Journal of Palaeosciences 71(2022): 45–74
0031–0174/2022

Monsoon in history and present

A.P. DIMRI[1,*], M. ROXY[2], A. SHARMA[3], A.K. POKHARIA[3], CH.R. GAYATHRI[4], J. SANWAL[5], AKA SHARMA[1], S.K. TANDON[6], D.R. PATTANAIK[7] AND U.C. MOHANTY[8]

[1]*School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India.*
[2]*Indian Institute of Tropical Meteorology, Pashan, Pune, India.*
[3]*Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow, India.*
[4]*School of Social Sciences, Jawaharlal Nehru University, New Delhi, India.*
[5]*Geodynamic Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India.*
[6]*Earth and Environmental Sciences, Indian Institute of Science Education and Research, Bhopal, India.*
[7]*Numerical Weather Prediction Division, India Meteorological Department, New Delhi, India.*
[8]*School of Earth Ocean and Climate Sciences, Indian Institute of Technology, Bhubaneswar, India.*
[*]*Corresponding author: apdimri@hotmail.com*

(Received 09 March, 2022; revised version accepted 11 May, 2022)

ABSTRACT

Dimri AP, Roxy M, Sharma A, Pokharia AK, Gayathri ChR, Sanwal J, Sharma A, Tandon SK, Pattanaik DR & Mohanty UC 2022. Monsoon in history and present. Journal of Palaeosciences 71(1): 45–74.

Monsoon in the Indian sub–continent remains a seasonal phenomenon which is awaited by all of the humans of the sub–continent. It has long drawn the reverence of monks, travellers, poets, traders and researchers. All mortals from the sub–continent have looked to it from their own perspective and it continues to be the subject of intense multi–dimensional engagement. The monsoon has provided the means of survival to many civilizations, besides sculpting the drainages and the palaeogeography of the subcontinent. The evolution of Himalayas has played a critical role in the evolution of the summer monsoon, which gave life to rivers, crops and human settlements. The present synthesis of the Monsoon illustrates how it is linked to the history of human cultures and their evolution. Furthermore, we have attempted to place the monsoon in a historical perspective using ancient literature, besides considering the present monsoon variability and forecasting systems available.

Key–words—Monsoon, Civilizations, Human Life and Society, Indian economy.

INTRODUCTION

THE Asian Summer Monsoon (ASM) system is a significant component of the global climate system and plays a key role in transporting the heat and moisture from tropical oceans to higher latitudes (Wang, 2006). Within the ASM system, there are two main monsoon sub–systems: the Indian Summer Monsoon (ISM) or South Asian Summer Monsoon (SASM) and East Asian Summer Monsoon (EASM). The anatomy of the EASM is fundamentally different from that of the SASM (Molnar *et al*., 2010). The SASM depicts the tropical monsoon circulation system, which dominates the northern summer Hadley circulation and plays an important role in the global atmospheric circulation (Trenberth *et al*., 2002). The SASM rain influences the Indian subcontinent, the Indo–China Peninsula and the South China Sea, since it is entirely contained inside an Intertropical Convergence Zone (ITCZ) that is displaced from the equator (e.g., Gadgil, 2003). The EASM displays a distinct extratropical nature in which the precipitation and winds are associated with the frontal systems and the jet stream influencing China, the Korean Peninsula and Japan. This paper focuses mainly on the long–term variations in SASM system, which contributes about 70–80% of the total rainfall over the South Asian countries (Webster *et al*., 1998; Gadgil & Gadgil, 2006) and thus influences the economic development of about two–thirds of the world's population (Benn & Owen, 1998). The orographic elevations also play an important role in the monsoon, right from the rising Himalaya and Tibet Plateau to the lower mountains of the Western Ghats on the west coast of India and the Arakan Yoma and Bilauktang ranges on the west coast of the Indo–China Peninsula (Xie *et al*., 2006). To a large extent, the intensity of the ISM precipitation can be linked with various moisture–producing factors like: mesoscale convective system (MCS), west–north–west moving synoptic systems, tropospheric cyclones, monsoon onset vortices and orographic heights (Rao, 1976). Interactions among these multi–scale systems, as well as diverse topographical and geographical variables, bring the spatio–temporal heterogeneity in the rainfall distribution over the different regions within the Indian subcontinent during the monsoon.

The total amount of SASM rainfall depends upon the intensity and duration of the summer moisture laden wind circulation (Haq & Choudhary, 2014). Rainfall patterns during the monsoon shape the distribution and abundance of flora and fauna by providing essential nourishment to plants and animals. Hence, it has a significant impact on the agricultural production of the country by providing water for major summer crops (Kharif) (Liang *et al*., 2015) and, to some extent, winter crop (Rabi) through the availability of water and soil moisture regionally (Prasanna, 2014). In the last five decades, archaeological research in the Indian subcontinent have yielded enough shreds of evidence that humans began living in settled monsoon–agriculture–based lifestyles and evolved in a more civilized manner throughout time (see Fig. 1). The presence of large number of microlithic sites in the Thar Desert also provides one of the best examples of culture–environment interrelationship in the desert. Observations of such occurrences from the Indian subcontinent provide the evidence for adaptation and mitigation (Gupta *et al*., 2003, 2006). The Holocene epoch is significant in many respects, particularly in terms of human development and the emergence of civilizations centres (Fig. 1). The changes in climate during this epoch have significant impacts on landscape, fluvial systems (Goodbred & Kuehl, 2000), vegetation, human population (Gupta, 2004; Gupta *et al*., 2006) and climate globally, but the rate of change has accelerated dramatically during the last hundred years, largely due to human impacts. Because of the gradual or abrupt climate changes during the Holocene, many civilizations evolved, developed and perished (Dixit *et al*., 2014, 2018; Kathayat *et al*., 2017; Dutt *et al*., 2019). The incidence of wars has also been linked to climate variations during the last millennium (Zhang *et al*., 2010), demonstrating the critical importance of climate changes for human well–being. As a result, more comprehensive records of high resolution proxy data on palaeomonsoon variability are required to improve the understanding of the present and future monsoon behaviour. Synthesis and summary of the long–term monsoon information are prerequisites for scientifically sound policy planning with a key aspect of societal relevance. In order to understand the evolution of the monsoon and its linkage with agricultural and human settlement, we integrate detailed multi–proxy records of (ancient literature, archaeological, chronology and settlement patterns) with available palaeoclimate proxies from marine and terrestrial data from the Indian subcontinent and few adjacent regions.

HISTORICAL SIGNATURES/LINKAGES: MONSOON SIGNATURES IN ANCIENT LITERATURE

No season is as eagerly awaited nor is as dramatic as the monsoon in India. This annual phenomenon completely transforms the entire geography in its aftermath and is considered the life force for agricultural production. Monsoon rains have been well entrenched in India's social, cultural and religious fabric from ancient times and perception about rains can be studied from the literary sources of various periods. Compared to other parts of Asia, such records in India and China are relatively longer and they provide informative evidence of past monsoonal rain. The term Monsoon is derived from the Arabic term "Mausim", meaning season (Das, 1968). Vedic litrature (1500–600 BCE) depicts the transition of nomadic pastoralists settling down and subsisting on rain–fed agriculture. Rains were designated as divinities of Indra, Varun, Maruts and Parjanya in the earliest religious scriptures. The Parjanya Sukta and the Aap Sukta (Rig Veda) and the Varuna Sukta (Yajur Veda) are recited even today to invoke rains. Vedic texts clearly understood aestivation/ monsoon culture. The frog hymn of Rig Veda describes the natural phenomenon of monsoon and Gautam Vajracharya analyzed this hymn to understand the effect of Indian seasons and their bearings on the migration and ideas of the people whose religious scriptures were Vedas (Gautama & Vajracharya, 2013).

The rainy season was considered as a period of retreat for Buddhism, Jainism and other Sramana sects. Buddhist monks were peripatetic preachers; yet, their peregrination was difficult during the three months of rain, because peasants complained about crushed green herbs, vegetative life and little living creatures (Davids & Oldenberg, 1881). The sacred canon of Theravada Buddhism, Vinaya Sukta, explicitly states that all bhikshus (Buddhist monks or devotees) are to enter Vassa, a three–month annual retreat during the rainy season observed by Theravada practitioners. The initial retreats of grooves and natural caves were gradually replaced by more permanent rock cut shelters, which marked the commencement of the Buddhist monasteries. The Vassa retreat proliferated with the patronage from not only kings but also from the wealthy traders and lay worshippers. Vassa was practiced even among Jains and other Sramana sects like Ajavikas. There are epigraphic shards of evidence that the Mauryan ruler Asoka and his descendant Dasrath donated the Barabar caves and Nagarjuni hills caves in Bihar to Ajavikas (Krishnan, 1980). Some of these monsoon retreats like Ajanta, Karle, Nashik, Bhaja, etc. are still standing today as testaments to the period's exquisite art and architecture. It is interesting to note that as early as 6^{th}–5^{th} Century BCE there were references to rivalry over river waters for irrigation. The Buddhist literature–Kunala Jataka refers to a conflict between two (neighbouring tribes) clans of Sakya

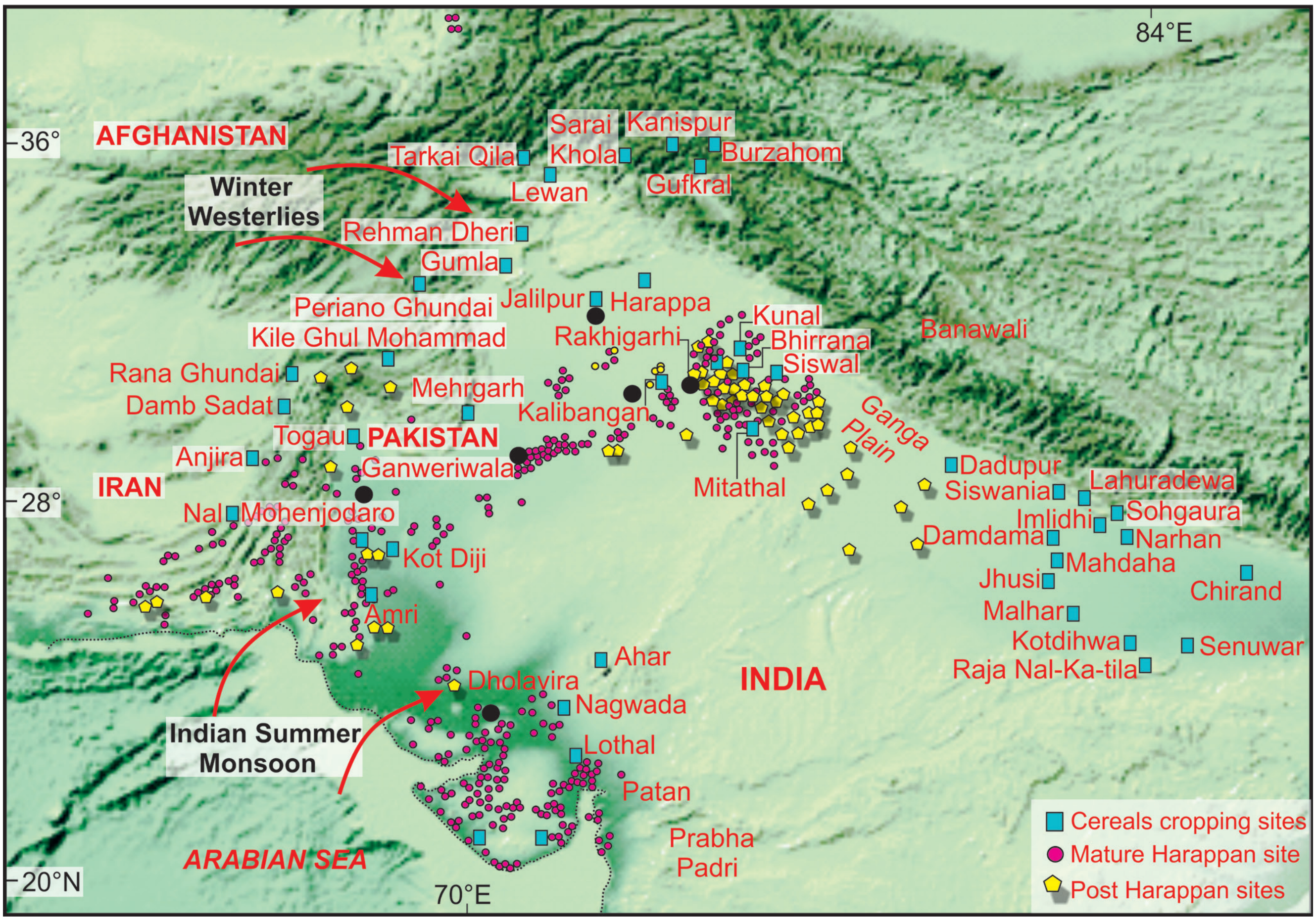


Fig. 1—Location of major excavated sites during different evolutionary phases and the locations of barley and rice cultivation in the Indian subcontinent.

