since its weakest phase during the Maunder Minimum in solar activity during AD 1600–1700. The increased monsoon strength has been linked to warming of the Indian–Eurasian land mass. Monsoonal changes over the last millennium have important implications for the human population of South Asia, which is marked by crucial political and socio-economic changes in the region. For example, a dry southwest monsoon phase at about AD 1800 to 1900, closely corresponds to a major famine in India in AD 1877. The strong SW monsoon during the Medieval Warm Period (MWP) AD 800–1200 coincides with a wet phase in India[56], signifying amelioration in the climate. The MWP should have been a period of heightened agricultural productivity and increased economical development of people in India during which time the region reached the height of its prosperity and increased trade with the European countries and the Middle East.

The past century has witnessed a steep rise in global surface air temperature and is projected to continue to rise at a rapid pace that might disproportionately affect the Arctic[57]. The linkage between the Arctic climate and global temperature is through hydrologic cycle, including atmospheric moisture transport from lower to higher latitudes, which is expected to increase with global warming[57]. With global warming, the annual discharge of freshwater from the Eurasian rivers to the Arctic Ocean has also increased during the past century[58], which will have important implications on ocean circulation and climate. The continuing warming and freshening of the Arctic Ocean is expected to reduce North Atlantic Deep Water (NADW) production and Atlantic thermohaline circulation[59]. If the warming is strong and sustained long enough, a complete shut down of NADW formation cannot be ruled out in the coming centuries[60] that might cause another cooling phase (or an ice age) in near future, as it happened during the Younger Dryas[60,61] and weaken the Asian southwest monsoon[12]. Thus, it is particularly important now to increase our understanding of the coupled atmosphere, land and ocean systems of the Arctic as well as the tropics for future climate (and monsoon) predictions.

Conclusions

The Indian monsoon influences the fauna and flora of the Asia–African region. The major droughts and widespread floods due to weak and intense monsoon respectively, bring important changes in the socio-economic policies of South Asia. Discrete intervals of century-scale changes have been observed in the monsoon during the Holocene, which have had significant impact on human societies in the region. Interactions between human societies and climatic changes enabled development of different civilizations throughout the world. Different human civilizations in South Asia have a close relation with changes in the monsoon. The Indian Ocean summer monsoon reached the peak of its intensification in the early Holocene 10,000–7000 cal yrs BP and thereafter weakened gradually. Several major rivers, including the Indus were flowing with full vigour during this time. The abundant summer rain in the early Holocene helped early people to augment their agricultural practices and grow a variety of cereals, lentils and grains. This brought about a change in the living style of the people from hunting, gathering and pastoralism to a subsistence economy, one centred around settled agriculture and domestication of wild animals. Weakening of the summer monsoon led to the beginning of the arid phase in South Asia ~ 5000–4000 cal yrs BP. This triggered a chain of changes in agricultural practices and food habits in the South Asian population. In some cases, societies adapted to monsoon failures by constructing ponds, dams and other rain harvesting structures. In other situations, people migrated eastward towards Ganga plain, where rainfall was sufficient to sustain the burden of new influx of human population.

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