(Sakyas) and Koliyas (Kolis) for sharing of river Rohini water (McConnell, 1990).

Even foreign writers who have visited India have mentioned the importance of rainfall for agriculture and the significance of rain forecasting. Megasthenese, a Greek historian and envoy to India in the 4th Century BCE, wrote in his Indica about India's prosperity and ascribed it to the monsoons. Since there is a double rainfall each year–one in the winter and the other in the summer–Indians virtually always get two harvests every year (Crindle, 1921). He further describes how the philosopher caste, i.e. Brahmins, at the beginning of the year forewarn the people about "droughts and wet weather and also about propitious winds and disease" and the philosopher who erred in his predictions had to face severe obloquy or even observance of silence for life (ibid, p. 41).

Kautilya's Arthasastra (50–125 CE), a treatise on statecraft, clearly recognises significance of rains for the nation's prosperity. It gives explicit instruction (Book 2 Chapter 5) for setting up rain gauge 'Varshaman' for measuring rains (Shamasastry, 1915). The measurements of rains (dronas), at various regions and forecasting the rain as per the position and motion of Jupiter and the rise and setting of Venus (ibid, p. 163), the superintendent of agriculture shall sow seeds, which require less or more water depending on the quantity of rainfall (Book 2, Chapter 24). Arthasastra also reflects rudimentary forecasting of rains:

"Three are the clouds that continuously rain for seven days; eighty are they that pour minute drops; and sixty are they that appear with the sunshine–this is considered good, well distributed rainfall, where rains interspersed with wind and sunshine is such that cow dung cakes can be dried three times (during the rainy season), reaping of a good harvest is certain" (ibid, p. 164).

The understanding of the rain process is based on the contemporary understanding of the cosmos. For example, Ramayana describes the process of rain as "The heavens, which drank the ocean" water through the Sun's rays, are giving birth to the elixir of life, their embryo carried for nine months (Lefeber, 2000). Unlike other texts which rejoice the arrival of rains, Ramayana shows an instance when rains were cause of grief to king Rama, who had to stall the search for queen Sita due to the onset of monsoon, which made the roads impassable and any expedition impossible (ibid, p. 164).

The uncertainty of the rains and winds was a matter of concern to the peasantry and they were dependent on the broad natural occurrences and variables of nature like the sky, dust, storms, wind patterns, etc. for speculating and forecasting rains. Krishi Parashara, an ancient Sanskrit text of the fourth century is considered the first agriculture almanac and it clearly held the knowledge of rainfall as the root of agriculture. The text also has many maxims concerning rainfall prediction with simple astrological models based on planetary movement (Sadhale, 1999). Varahamihira, a sixth century Indian mathematician, astronomer and astrologer, explains predicting seasonal rainfalls using lunar mansions or nakshatras in his work Brihat Samhita. He also discussed in detail Hydrometeorology in three chapters, i.e. comprising of pregnancy of clouds (chapter 21), pregnancy of air (chapter 22) and quantity of rain (chapter 23).

"Which science is superior to this astrological science which determines the exact time of the rain, since by knowing this science alone one gets the power of visualizing the past, present and future, even in this kali age which destroys all good things (sloka 4)" (Sastri & Bhat, 1943).

The ancient writings and even the popular folk traditions and idioms, were replete with the common man's proverbial knowledge of monsoons and their significance. Though most of these popular traditional sayings sounded superstitious, they were based on experience, observation and contemporary understanding of weather and climate. DakVachan is one such repository of traditional knowledge and wisdom and is popular as Dakar Bachan or sayings of Dak and Khana in Bengal, DakVachan in Bihar and Ghagh–Bhaddari sayings in Uttar Pradesh.

"Rat nibaddar din ken chayya, KahenGhag je barkhagaya"–Meaning if you see a cloudless night and a cloudy day, be sure, the rains are at end says Ghagh (Christian, 1891).

Monsoons have always held the imagination of poets and artists. The most celebrated classical Sanskrit poet Kalidasa in his elegiac poem Meghdhootam, describes the course of monsoon clouds from the Bay of Bengal through central India, north Indian plains to Himalaya. In his other poem, Ritusamharam rains have been described using beautiful metaphors.

The rain advances like a king in awful majesty;
Hear, dearest, how his thunder ring Like a royal drum
And see his lightening bannes wave; a cloud for elephant he rides
and finds his welcome from the crowd of lovers and of brides

(Ryder, 1914).

While monsoon rains were important for agriculture, monsoon winds played a significant role in the Indian Ocean trade. From the beginning of the Common Era (CE) there were trade links between India and Roman Empire by sea. The discovery of monsoon winds or trade winds was attributed to Hippalus, a Greek navigator, in Periplus of the Erythraean Sea. Hippalus comprehended the monsoon phenomenon and navigated from the Red Sea to India (Schoff, 1912). The monsoon, or the seasonal winds, reversed twice a year and these winds were used by the navigators to make a round trip to India for trade within the same year. The same pattern was operated in the Bay of Bengal, enabling trade with South East Asia. There were prosperous maritime trade exchanges between Roman, Greek traders and the southern dynasties of Cholas, Pandyas and Cheras. These economic connections and cultural exchanges persisted until almost the 7th Century. With the fall of the Roman Empire, these trade routes were later dominated by Persia and from the 9th Century onwards by Arabs (Tibbetts, 1971). In the 10th Century, one of the well–known climatologists of his time Al–Masudi–the famous Arab Scholar, world traveller and a prolific writer, coined the term "Mausam" (Monsoon). Al–Masudi gave a comprehensive description on the Indian monsoons during his journey to India. Later, Al–Balakhi gathered climatic data and information from Arab travelers and based on that; he prepared the first climatic atlas of the world entitled, Kitabul–Ashkal. Arabs were the first who put forward the idea of the periodic nature of the monsoon. Traders in Venice and Genoa bought Indian goods from Arab merchants and this monopoly continued till the 15th Century. The Portuguese succeeded in establishing direct trade relations with India and the Dutch and English followed them. Vasco da Gama's discovery of the maritime passage from west to India opened up a new era of imperialism as unlike the earlier traders these western traders had state support.

With its agenda of imperial rule and profit–making, the colonial rule led to many departments and surveys to understand various aspects of Indian systems. According to the Imperial Gazetteer:

"It is now fully established that years of drought in west or northwest India are invariably years of low Nile flood. The relation is further confirmed by the fact that years of heavy rains than usual in western India are also years of high Nile flood" (The Imperial Gazetteer of India, 1909).

LIVELIHOOD/STATE OF LIVING AND MONSOON

Before delving into the livelihood/state of living during the Holocene and its linkages with the monsoon, a brief introduction to human evolution is provided here for better understanding. Geologically, the story of human begins in the Miocene Epoch when the great apes, from whom humans most likely evolved, were flourishing in large part of the globe and monsoon was in place. Proto–humans succeeded apes and appeared in the Pliocene (~5 million years ago); however, they evolved culturally during the Pleistocene (~2.6 million years ago). Modern humans evolved much later, ~150,000 years ago and were biologically and culturally different from the apes. They evolved in Africa first and subsequently migrated to other parts of the Earth. Surprisingly, humanity did not learn to write until approximately 5000 years ago. The historical record is also meagre because the material used for writing was usually perishable and therefore not preserved and lost in due course of time. The impetus came in written history sometimes in the Medieval Period with the invention of printing technology. All of this implies that human history can only be reconstructed through non–literary techniques, particularly archaeological discoveries (material objects such as tools, weapons, utensils, houses, clothes, ornaments and so on). However, by combining archaeological information with other scientific disciplines such as geology, palaeontology, palaeobotany, anthropology and chemistry, among others, trustworthy data regarding geology, vegetation, soil fertility, climate, food habits and so on has been collected. It is to note here that like any other creature, humans too have had to adapt themselves to the environment, which includes climate, flora–fauna and topography and humans have managed so with the help of technology and material culture.

Human colonization, particularly in India, though encompasses a span of at least half–a–million years and can be divided into prehistoric and historical periods. The prehistoric period is again divided into stone, bronze and iron ages. Besides being technological stages, these ages also have economic and social implications depending on the monsoon. As the name suggests, in the Stone Age the technology was primarily based on stone; however, based on the nature and type of stone tools used, the entire Stone Age is further divided into Palaeolithic, Mesolithic and Neolithic periods. The time covered by the Palaeolithic Period was much more extensive (early Pleistocene, ~2 million years ago to the beginning of Holocene or more precisely to ~10,000 years before present; BP) than the Mesolithic and Neolithic periods. The Mesolithic Period provides a history of ~8,000 years (~10,000 to 2,000 years BP). Surprisingly, people maintained a nomadic existence throughout the Palaeolithic and a significant portion of the Mesolithic periods, relying heavily on hunting and gathering. During these times, man preferred to live either in or near forest because forests provide flora and fauna in plenty, needed for survival. Till humans were dependent on hunter and gatherer lifestyles, forests were their preferred choice for livelihood. Since this article aims to restrict to history of humans' life of last ~10,000 years only, most of the discussion on Mesolithic and Neolithic life and their linkages with monsoon is given in the following sections.

Mesolithic culture, life and characteristics

The major subsistence practiced during the Mesolithic Period was hunting and gathering; however, it progressively moved towards the sedentary lifestyle in the later part of this period. In the Indian subcontinent, Mesolithic sites are well represented in terms of population; this period registered a substantial growth, which is adequately attested by the significant increase in settlement sites distributed all over the country (Misra, 2001). One of the plausible explanations for this dramatic increase in human growth may be linked to the increased rainfall and the growth of plants and animals, which ultimately provided food security to a relatively larger population. There are enough lines of evidence, for example, the pollen data from the salt lakes of western Rajasthan (Singh *et al*., 1974), deep weathering of sand dunes in Rajasthan and Gujarat (Misra, 1973) and the presence of windblown black clay deposits in central Indian rock shelters (Allchin *et al*., 1978; Misra & Rajaguru, 1986; Joshi, 1978) suggesting a relatively wetter early Holocene Period (see Fig. 2). The increased food supply would have dramatically increased the human population and their longevity (Petraglia & Allchin, 2007). This resulted in a shift from nomadic to seasonally sedentary life, as evidenced by increased size of Mesolithic sites, thick open–air and rock shelter habitation deposits and extensive cemeteries found in different parts of the country (Misra, 1973, 1997, 2001; Lukacs *et al*., 1982; Sankalia & Karve, 1949; Ehrhardt & Kennedy, 1965; Varma, 1986; Sharma, 1973; Kennedy *et al*., 1986, 1992; Sharma *et al*., 1980; Varma *et al*., 1985; Pal, 1992). The emerging archaeological evidences based on the pioneering work under the direction of Jean–Francois Jarrige since 1974 at Mehrgarh, Baluchistan in Pakistan suggest that the sedentary lifestyle farming communities can be traced back to ~9,000 yr BP and is also evident by the presence of winter crops *Triticum* sp. (wheat) and *Hordeum vulgare* (barley) at Mehrgarh (Costantini, 1984; Costantini & Biasini, 1985). The cultural history of the Mehrgarh Site has been divided into eight periods. The earliest period is dated from ~8000 yr BP to 6400 yr BP. and the subsistence economy consisted of a combination of hunting, stock–breeding and plant cultivation. The domesticated animals comprise cattle, sheep, goat and water buffalo, while the cultivated plants comprise wheat and barley.

With the progression of time, the significance of hunting waned, while agriculture flourished and pottery appeared. The quality of pottery gradually improved over the latter part of the 5th Millennium BC. The finding of a copper ring and a bead demonstrates the evolution of metal technology. The appearance of a new variety of barley, *Hordeum sphaerococcum*, which can only be grown in irrigated fields depending on monsoon rains, indicates that farming technology has advanced. The presence of cotton seeds imply that this fibre might have been used to make textiles. Following that, it is believed that the settlement's size increased and the ceramic industry saw a spectacular development. In agriculture, oats and another variety of wheat were grown. The granary size increased with multiple rectangular cells. Until 5000 years ago (3rd Millennium BCE), the advent of polychrome pottery is documented, coupled with considerable usage of timber in the construction of houses. Ceramics, notably the Pipal leaf and humped bull motifs on potteries, have similarities to the Harappan Civilization (Jarrige, 1990). Interestingly, the population explosion due to agricultural economy allowed people to overflow from the narrow valleys of Baluchistan to the vast Indus plain.

Similarly, cereal–based farming methods began in central India (southwestern Madhya Pradesh) around 9000 years ago (Quamar & Chauhan, 2012). The phytoliths–based study documents the evidence of wild rice (*O. rufipogon*) during Holocene and cultivation of indigenous summer rice crop (*O. sativa*), since ~10,000 yr BP at Lahuradewa, central Ganga Plain (Saxena *et al*., 2006; Tewari *et al*., 2006). Later, (Chauhan *et al*., 2009) also demonstrated that an agricultural–based culture existed in the Ganga Plains for 8000 years BP at the Lahuradewa archaeological site. Recent palynological studies (appearance of Cerealia pollen) carried out in central Ganga Plain, have revealed that ~7500 cal years BP incipient agrarian practices were operational. Since there are few such old archaeological sites excavated from the Ganga Plains, we continue with the established archaeological theory that agricultural–based life was initiated first in the western margins of the Indian subcontinent and migrated to the eastern part in later periods as per the monsoonal rain.

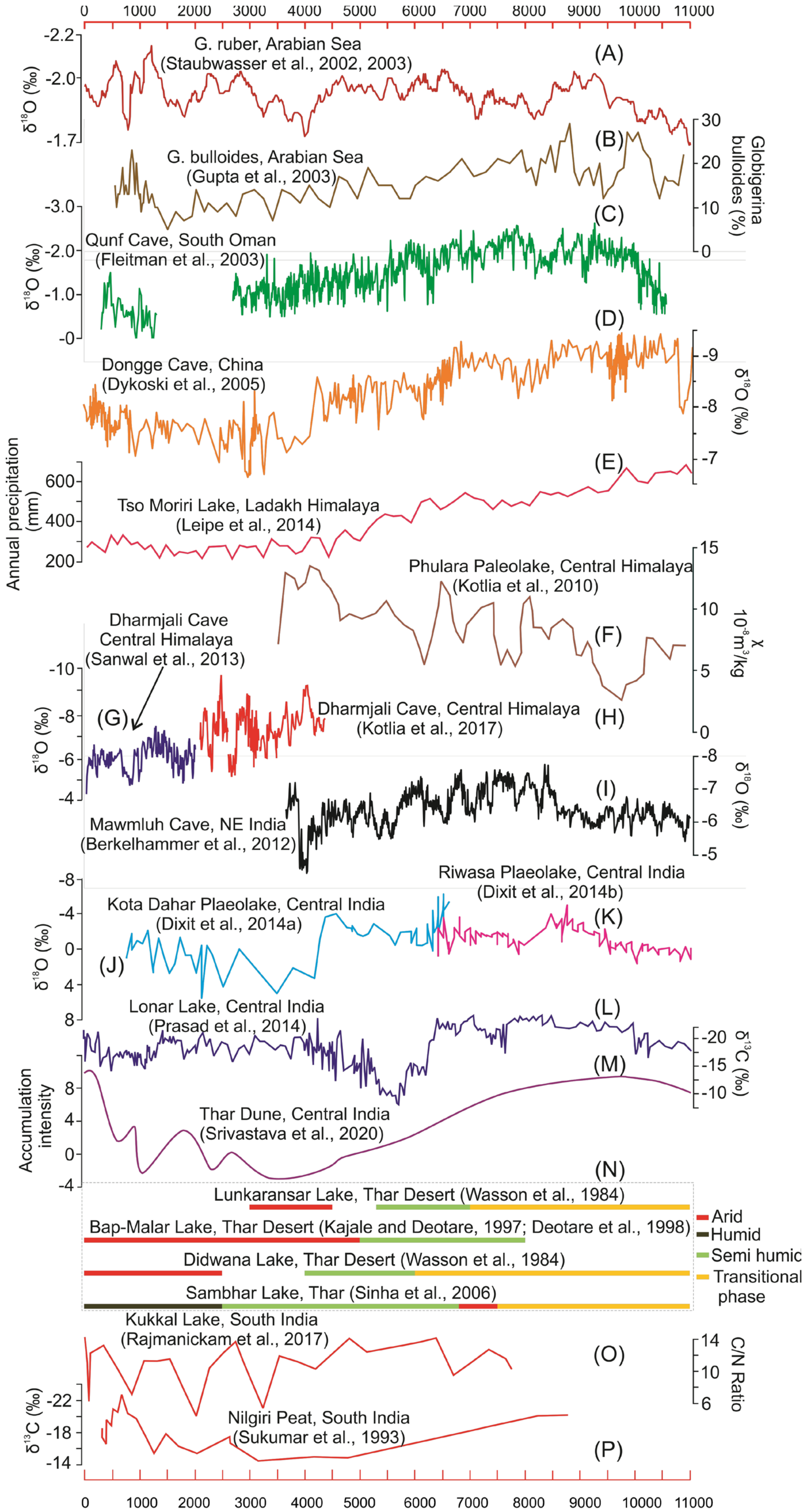
During this time the hunting–gathering way of life was gradually replaced by agricultural practices dependent on monsoon, however; this way of life was not fully abandoned, but it was restricted to select tribes in different areas of the country (Malhotra *et al*., 1983; Nagar & Misra, 1989, 1990, 1993). Interestingly, humans acquired a thorough knowledge of their characteristics, utility and behaviour during this period of interaction with wild animals and plants. This knowledge eventually culminated in the breeding of selected wild animals and the cultivation of selected wild grasses. This new subsistence economy based on food production had a lasting impact on the evolution of human society and the environment. In the humid lands extending from the middle Ganga Valley to China and Southeast Asia, rice cultivation and domestication of the pig was accomplished probably around the same time because rice and pig existed in wild form in this region. In the new economy, the old and the young people, who could not contribute to the food acquisition during the preceding hunting–gathering stage, became active participants. They could take care of the cattle, sheep and goats and protect crops from pests, especially birds. Eventually, as the efficiency of agricultural production improved having wetter climate, some farmers were able to generate surplus food. Consequently, it freed a large section of population from food production and their talents and energies were diverted to other tasks such as the production of pots, baskets, quarrying of stone, bricks making, masonry and carpentry, etc. Subsequently, society saw the emergence of other occupations such as the oil presser, washer–man, barber, musician, dancer, priest, etc. The egalitarian hunting–gathering society thus became divided into occupational groups. The production of agricultural wealth also led to the division of the society into rich and poor and exploiters and exploited. This transition from hunting–gathering to food production based on wetter climate has been aptly designated as the Neolithic revolution (Childe, 1936).

Neolithic and Chalcolithic cultures

Several excavations, investigations and the discovery of over a thousand sites in all parts of the Indian subcontinent except the west coast, including Kerala, have drawn attention to the dispersion of monsoon–based farming and corresponding settled village life beyond the domain of the

→

Fig. 2—A few marines and continental proxy records of the ISM variability and palaeoclimate during Holocene. (A) the Globigerinoides ruber (63KA/41KL) $\delta^{18}O$ record (210 year average) from the northern Arabian Sea (after Staubwasser *et al*., 2002, 2003); (B) the Globigerina bulloides (H–723A) record from in the western Arabian Sea (after Gupta *et al*., 2003); (C) the stalagmite $\delta^{18}O$ records from Qunf Cave, Oman (after Fleitmann *et al*., 2003); (D) the stalagmite (D4) $\delta^{18}O$ record from Dongge Cave, China (after Dykoski *et al*., 2005); (E) the mean annual precipitation reconstruction from Tso Moriri Lake, Ladakh (after Leipe *et al.*, 2014); (F) the magnetic susceptibility record from Phulara palaeolake, central Himalaya (after Kotlia *et al*., 2010); (G and H) the stalagmite (DH2 and DH1) $\delta^{18}O$ records from Dharamjali Cave, central Himalaya (after Sanwal *et al*., 2013; Kotlia *et al*., 2017); (I) the stalagmite $\delta^{18}O$ record from the Mawmluh Cave, NE India (after Berkelhammer *et al*., 2012); (J and K) the Gastropod $\delta^{18}O$ records from Kotla Dahar and Riwasa palaeolakes (Dixit *et al*., 2014); (L) the stable carbon isotope ($\delta^{13}C$) record from Lonar Lake, central India (after Prasad *et al*., 2014); (M) the accumulation intensity curve from the Thar dune records (after Srivastava *et al*., 2020); (N) the schematic representation of palaeolimnological reconstruction from Lunkaransar, Bap–Malar, Diswana and Sambhar lakes in the Thar (after Wasson *et al*., 1984; Kajale & Deotare, 1997; Deotare *et al*., 1998; Enzel *et al*., 1999; Sinha *et al*., 2007); (O) the geochemical (C/N ratio) record from Kukkal Lake, Tamil Nadu (after Rajmanickam *et al*., 2017); (P) the $\delta^{13}C$ record from Nilgiri Peat, south India (after Sukumar *et al*., 1993).


0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000
G. ruber, Arabian Sea
(Staubwasser et al., 2002, 2003)
(A)
δ18O (‰)
-2.2
-2.0
-1.7
G. bulloides, Arabian Sea
(Gupta et al., 2003)
(B)
Globigerina bulloides (%)
30
20
10
0
(C)
Qunf Cave, South Oman
(Fleitman et al., 2003)
-3.0
-2.0
-1.0
-0
(D)
Dongge Cave, China
(Dykoski et al., 2005)
δ18O (‰)
-9
-8
-7
(E)
Annual precipitation (mm)
600
400
200
Tso Moriri Lake, Ladakh Himalaya
(Leipe et al., 2014)
15
Phulara Paleolake, Central Himalaya
(Kotlia et al., 2010)
10
5
0
χ 10-8m3/kg
(F)
Dharmjali Cave
Central Himalaya
(Sanwal et al., 2013)
-10
-8
-6
-4
(G)
Dharmjali Cave, Central Himalaya
(Kotlia et al., 2017)
(H)
-8
-7
-6
-5
(I)
Mawmluh Cave, NE India
(Berkelhammer et al., 2012)
Riwasa Plaeolake, Central India
(Dixit et al., 2014b)
-8
-4
0
4
8
Kota Dahar Plaeolake, Central India
(Dixit et al., 2014a)
(J)
(K)
Lonar Lake, Central India
(Prasad et al., 2014)
(L)
-20
-15
-10
δ13C (‰)
(M)
Accumulation intensity
8
4
0
-4
Thar Dune, Central India
(Srivastava et al., 2020)
(N)
Lunkaransar Lake, Thar Desert (Wasson et al., 1984)
Bap-Malar Lake, Thar Desert (Kajale and Deotare, 1997; Deotare et al., 1998)
Didwana Lake, Thar Desert (Wasson et al., 1984)
Sambhar Lake, Thar (Sinha et al., 2006)
Arid
Humid
Semi humic
Transitional phase
Kukkal Lake, South India
(Rajmanickam et al., 2017)
(O)
14
10
6
C/N Ratio
δ13C (‰)
-22
-18
-14
Nilgiri Peat, South India
(Sukumar et al., 1993)
(P)
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000

Indus Civilization over the last five decades. These sites can be classified into two cultural groups; Neolithic and Chalcolithic. However, they flourished simultaneously during 6000 to 4000 yr BP (4th to 2nd Millennia BCE) in India. Although both cultures represent agricultural–based sedentary village life, the chalcolithic group depicts a more advanced stage and the role of individual components differs from one culture to the other. Both groups display the differences between the distribution pattern, technology, ceramics and architecture. The Neolithic cultures have a comparatively restricted distribution, confined to the Kashmir Valley, the northern Vindhyas, middle Ganga Plain, eastern, northeastern and south India. The Chalcolithic cultures have a much wider distribution, being found in the entire Ganga Plain, eastern Rajasthan, Malwa or western Madhya Pradesh, some parts of Gujarat, western Maharashtra and the northern Vindhyas (Fig. 1). Technologically, the main component in the Neolithic cultures consists of ground or polished stone tools like axes, adzes, wedges and chisels, while in the Chalcolithic cultures these types are represented by their copper counterparts. The oldest agriculture–based Neolithic settlements, which were using only stone tools in western Asia are dated back to ~6000 yr BP (4th Millennium BCE), from Rana Ghundai and Kili Ghul Mohammad in the hilly terrain of Baluchistan. It is interesting to know that the population growth due to the agricultural economy allowed people to overflow from the narrow valleys of Baluchistan to the vast Indus plain. There are numerous Neolithic settlements in the north and east of Baluchistan, such as Periano Ghundai, Gumla and Rahman Dheri in the Gomal Valley and those of Jhang and Sarai Khola west of Islamabad (Allchin & Allchin, 1982) indicating that people had moved out from the valley and began settling into the plains between 7000 and 6000 yr BP (5th and 4th Millennia BCE). As the Indus Civilization is the largest of the world's three oldest civilizations, a separate discussion is provided in the following section. Interestingly, all three civilizations flourished along large perennial rivers flowing through the desert environment.

Harappan Civilization

During the mid–Holocene (~6000 yr BP), permanent settlements appeared in the Indus Valley and the presently dried–up Ghaggar–Hakra River Valley, which was flowing parallel to and east of the Indus (see Fig. 1). It was discovered in 1921–1922 during excavations at Mohenjo–Daro and at Harappa (both now in Pakistan) (Kenoyer, 1998). More than 1500 sites of this civilization are now marked in the subcontinent, encompassing Saurashtra, Kutch, the western plain of mainland Gujarat, northwestern corner of Rajasthan, entire Punjab and Haryana, western Uttar Pradesh and southern part of Jammu in India; almost entire Pakistan and southern part of Afghanistan (Mughal, 1997) (Fig. 1). The ancestors of this civilization were highly advanced and their socio–economy and religious conditions are reflected through architecture, town planning, pottery and intensive agriculture. Agriculture based on double cropping (Rabi and Kharif) was extensively practiced throughout the region and played a significant role in the rise and characterization of the civilization. The available evidence suggests that both winter (barley, wheat, field–pea, lentil, chick–pea, grass–pea, linseed & Indian mustard) and summer crops (rice, green/black gram, horse gram, sesame & cotton) were part of the agricultural systems broadly during the Early (5000 and 4600 yr BP), Mature (4600 and 4200 yr BP) and Late Harappan (4200 and 3500 yr BP) phases in the core zone or Upper Indus Valley (Tengberg, 1999; Saraswat & Pokharia, 2002, 2003; Pokharia *et al*., 2014). Rice cultivation in the Indus Valley (Haryana–Punjab–Rajasthan), outside the zone of its natural habitats in Ganga Plain, expanded due to its early dispersal, owing to suitable moisture conditions in the NW region (Pokharia *et al*., 2014) (Fig. 1). The Neolithic of Ganga Plain (4600 and 4200 yr BP) also revealed a large number of crops (winter and summer) of almost all kinds cultivated in the Indus Valley and indigenous rice. The Neolithic (4800 and 4200 yr BP) in south India indicates that the likely staples were millet–grasses (*Brachiaria ramosa* and *Setaria verticillata*) and pulses (*Vigna radiata* and *Macrotyloma uniflorum*), which were indigenous to the Indian peninsula. At some sites, there is evidence for limited cultivation of winter (*Triticum dicoccum, Triticum durum/aestivum, Hordeum vulgare, Linum* sp.) and summer crops that originated in Africa, including pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*) and hyacinth bean (*Lablab purpureus*). In addition, there is evidence of fibre crop (*Gossypium* sp.) (Fuller *et al*., 2004).

The agricultural economy of the Harappans was based on the cultivation of wheat and barley in the Indus plains and of millets like jowar (*Sorghum bicolor*), bajra (*Pennisetum typhoideum*), ragi (*Eleusine coracana*), little millet (*Panicum miliare*) and Italian millet (*Setaria italica*) in the semi–arid region of Gujarat. At a later stage, probably when the Harappans came into contact with the rural societies of the Ganga plains, rice was also added to their agriculture (Weber, 1991). The Harappans also had traded with contemporary hunting–gathering communities (Misra, 1976; Possehl & Kennedy, 1979). In a detailed multiproxy study, Prasad *et al*. (2014) have adequately reviewed and provided additional data to establish the climate–culture relationship; however, there are still gaps and need comprehensive work to resolve the discrepancies. The archaeological data shows the transition from haphazard pastoral and village farming communities of early Harappan (5200–4500 yr BP) to culturally advanced well developed urbanized centres of mature Harappan (4500–3900 yr BP) community (Possehl, 2002). The transition from early to mature Harappan community and its subsequent decline was fairly abrupt (Possehl, 2002). The subsistence economy of pre–Harappan was primarily based on the winter–spring crops (wheat, barley, peas, lentils, grass pea and linseed) (Meadow, 1996; Tengberg, 1999; Fuller & Madella, 2001;

Fuller, 2002; Weber, 2003; Pokharia, 2011). Thus, before the rise of the Harappan Civilization, high winter rainfall activity must have contributed mainly to spreading the winter/spring harvested cropping system (Fuller, 2002; Weber, 2003; Pokharia, 2011). The earlier studies also suggest that wheat cultivation started much before the mature Harappan phase and the introduction of millets, pulses and non–staple summer crops by mature Harappan indicates changing pattern of agricultural practices and subsistence regime probably due to changing rainfall pattern (Madella & Fuller, 2006; Pokharia, 2011). High–resolution palaeoclimatic data emerging from the region is suggestive of declining winter rainfall after 5th Millennia BP (Bryson & Swain, 1981; Singh *et al*., 1990). The study also supports that a decrease in the festucoid phytolith morphotypes between ~6795 and 5565 yr BP indicates a decline in the winter rainfall activity. Changing pattern of palynoassemblage from wet evergreen to deciduous vegetation during this period also suggest a shift from wet climate to seasonally dry climatic conditions and reduced rainfall activity has been implicated. A multi–cropping subsistence strategy based on drought–tolerant cultivars and cultivation near riverine sources most likely shows mature Harappan agricultural intensification attempts to resist environmental challenges under regionally expanding aridity conditions between 4800 and 4200 years ago. Fluvial landscape studies near Ghagghar–Hakra and the Indus River show large scale flood events prior to the mature Harappan phase and a significant decrease in flood intensity due to a weak monsoonal climate during the mature Harappan phase (4600–4200 yr BP), which stimulated intensive agricultural activity in the low lying, river interfluve regions (Wright *et al*., 2008; Giosan *et al*., 2012). It has been discussed that there is an inverse, co–varying trend in rainfall seasonality in the northwestern region, as yearly monsoon rainfall diminishes and winter rainfall increases proportionately (Wright *et al*., 2008). Further, the innovative methods in agricultural activities during the mature Harappan phase adapt to changing rainfall pattern. Multi–cropping strategy with the introduction of summer crops (millets, gram), fruit cultivation and non–staple food crops like sesame and cotton and cultivation along the riverine sources strongly indicates agricultural practices in order to maximize agricultural yield to mitigate environmental deterioration (Madella & Fuller, 2006; Pokharia, 2011). According to Danino, (2008), the water scarcity and anthropogenic land degradation due to the prolonged drought conditions at around 4200 yr BP may have played a significant role in the breakdown of the Harappan culture. The extensive database of proxy evidence suggests that in the Mature–Harappan Period (4600 and 3900 yr BP), the monsoon severely declined, resulting in the aridification of Indian subcontinent and the Harappan culture might have faded away gradually during this climatic deterioration.

Metal technology and expansion of settled life

The first evidence of metal in the Indian subcontinent comes from the Mehrgarh Site, Baluchistan, after dating a small copper bead at ~8000 yr BP (Fig. 1). The extraction and smelting of copper began in West Asia around ~7,000 yr BP and a new raw metal was added to employ in technology. Eventually, the manufacturing of stronger metal bronze began by incorporating tin into copper. After the development of the wheel, which marked the beginning of pottery manufacture and transportation, the use of bronze ushered in a revolution. The advent of iron technology was critical to the spread of agriculture–monsoon–based settled life, particularly in the sub–humid region of the Ganga Plain. Once this technique was mastered, ordinary people could purchase iron tools, weapons and vessels and stone tools were eventually phased out. The Stone Age came to an end with the invention of iron technology. With the use of iron tools, ambitious farmers cleared the impenetrable forests of the middle and lower sub–humid Ganga plains, paving the way for efficient human settlement on this vast fertile plain. Iron tools were used to quarry stone for megalithic sepulchral and memorial monuments in mountainous and rocky peninsular India, as well as to dig wells and irrigation tanks in hard rocks. The agricultural surplus generated by the combination of iron technology, fertile soil, perennial availability of water from rivers, lakes and wells and human enterprise led to the emergence of second urbanization in the country. According to Roy (1983), the first urbanization occurred during the Bronze Age and was confined to the semi–arid northwestern subcontinent; the second urbanization took place in the Ganga Plain and gradually expanded over peninsular India.

The geographical focus of cultural development gradually shifted to the Ganga plains and the events of the two great Indian epics–the Mahabharata and the Ramayana, took place in the upper and middle Ganga Plain, respectively. Subsequent to the epic periods, the focus of cultural development shifted further east to eastern Uttar Pradesh and Bihar. In this region, Buddha and Mahavira started the revolt against the ritual and animal sacrifice–ridden Brahmanical religion and preached their message of non–violence and righteous conduct. The first political entities, the Mahajana–padas and the first Indian empire of Magadha, developed in this region. Based on luminescence dating of pottery, this culture has been dated between ~3450 to 3200 yr BP. The society was largely dependent on agriculture under favourable climate. Although today' life is technology–driven and a significant number of people are leaving agriculture and adopting other professions, however, more than 50% of population is still engaged in this occupation and therefore, climate/monsoon has immense importance to us.

VARIABILITY IN THE ISM FROM THE DAWN OF AGRICULTURE AND CIVILIZATION

The emergence of agriculture during the Holocene, notably within the last 10,000 years, caused profound changes in modern cultures. Societies have been subjected to considerable climate change and monsoon fluctuations since the advent of agriculture. The influence of monsoon variations on peninsular communities has been widely documented throughout history (Cook *et al*., 2010). According to Ponton *et al*. (2012), the link between people and the monsoon has existed since prehistoric times, as indicated by the steady growth in aridity–adapted plants as detected by the isotopic signature of leaf waxes. As agriculture involves a relationship with both animals and plants and its linkages with the monsoon, these organisms remain to provide the most direct evidence of the pale monsoon behaviour over the centuries (Fuller, 2006). These records include annual to decadal–scale monsoon fluctuations and large–magnitude changes over the centennial to multi–millennial timescales. The proxy records are vital to emplace the contemporary monsoon variations in perspective, yet the knowledge regarding variability in ISM strength in time and space is limited. Nevertheless, the recent high–resolution proxy records revealed that the Holocene climate is characterized by various short–lived abrupt climatic oscillations (Alley *et al*., 1997; Bond *et al*., 1997, 2001; Björck *et al*., 2001; Singhvi *et al*., 2009). In order to reconstruct the long–term monsoonal variations, efforts are being made by using the marine and terrestrial proxy records. In the following section, we summarize several proxy records from the Indian subcontinent and adjacent regions to determine the intensity of ISM duirng the last ~10000 years (Fig. 2). The evidence of more effective monsoon at ~10000 yr BP are documented from the Arabian Sea (Sirocko *et al*., 1993; Overpeck *et al*., 1996; Naidu & Malmgren, 1996; Sarkar *et al*., 2000; Staubwasser *et al*., 2003; Gupta *et al*., 2003; Singh *et al*., 2006; Govil & Naidu 2010; Rao *et al*., 2010; Kessarkar *et al*., 2013) (see Fig. 2A & B) and Bay of Bengal (Chauhan & Suneethi, 2001; Chauhan, 2003; Chauhan *et al*., 2004), with maximum expansion of mangroves between 10400 and 9000 yr BP (Hait & Behling, 2009).

Various proxy records link the commencement of agriculture, development and the establishment of civilization centres to the early Holocene intense monsoon phase. Misra (2001) documents evidence of continued human habitation between ~9000 and 4600 yr BP from Mehrgarh, Baluchistan and While, Quamar and Chauhan (2012) have reported cereal–based agricultural practices in central India back to ~9000 yr BP under strong ISM. Wheat and barley cultivation in NW Indian (Jarrige, 2008) and a Neolithic Site on the northern Kopet Dag foothills of western central Asia (Harris, 2010) are dated back to ~8000 yr BP. A precisely dated lake sediment record from Lunkaransar, Rajasthan, indicates that the monsoon fluctuated frequently in the last ~10000 yr BP and intensified abruptly at ~6300 years ago (Enzel *et al*., 1999) (Fig. 2 N), corresponds with the palaeolake sediment record from NW India, at ~9400 yr BP (Dixit *et al*., 2014) (Fig. 2K). In the Ganga Plain the forest groves interspersed with open grasslands between 12500 and 8700 yr BP (Chauhan *et al*., 2015) and a speleothem record from the core monsoon zone (ISM) also reports rapid increase in ISM (Yadava & Ramesh, 2005). The multiproxy records from Kukkal Lake, Tamil Nadu, south India by Rajmanickam *et al*. (2016) also documents the strengthening of ISM between 9000 and 8700 yr BP (Fig. 2O). In the Himalayan region, pollen–based and stable carbon isotope based reconstruction of the mean annual precipitation (Fig. 2E) reveals a rapid increase in MAP during the early Holocene from both northwestern and eastern Himalaya (Leipe *et al*., 2014; Ali *et al*., 2018). This observation is further corroborated by other Himalayan palaeoclimatic reconstructions (Demske *et al*., 2009; Bhattacharyya *et al*., 2011; Trivedi & Chauhan, 2009; Rawat *et al*., 2015; Kotlia *et al*. 2010; Ghosh *et al*., 2020) (Fig. 2F). The evidence of strong ISM at ~11500 yr BP onwards are recorded by Brown *et al*. (2003) and between ~10000 and 8000 yr BP by Gasse *et al*. (1991) from Tibet and Karakoram. A high–resolution stalagmite record from Qunf (Fig. 2C) and Defore Cave, Oman, convincingly demonstrates a period of increased ISM–driven precipitation between 10500 and 9600 years ago (Fleitmann *et al*., 2003, 2007). Collectively, the increasing strength of ISM during 10000 yr BP was linked with the migration of the ITCZ (Dutt *et al*., 2015).

The onset of an abrupt cold excursion with depleted intensity of ISM is observed around 8000 yr BP, as evidenced by the several precisely dated proxy records from Indian subcontinent. This dry climatic phase corresponds to the globally recognized 8.2 ka cooling event. During this phase, the summer and winter annual sea surface temperatures (SSTs) of the western Arabian Sea show a sudden cooling approximately 8200 years ago (Naidu, 2006; Gupta *et al*., 2003) (Fig. 2B), which coincides with the cold event in Greenland and the North Atlantic Ocean. Similar weakening of the ISM is observed between ~8300 and 7900 yr BP in NW India (Dixit *et al*., 2014, 2015) (Fig. 2K). The increasing aridity and a cold climatic phase are also observed in Himalayan region (Kotlia *et al*. 2010; Rawat *et al*., 2015; Demske *et al*., 2009; (Fig. 2F) and Rajasthan as well as western Tibet (Gasse & Van Campo, 1994). The speleothem records from Hoti and Qunf Caves in Oman (Fig. 2C) also indicate the weakening of ISM at ~8200 yr BP (Neff *et al*., 2001; Fleitmann *et al*., 2003; Cheng *et al*., 2009). Although the impacts of this cold event on early farming communities in the Indian subcontinent remain unknown, however, the eastward expansion of the Neolithic into Central and Eastern Iran may have occurred concurrently with this event (Weeks *et al*., 2006; Weeks, 2013). This 8.2 ka event is linked to the

North Atlantic Cooling (Wang *et al*., 2005; Gupta *et al*., 2003; Staubwasser *et al*., 2002), which is driven by the variations in solar irradiance.

Eventually, improvement in the strength of ISM is observed in different parts of India and adjacent regions after ~7000 yr BP, which marks the warm and wet Holocene Climate Optimum (HCO) recorded between 7000 and 5000 yr BP (Bradley, 1999). This period is also important in the Holocene Era for tracking the influence of climate on flourishing human communities in and around the Indian subcontinent. The botanical evidence based on the dated millets between ~7000 and 6000 yr BP, from Qasim Bagh, Kashmir, documents a long term agricultural transformation towards multi–season crop farming in the valley and further suggested the multiple and varying routes of exchange with South, East and Central Asia (Spate *et al*., 2017). Advancement in the crop husbandry as evidenced by the appearance of highly evolved hexaploid forms of bread wheat (*Triticum aestivum*), club wheat (*T. compactum*) and dwarf wheat (*T. sphaerococcum*), in addition to einkorn, emmer and hulled and naked forms of barley already encountered in the Baluchistan region. Besides, cereals, fruit remains of *Phoenix dactylifera, Prunus* sp. and *Ziziphus* sp. have also been recorded during this period (Costantini & Biasini, 1985). During ~6000 yr BP, several societal collapses and severe water shortages were reported due to an abrupt failure of ISM (McGhee, 1981; DeMenocal, 2001; Weiss & Bradley, 2001; Pandey *et al*., 2003; Staubwasser *et al*., 2003; Gupta *et al*., 2006; Wanner *et al*., 2008). However, the palynological investigation of lacustrine sediments in the Rajasthan Desert by Singh *et al.* (1974) revealed that the region received > 50 cm more rainfall 5000 years ago than it does today. The investigations made by Swain *et al*. (1983), Wasson *et al*. (1984) and Enzel *et al*. (1999) substantially support the findings from western Rajasthan. Later, Deotare *et al*. (2004) discovered evidence of this large episode of intense monsoon from the Thar Desert 7000 years ago and Prasad and Enzel (2006) identified a comparable occurrence between 7000 and 5300 years ago, as evidenced by high levels of lakes Lunkaransar and Didwana in the Thar Desert (Fig. 2N). A multi–proxy based study from Wadhwana Lake, Gujarat recorded this moist climate phase between ~7500–5560 yr BP and eventually merged with an event of declined monsoon between 5560 and ~4255 yr BP (Prasad *et al*., 2007). In South India, strengthening of ISM is observed at ~6,000 yr BP (Nair *et al*., 2010) and between 5000 and 4000 yr BP (Limaye *et al*., 2014; Veena *et al*., 2014). In higher Himalaya, intensified monsoons are recorded between 7200 to 5000 yr BP with maximum intensity at ~5000 yr BP (Phadtare, 2000). These results correspond well with the expansion of oak forest under strong monsoon conditions between 6125 and 4330 yr BP (Trivedi & Chauhan, 2009). The Valley of Kashmir has evidenced for long term sedentary occupation to as early as the 4700 yr BP. Botanical evidences from Neolithic sites (Kanispur, Burzhaom, Gufkral) reflect agriculture based on winter adapted crops such as barley, wheat and pulses, similar to early Harappan assemblages in NW India (Pokharia *et al*., 2017a). Recent records from Anchar (Lone *et al*., 2020) and Wular (Shah *et al*., 2020) lakes in the Kashmir Valley indicate higher precipitation between ~5000 and 4000 yr BP. Motuzaite *et al*. (2020) document a similar situation at Chap in Kyrgyzstan and integrated this phase with high–altitude cultivation into agro–pastoralist systems. In the central Himalaya, Kotlia *et al*. (2010) recorded the climatic change from ~6000 yr BP onwards (Fig. 2F) and declined monsoon phase is recorded between 4600 and 3500 yr BP (Kotlia & Joshi, 2013). A phase of the increased summer monsoon is observed between 5400 and 4200 yr BP in the proxy records from Pakistan (Ivory & Lézine, 2009).

The monsoon trend between ~5000 and 4000 yr BP is significant to understand the abrupt aridity during 4.2 ka event. This phase of declined ISM primarily affected the human population and surroundings; the impact of this dry climate is well documented in the archaeological records from the central and western parts of the country. According to Ponton *et al*. (2012), the cultural changes occurred across the Indian subcontinent as the climate became drier after 4000 yr BP and the mass migration began and the small settlements drastically increased in the plains of the upper Ghaggar–Hakra and Ganga, at the foothills of the Himalaya (Possehl, 1997a, b, 2002; Enzel *et al.*, 1999; Gupta *et al*., 2003; Staubwasser *et al*., 2003; Staubwasser & Weiss, 2006; Giosan *et al*., 2012, 2018; Ponton *et al*., 2012; Dixit *et al*., 2018) (Fig. 2). Further, the modification in the Indus and Narmada deltas' coastline may have contributed to the migration by submerging crops before it was sustained ~5000 yr BP (Gourlan *et al*., 2020). Based on the marine record from the NE Arabian Sea, the aridity at ~4200 yr BP is linked with the insolation–induced southward migration of the ITCZ (Burdanowitz *et al*., 2019). The era between ~5000 and 4200 yr BP witnessed pre–urbanized and urbanized society (Indus Civilization), which flourished in present–day Pakistan and northwestern India (Possehl, 2002). The period between ~4200 and 3500 yr BP (Late Indus Period), witnessed the disintegration of larger cities into small village type settlements in the region of northwest India. The globally recognized arid event at ~4200 yr BP prompted the settlers to adopt drought–resistant small–grained millets for sustenance (Weber, 1991; Reddy, 1994; Pokharia, 2011, 2017b) in the peripheral zone (Gujarat), as this region lacks any major perennial rivers. Adverse climatic conditions due to the declining ISM might have provided suitable conditions for these crops in the region of Gujarat, thus providing clues about human adaptation capabilities such as changes in subsistence patterns and changing food habits (Fuller, 2006; Pokharia, 2011; Goyal *et al*., 2013). Despite rapidly changing monsoon, diversification in crop economy during the Chalcolithic (4200 to 3500 yr BP) phase is evident by wheat, barley, rice, millets, pulses, oil–yielding crops and fibre crop cultivation from archaeological sites of northern Rajasthan and Ganga

Plain (Saraswat, 1992, 2004; Pokharia, 2008, 2011; Pokharia *et al*., 2009). A majority of the sites are close to rivers or seasonal drains (Misra, 2001; Singh & Singh, 2005; Fuller, 2011) suggesting the role of water for irrigation. According to Puri (2008), the ancient Vedic Civilizations, e.g. Indus Valley Civilization, Ghaggar–Hakra Civilization or Indus–Sarasvati Civilization with several thousand prosperous towns thrived along the banks of the Indus, Ghaggar and Sarasvati rivers between ~4600 and 4100 ka BP and most of these rivers flowed strongly across the foreland domain (Valdiya, 2002, 2017). Harappan Civilization was thought to have flourished during the higher rainfall monsoonal climate and collapsed during the arid phase of mid–Holocene (Singh *et al*., 1974; Bryson & Swain, 1981; Agrawal, 1982; Swain *et al*., 1983), though it was criticized in many archaeological studies (Misra, 1984; Ratnagar, 1987, 2000; Shaffer & Liechtenstein, 1989; Possehl, 1997a, b; Fuller & Madella, 2001). Further, high–resolution studies (Enzel *et al*., 1999; Prasad & Enzel, 2006) indicate that the onset of the mid–Holocene aridity precedes the urbanization phase of Harappan Civilization. Large number of pre–Harappan sites shows rich macrobotanical remains indicating extensive agricultural activity based on monsoonal rains that would have provided subsistence base and surplus food to the expanding Harappan cultural practices (Costantini, 1983).

After 4000 yr BP, there is a significant increase in the number of archaeological sites in the northern peninsula (Misra, 2001) and migration to locations distant from the rivers, probably in response to a wetter climate. The cultivation systems of this period incorporated winter crops, like wheat and barley and indigenous monsoon grew rice and millets (Saraswat, 1992; Fuller, 2011). Wheat and barley cultivation might have been facilitated by relatively wetter conditions of this period as they would have needed to be grown on water retained by clay–rich soils in the northern peninsula or by artificial irrigation. The period between ~3500 and 3000 yr BP coincides with the Vedic Period of Indian history, known for advanced medical sciences (Ayurveda), spirituality and discovery of Iron. The evidence of horticultural and medicinal plants from archaeological sites in the Ganga Plain point to the existence of highly advanced medicinal system (Saraswat, 1992; Pokharia *et al*., 2016). Agriculture data from central India and the Deccan gives us a good picture of the cultivation of many types of winter and summer crops and fruit trees (Saraswat, 1992). Following the Vedic Period (3000 to 2000 years BP), the early historic period is noted for technological diversity that led to water storage, dams and appropriate irrigation (Shaw *et al*., 2007; Pandey *et al*., 2003). The various historical, archaeological and geological records show an abrupt drying trend at 4000 years ago; within age uncertainties; these records coincide with the end of the Harappan Civilization in the Indus Valley and the collapse of other civilizations westward (Staubwasser & Weiss, 2006) and the Neolithic culture in central China (Shao *et al*., 2006). This dry climatic episode is also associated with the most extraordinary historical record of drought in tropical Africa known as the "First Dark Age" (Thompson *et al*., 2002). The collapse of numerous other human communities in the Middle East (Bell, 1971; Hassan, 1981; Hassan & Stucki, 1987), Turkey and Yemen (Dalfes, 1997), the Akkadian Empire in Northern Mesopotamian and Iranian civilizations (Weiss *et al*., 1993; Cookson *et al*., 2019; Cullen *et al*., 2000; Leick, 2009) and the Egyptian Old Kingdom (Marshall *et al*., 2011; Welc & Marks, 2014) have been attributed to the declining precipitation (Stanley *et al*., 2003; Kuper & Kröpelin, 2006; Weiss *et al*., 1993; Weiss, 2017). Based on eighteen archeological surveys in the Middle East, the latest study by Lawrence *et al*. (2021) also documents the decline in the urban and rural growth around 4200 yr BP. The oxygen isotope records of the Indus River discharge also indicate decreased water flow around 3200, 2500 and 2100 yr BP, which may have restricted Harappan farming in the Indus Valley relinquish the large city populations unsustainable (Staubwasser *et al*., 2003). Based on the OSL ages of Saraswati River sediment, Saini *et al*. (2009) demonstrate that the river became very sluggish between 4300 and 2900 yr BP. The deterioration of the Harappan de–urbanization is documented at ~4000 yr BP (Wright, 2010; Dixit *et al*., 2014) and the beginning of fall culture is documented at ~3800 yr BP (Winner, 2012). According to the most recent modelling research, MacDonald (2011) determined that the Indus Civilization progressively fell between 3900 and 3000 years BP due to rising water shortages caused by decreased rainfall.

Several multi–proxy records also provide evidence of this arid event between ~4000 and 3000 yr BP and have been associated with weak ISM. The evidence of weak monsoon is documented from NW India at ~3500 yr BP, followed by the strengthening of ISM after ~3500 yr BP and a short pulse of dry climatic between ~3238 and ~2709 yr BP (Prasad *et al*., 2007, 2014). Several lakes in the Thar like the Bap–Malar, Didwana, Lunkaransar also showed high salinity levels or dried up between ~3500 and 1500 yr BP (Wasson *et al*., 1984; Singh *et al*., 1990; Kajale & Deotare, 1997; Deotare *et al*., 1998; Enzel *et al*., 1999) (Fig. 2N). Based on the sedimentological records and luminescence dating, Jain and Tandon (2003) and Jain *et al*. (2004) suggested that the streams in the southern Thar dried up between ~3500 and ~1500 yr BP. In Himalaya, several studies indicate aridity between 4000 and 3500 yr BP (Kotlia *et al*., 2010; Chauhan & Sharma, 2000; Phadtare, 2000). Pollen records from Ladakh Himalaya between 5379 and 2228 yr BP reports weakening of monsoon (Bali *et al*., 2016), similar to this Phadtare (2000) documents a progressive declined monsoon between 4500 and 3500 yr BP. The decreasing lake level is observed in the northwest Himalaya between ~4000 and 3400 yr BP by Mishra *et al.* (2015) and enhanced aridity between ~3800 and 3600 yr BP and less discharge in the Indus River after ~3200 yr BP (Leipe *et al*., 2014) (Fig. 2E). The speleothem–based study from Sainji Cave in central Himalaya identified the start of cold climate between 4000 and 3000 years ago, with the lowest precipitation event occurring around 3200 years ago (Kotlia *et al*., 2015). Later, more detailed records from Dharamjali Cave show significant precipitation between 4000 and 3700 yr BP, followed by a progressively declining trend from 3700 yr BP onward, with three dry periods at 3400, 3200 and 3000 yr BP (Kotlia *et al*., 2017). The maximum aridity around 3400 yr BP is also apparent in the Tityana Cave data (Fig. 2H) (Joshi *et al*., 2017). The Mulwah Cave speleothem record (Fig. 2I) indicates the low strength of ISM during 4000 years ago (Berkelhammer *et al*., 2012). These Himalayan records appear to be consistent with speleothem records from Soreq Cave, Israel in the eastern Mediterranean and Qunf Cave, Oman in the Middle East region, which have higher δ^{18}O values at 3500 yr BP (Bar–Matthews *et al*., 2003) and a higher amplitude peak at 3400 yr BP (Fleitmann *et al*., 2007), indicating declined ISM. Dykoski *et al*. (2005) found this phase in Dongge Cave, China, about 3600 ka BP (see Fig. 2D), while this aridity (weak ISM) is observed between ~4000 and ~3000 yr BP in western Tibet and Africa (Swain *et al*., 1983; Gasse *et al*., 1991; Gasse & Van Campo, 1994; Fontes *et al*., 1996; Haug *et al*., 2001). Improvement of monsoon is observed after ~3400 yr BP, with the gradual decrease in the speleothem δ^{18}O from Tityana Cave (Joshi *et al*., 2017). A similar situation was prevailed in the Indus River by the high monsoonal runoff between ~ 3500 and 2200 yr BP (Von Rad *et al*., 1999) and in the Basaha Lake, central Ganga Plain from ~3300 yr BP onwards (Chauhan & Chatterjee, 2008). Another record from the Central Indian Core Monsoon Zone also documents increase in monsoon rainfall between ~2807 and 1125 yr BP (Quamar & Chauhan, 2012). Results from central Himalayan describes a fluctuating trend in the speleothem δ^{18}O from ~3000 yr BP onwards indicating heavy rainfall at ~2700 yr BP, which gradually decreases between ~2700 and 2450 yr BP, along with severe aridity at ~2500, ~2400 and ~2100 yr BP (Kotlia *et al*., 2017) (Fig. 2).

The period between ~2000 and 1500 yr BP has been described as an interval of long warm–humid phase, particularly in the Mediterranean region; this phase is recognized as "Roman Climatic Optimum (RCO) or Roman Warm Period (RWP)," characterized by the development of Ancient Roman Civilization. According to Margaritelli *et al*. (2020), the favourable climatic conditions during this period may have contributed to the expansion of the Roman Empire. A progressive cooling trend is observed in all the Mediterranean Sea Surface Temperature (SST) records until LIA by the end of this period. The multi–proxy records of this prolonged wet climatic–phase are well documented from the Himalayan region between ~2000 and 1000 yr BP (Bali *et al*., 2016; Bhattacharyya *et al*., 2007; Chauhan, 2003; Kar *et al*., 2002; Singh *et al*., 2020; Trivedi & Chauhan, 2009; Ali *et al*., 2018, 2020a, b). The speleothem–derived δ^{18}O records from NE India show high monsoon intensity in the last 2000 years (Dutt *et al*., 2021) and a pollen–based study from the NE–Brahmaputra flood plains indicates the proliferation of deciduous tree taxa under increased precipitation between 1950 and 989 years ago (Dixit & Bera, 2013). The monsoon–driven ancient catastrophic flood events are also dated between 1750 and 1560 yr BP and 1320 and 1110 yr BP from a fluvio–lacustrine terrace of Tsangpo River, in eastern syntaxis of the Himalaya (Montgomery *et al.*, 2004). The increased intensity of ISM during this interval is linked with the warming of the circum–North Atlantic region (Martín–Puertas *et al*., 2009), synchronous with intense solar insolation and associated with the northward shift of the ITCZ (Haug *et al*., 2001; Solanki *et al*., 2004). In contrast, several studies from the west and south India documented a significant phase of weak monsoon precipitation between ~2000 and 1,500 yr BP (Wasson *et al*., 1984; Singh *et al*., 1990; Kajale & Deotare, 1997; Deotare *et al*., 1998; Enzel *et al*., 1999; Jain & Tandon, 2003; Jain *et al*., 2004; Limaye *et al.*, 2014) (Fig. 2N). Based on previous studies, the evidence of adaptation to semi–arid conditions in central and south India is well documented. Gunnell *et al*. (2007) have clearly documented the development of cultural adaptation to rising aridity, as seen by the rapid increase of rainfall harvesting structures after 1,700 years BP in the semi–arid parts of south India and similar dry event has also been reported from the Himalaya (Ali *et al*., 2020b).

The behaviour of ISM has changed dramatically during the last 1000 years, defined by recurrent natural disasters caused by catastrophic flood and mega–drought events, which have had a significant impact on the human population (Berkelhammer *et al*., 2010; Buckley *et al*., 2010; Cook *et al*., 2010; Sinha *et al*., 2011; Dixit & Tandon, 2016). This period is characterized by two globally recognized (weak and strong monsoon) centennial phases–the Medieval Warm Period (MWP) between ~1150 and 750 yr BP (800 and 1200 CE) (see Broecker, 2001) and a relatively cold Little Ice Age (LIA) between ~450 and 100 yr BP (1500 to 1850 CE) (Graham *et al*., 2011; Grove, 1988, 2001). Because of the enormous variability in the commencement, length and amplitude of these intervals globally, the chronology of MWP and LIA remains varied (Bradley & Jones 1993; Cronin *et al*., 2010; Mann *et al*., 2009; Matthews & Briffa, 2005; Wanner *et al*., 2008). These intervals also show precipitation irregularity on a regional and global scale (Cook *et al*., 2007; Feng & Hu, 2008; Graham *et al*., 2011; Ljungqvist *et al*., 2012; Newton *et al*., 2006; Seager *et al*., 2007; Wanner *et al*., 2015). This timeframe also includes several decadal to multi–decadal periods of weak monsoon, between 930 and 850 years ago and 800 and 570 years ago; records of these significant droughts are well documented in historical archives and proxy–based reconstructions. During the MWP, a progressive trend of cumulative ISM is observed in the records from the marine (Gupta *et al*., 2005) and diverse terrestrial ecosystems of the Indian subcontinent (Sukumar *et al*., 1993; Breitenbach *et al*., 2010; Sinha *et al*., 2011; Quamar & Chauhan, 2014; Singh *et al.*, 2015; Leipe *et al.*, 2014; Ali *et al.*, 2020b). According to An *et al.* (2012), Tibet also experienced slightly higher rainfall during this interval. The increasing strength of ISM during MWP is attributed to the northward migration of the ITCZ (Haug *et al.*, 2001) caused by the higher solar insolation (Fleitmann *et al.*, 2003; Gadgil, 2003). Later, Liang *et al.* (2015) explained the mechanism for strengthening of ISM during MWP by linking it with the warming of the North Atlantic Ocean caused by the circulation of warm water from the warmer Eurasian landmass generating a pressure gradient between the Indian Ocean and the Eurasian continent.

The earlier studies on ISM suggest a considerable heterogeneity in the latitudinal monsoon precipitation during the LIA due to the rapid southward migration of the ITCZ (e.g. Newton *et al.*, 2006; Kotlia *et al.*, 2012; Sanwal *et al.*, 2013). In general, the low intensity of the ISM is documented in the marine and coastal proxy records during the LIA period (Anderson *et al.*, 2002; Gupta *et al.*, 2003; Manoj *et al.*, 2021). The speleothem records from Dandak and Jhumar caves, Peninsular India, suggest a weakening of ISM during LIA, between 550 and 250 yr BP (Berkelhammer *et al.*, 2010; Sinha *et al.*, 2007, 2011). The dry condition between ~710 and 210 yr BP, are also evident from the drought–resistant crops (millets) dominated the ancient settlers' at Chandravati, Sirohi, Rajasthan (Pokharia, unpublished data). The multiproxy record from the Nikahari Lake, Gandak River Basin documents the consistent occurrence of Cerealia with other cultural pollen taxa indicating the prevalence of agrarian practices at ~650 yr BP, followed by weak ISM between ~650 and 500 yr BP and a significant expansion of forest groves under enhanced rainfall between ~530 and 330 yr BP, followed by weak ISM between 330 and 200 yr BP (Saxena & Singh, 2017). In contrast, a short phase of weak ISM is observed at the onset of LIA, followed by the increased precipitation during the middle LIA in a speleothem record from Akalagavi Cave, Western Ghats (Yadava *et al.*, 2004). Similarly, teak tree–ring records from Western Ghat indicate wet conditions during LIA (Borgaonkar *et al.*, 2010). A negative $\delta^{18}O$ excursion in the speleothem records from Wah Shikhar Cave, NE India, is interpreted as strong precipitation between ~440 to 290 and 270 to 230 yr BP during LIA (Sinha *et al.*, 2011). Another latest multi–decadal speleothem record from the Wah Shilar Cave agrees with the monsoon intensification during the onset of LIA (Gupta *et al.*, 2019). A tree rings–based reconstruction coupled with model simulations of the discharge in Brahmaputra River by Rao *et al.* (2020) documents a phase of strong monsoon precipitation over the basin during LIA between ~550 and 100 yr BP, to increased discharge towards the end of this period. The depleted values of $\delta^{18}O$ are observed in the speleothem records from central Himalaya during LIA (Kotlia *et al.*, 2012), between 570 and 130 yr BP (Sanwal *et al.*, 2013) (Fig. 2G) and ~500 and 300 yr BP (Liang *et al.*, 2015) indicating more precipitation. Stalagmite records from Siddha Baba Cave, central Nepal, indicate more moist conditions between 400 and 310 yr BP (1550–1640 CE) (Denniston *et al.*, 2000). The results from elsewhere occurring at similar latitudes show the wetter conditions during LIA (Chu *et al.*, 2002; Chen *et al.*, 2005; Tripathi *et al.*, 2004). The various records from the Indo–Pacific region also suggest wetter conditions during LIA (Liu *et al.*, 2008; Newton *et al.*, 2006; Oppo *et al.*, 2009; Tierney *et al.*, 2010). Similarly, in the higher Himalayan peat deposit, moist climate is observed at around ~340 yr BP (Phadtare & Pant, 2006) and pulsatory cold climatic phase after ~350 years ago (1650 CE) is reported by Bali *et al.* (2016), evident by a sharp decline in the broad–leaved forests.

Integrating these proxy records of monsoon reconstruction in the last 1000 years reveals that the monsoon variability across the ISM–dominated–Indian peninsula and north Indian regions is broadly synchronous with the strong monsoon during MWP. In contrast, the ISM's intensity during LIA displays a large heterogeneity by showing a low precipitation trend over peninsular India, while the northern regions experienced increased monsoon precipitation. A comparable study was conducted by Kumar *et al.* (2019) to understand the role of diverse precipitation regimes over central and north India during Holocene by combining the high–resolution proxy records and simulation modelling. This study suggests that ITCZ's migration from the Bay of Bengal to the Arabian Sea is caused by the changes in solar insolation, influencing the precipitation pattern over the core monsoon zone and Himalayan regions during the mid to late Holocene. Furthermore, the systematic compilation of the maximum available proxy records on the monsoon variability is well documented in the recent reviews from Indian subcontinent by Dixit and Tandon (2016) to understand the hydroclimatic variations and associated mechanisms during the last 1000 years. These reviews clearly show heterogeneity in the monsoon precipitation over southern and northern regions, suggesting dry–south and wet–north trends during LIA. Although this may not apply to the entire south or north Indian regions, the evidence from Aklagavi Cave and tree rings from the Western Ghats indicate that this region was under wet conditions during the LIA.

The increased precipitation in north India and the Western Ghats during LIA may be attributed to the 'break event" and winter westerlies at the same time. Liang *et al.* (2015) suggested that the increased precipitation during LIA may be the combined impact of 'break event" and western jet. Along the 'break event,' the cooler temperature may have pushed the depressions originating in the Mediterranean Ocean southward during the LIA and carried along the south margin of the Tibet Plateau by the southern winter jet, causing increased winter precipitation in the areas situated below the southern track of the subtropical winter jet stream. The intensity of ISM declined after the 18th Century; during post–LIA, Sontakke and Singh (1996) extended the all–India summer rainfall record from 1813 CE, suggesting the middle of the 19th Century was driest in India. Declined rainfall after

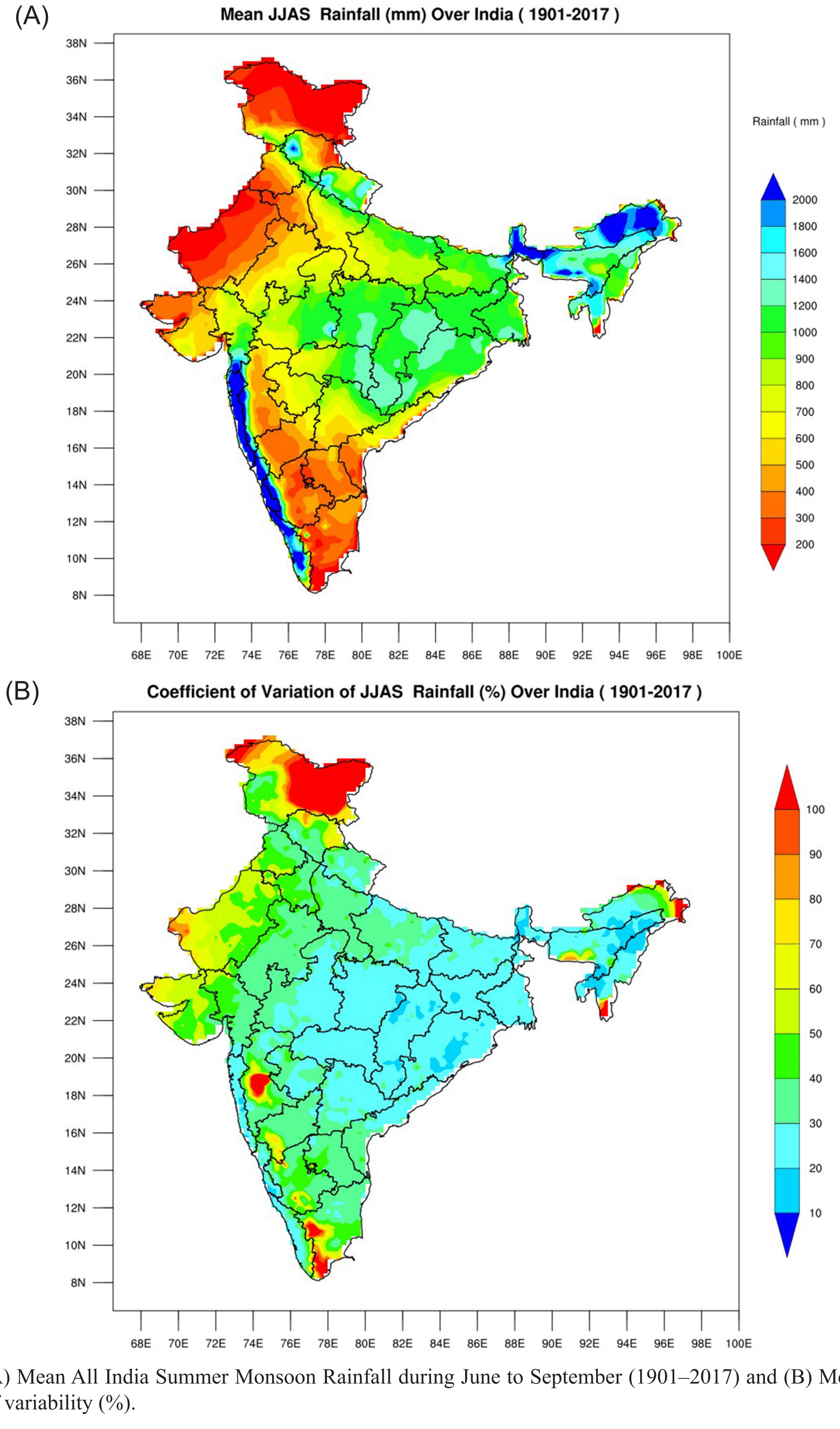


Fig. 3—(A) Mean All India Summer Monsoon Rainfall during June to September (1901–2017) and (B) Mean Co–efficient of variability (%).

~1880 CE is also observed in the speleothem records from central Himalaya (Sanwal *et al*., 2013). The tree ring records from NW Himalaya suggest weak ISM between 1932 and 1941 CE (Singh & Yadav, 2005). The record of ISM from central and western India reconstructed using a comprehensive study on the flood events indicate dry condition between the 14th and 19th centuries (Kale & Baker, 2006).

PRESENT MONSOON VARIABILITY AND MONSOON FORECAST

The ISM is a component of the Asian Summer Monsoon and consequently a unique feature of the tropical circulation. Unique geographical and physiographical features characterize the region of South Asia. The diverse geographical pattern facilitates the development of centres of intense convection, primarily due to differential heating of land and sea, resulting in the intensity of rainfall in a particular period of the year. Such events are the results of exceptional seasonal reversal of winds. For the millions inhabiting monsoonal regions (especially the Indian sub–continent), the seasonal variation of the rainfall associated with the monsoon system is of far greater importance than the seasonal variation of wind. It is a general perception that life in India revolves around the monsoons. Prior to the onset of the monsoon, the Indian Monsoon Zone is characterized by a heat low centered near central Pakistan and adjoining northwestern parts of India. The onset of monsoon over the southern tip of India (Kerala Coast) is marked as the beginning of the monsoon season. Once the monsoon covers the entire country, the intertropical convergence zone (commonly known as the monsoon trough) gets established over the region. Over a large part of the Indian region, most of the rainfall (about 80%) occurs in June to September during the ISM with an extended period average (LPA) of 89 cm with a coefficient of variability ≈10%. ISM exhibits large spatial variability with regions of high rainfall (the West Coast of the peninsula and over the north–eastern regions) and lowest variability with the regions of lowest rainfall (northwestern parts of India) as seen from the mean and coefficient of variability maps of AISMR shown in Fig. 3A and Fig. 3B respectively.

Two primary heat sources mainly drive the ISM during June to September: sensible heating of the Asian landmass and condensational (latent) heating within the troposphere over the Asian Plateau. Latent heat from moisture collected over the southern subtropical Indian Ocean is transported across the equator and released during rainfall over Asia and Africa. Sensible and latent heat mechanisms contribute to the land–sea temperature and pressure differences that ultimately drive ISM circulation. Although the ISM comes with reassuring regularity, it exhibits a wide range of variability on the spatial, temporal, intra–seasonal, inter–annual, decadal and millennium scales. However, the variation of monsoon rainfall in inter–annual and intra–seasonal time scales is very crucial.

Monsoon variability and Indian economy

The Indian Summer Monsoon Rain (ISMR) has a distinct character owing to its large inter–annual variability. The irregular nature of ISMR has a direct impact on agriculture, water resources, transportation, health, power and everyone's livelihood. The droughts (deficient rainfall) and floods (excess rainfall) are two extremes of the interannual variability of ISMR. An overwhelming majority of cropped area in India (around 68%) falls within the medium and low rainfall range regions. Large areas are therefore affected if the ISM plays truant. Most parts of the peninsular, central and northwest Indian regions are prone to frequent droughts. These regions receive less than 100 cm of rainfall. The ISMR during JJAS has a unique identity due to its large inter–annual variability with the long period average (LPA; 1951–2010) of ISMR is found to be about 89 cm with a CV of ≈8.9cm (10% of LPA). As pointed in many earlier studies, there is a close correspondence between deficit monsoon rainfall and El Nino (Sikka, 1980; Pant & Parthasarathy, 1981; Rasmusson & Carpenter, 1983). However, Kumar *et al*. (1999) have suggested that the link between ISM and El Nino has weakened in the last decade and in fact, the ISMR anomaly was positive in the recent intense warm event of 1997. Several studies also linked tele–connection patterns other than El Nino Southern Oscillation (ENSO) to explain the observed inter–annual variability of ISMR and decadal and epochal variability of ISMR (Pattanaik, 2012). The inter–annual variation of ISMR during the last 142 years (1875–2016) is shown in Fig. 4. As seen from figure 4, the period from 1901 to 2016 witnessed many deficient and strong monsoon events. The deficient or strong years of monsoon are identified based on the rainfall departure of ±1 CV. Large areas are therefore affected if the ISM plays truant. The drought of 1965–67 and 1979–80 affected relatively high rainfall regions, while the drought of 1972, 1987, 2002, 2004 and 2009 affected low–rainfall regions, mostly semi–arid and sub–humid regions. Recently, India witnessed two consecutive drought years of 2014 and 2015. In inter–annual variability of ISMR, more deficient years (26 years ≈ 18.3 %) than the excess years (19 years ≈ 13.4 %) during the period from 1901 to 2016 are seen. As seen in figure 4, among the drought years, the years 1918 (75.1% of LPA), 1972 (76.1%) and 2009 (78.2%) with negative departures are exceeding 2 SD (≈–20% of LPA) value. Similarly, the excess rainfall ever recorded is found to be in 1917 (122.9% of LPA) followed by 1961 (121.8% of LPA), where the positive departures of seasonal rainfall exceed 2 SD (≈ +20%) value. It may be mentioned here that even in a year of excess (deficient) monsoon on all India scale, there are pockets of deficient (excess) rainfall over some parts of the country leading to drought (flood) situations. It is further seen in figure 4 that no excess monsoon year is reported after 1994. Drought poses many problems. Irrigation facilities available in the country are limited and therefore, the drought years cause partial or complete crop failure. If failures occur in consecutive years, it becomes a national calamity, putting tremendous strain on the country's economy. Meteorological drought happens when the actual rainfall in an area is significantly less than the climatological mean of that area. Drought has both direct and indirect impacts on the country's economic, social and environmental fabric. The agricultural sector feels the immediate visible impact of monsoon failure leading to drought. The drought of 2002 caused a reduction in food grain production to the tune of 13% in India. In 2009 the ISMR departure was ≈–22% and the percentage area affected by moderate drought (when rainfall is 26–50% below average) was 59.2%. Due to this drought condition, there was a fall in GDP by about 0.5%.

Monsoon forecasting in different time scales

Monsoon forecasting is a challenging problem over the Indian subcontinent, where monsoon constitutes a significant weather system affecting a large population. Monsoon forecasting is essential for various weather–sensitive activities such as farming operations, flood forecasting, water resource management, sports, transport, etc. The fluctuation in ISMR in different time scale is influenced by the occurrence and movements of different weather systems during the season. Depending on the time scale, the monsoon prediction can be classified into the following four categories, viz. (i) Short–range–Up to 3 days, (ii) Medium range–about 4 to 7 days in tropics, (iii) Extended range or intra–seasonal–Beyond 7 days up to a month and (iv) Long–range or seasonal–one season.

Short Range

Heavy rainfall associated with the monsoon current and synoptic systems is widespread during the ISM over India along the monsoon trough axis. Forecasting location–specific heavy rainfall events during the ISM season is the main challenging area of monsoon forecasting in this time scale. Synoptic charts, satellite pictures, radar products, etc. are handy in forecasting monsoon on this time scale. In addition to the synoptic method, numerical models are also used for short–range weather forecasting. Currently, weather forecast services in the short range are based on conventional synoptic methods (synoptic charts, satellite pictures, radar images) supplemented by the use of Numerical Weather Prediction

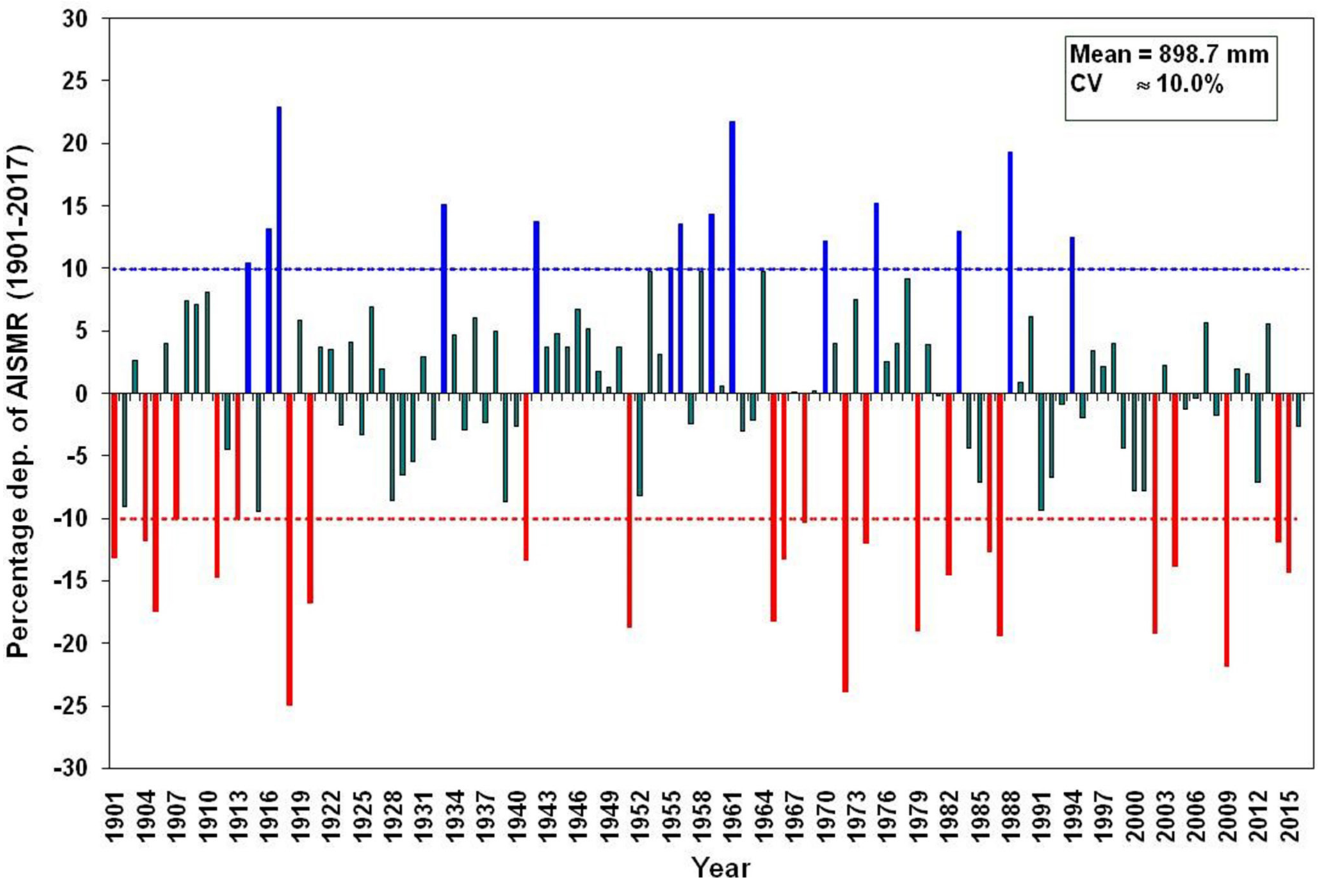


Fig. 4—All India Summer Monsoon Rainfall (AISMR) departure during June to September from 1875 to 2016.

(NWP) products of different centres. Due to the complex issues involved, forecasting monsoon weather systems and associated rainfall with short spells of heavy rainfall events are challenging areas in NWP. These include the impact of topography, real genesis and movement of synoptic–scale systems, representation of mesoscale convective systems and the problem of good quality mesoscale observations, particularly over the ocean. In the past, synoptic methods have been the mainstay of tropical weather forecasting. Of late, NWP methods have acquired more excellent skills and are playing an increasingly important role in tropical weather prediction, though the progress of dynamical modelling efforts in the tropics has been relatively slow compared with the extratropics. The roots of NWP can be traced back to the work of Vilhelm Bjerknes in 1904, a Norwegian physicist who has been called the father of modern meteorology, where he suggested that it would be possible to forecast the weather by solving a system of nonlinear partial differential equations. Since 1975 there have been significant developments in NWP, starting from short–range weather prediction (1 to 3 days) using NWP model to seasonal prediction using the coupled model. Work on short–range NWP scale in an organized manner began in India in the 1960s. After 1975 there have been significant developments in the field of NWP, starting from short–range weather prediction (1 to 3 days). The use of mesoscale models for short–range weather forecasting commenced in India during the 1990s. Many Indian scientists have contributed to the development of the NWP system for short–term weather forecasting.

Medium–Range

A Medium–Range Weather Forecast (MRF) is a weather forecast that extends beyond 3 days and up to 10 days. The European Centre for Medium–Range Weather Forecasting (ECMWF) Charter defines medium–range as "the time scale beyond a few days in which the initial conditions are still important". Thus, in tropics, the medium–range forecast may be from days 4 to days 7. The numerical models based on thermo–hydrodynamics of the Earth's atmosphere are the primary tools used for medium–range weather forecasting (i.e. using General Circulation Models of the Atmosphere–AGCM). Since the 1950s, the application of dynamical models for predicting weather on the aforementioned scales has made remarkable progress in advanced and industrialized countries. These advancements resulted from advances in theory, computational aspects, data availability up to stratosphere levels, data initialization and data assimilation systems, higher resolution in models and parametrization of a variety of physical processes for the atmospheric boundary layer, convection, radiation and so on. Many scholars, mostly from the developed world such as Europe, North America, Japan and Australia, have contributed to novel modelling research. The establishment of the National Centre for Medium–Range Weather Forecasting (NCMRWF) in 1988 provided much–needed impetus to medium–range weather forecasting in India. Since 1992, NCMRWF has been producing operational forecast products utilising Global AGCM. An accurate medium–range prediction of 7 days throughout the monsoon season is critical because it will provide better information concerning the monsoon's start and progression, the origin, movement and decay of monsoon lows and depressions, the persistence and cessation of dry spells and so on. Though a single AGCM may be used to forecast monsoon in the medium term, various additional factors like as downscaling, statistical interpretation, ensemble forecasting, multi–model ensemble and so on are taken into account to enhance forecast quality and minimize forecast errors.

Extended Range

The day–to–day variability of ISMR is characterized by ‘‘active’’ periods with high rainfall over central India, when the monsoon trough is over the northern plains and ‘‘break’’ periods with weak or no rainfall over central India and high rainfall over northern India, when the monsoon trough is over the foothills of the Himalaya. Long breaks during the significant growth phases of crops lead to substantially reduced yield; hence, forecasting ISMR on an extended range time scale is vital for the large farming community of the country. Forecasts of rainfall on this intermediate time scale are critical for the optimization of planting and harvesting. Therefore, the prediction of monsoon break two to three weeks in advance is of great relevance for agricultural planning (sowing, harvesting, etc.) and water management. The forecasts on the time scale of two to four weeks can enable tactical adjustments to the strategic decisions based on the more extended lead seasonal forecasts which also help in timely review of the ongoing monsoon conditions for providing outlooks to the farmers. The duration and frequency of the active/break spells within a particular monsoon season contribute to the seasonal mean and thus, also modulate the inter–annual variability. The daily all India rainfall during the monsoon season in 2009 indicated three long dry spells, one during June, the second one during the last week of July to the first half of August and the third one towards the second half of September (Fig. 5). Consequently, the seasonal rainfall during 2009 ended with a shortfall of monsoon rainfall of about 22%. One of the factors, which influence the intra–seasonal oscillation of monsoon, is the Madden Julian Oscillation (MJO), one of the most critical atmosphere–ocean coupled phenomena in the tropics. The MJO is the primary mode of tropical intra–seasonal climate variability and is characterized by the organization on a global spatial scale ranging from 30–60 days. Of late, there have been efforts by various research groups in India to predict the monsoon on an extended range time scale using statistical and dynamical models. The statistical model uses principal components (PC’s) of empirical orthogonal function

(EOF) analysis of 20–90 days anomalies of outgoing long–wave radiation (OLR) and the OLR anomalies are predicted for about four pentads. Forecast models are developed for each lead time in the form of OLR anomalies, representing convective activity. There are also methods developed based on analogs of the OLR anomalies at the lead period of 1 pentad to 4 pentads. Similarly, another empirical model is also developed to predict monsoon intra–seasonal rainfall activity based on the nonlinear pattern recognition technique known as the Self Organizing Map (SOM). The SOM falls under the class of unsupervised learning of synapses in an Artificial Neural Network algorithm. The wind, geopotential height, specific humidity and the mean sea level pressure are used for the SOM rainfall classification. The basis of this model is that the nonlinear combinations of all the indices sufficiently represent the complex intra–seasonal variation of the ISMR and the indices themselves have the capability of capturing the seasonality. Thus, using current dynamical indices from the observational data in the real–time mode, the forecast of rainfall anomalies can be done using this method.

The other methods used for forecasting monsoon in this time scale are Atmospheric GCM and coupled GCM. Though there has been significant improvement in the dynamical modelling system by improving model physics and dynamics in the last few years, the present–day AGCM could not successfully simulate the mean and inter–annual variability of ISM. It is also found that the skill of the AGCM is poorer in simulating ISM, which can be due to a lack of proper representation of realistic Sea Surface Temperature (SST). However, to use the forecast from the dynamical model in the best possible way, combinations of ensemble members are used to reduce the forecast errors. Therefore, the focus is mainly on seasonal and inter–annual monsoon prediction and multi–model ensemble/super ensemble forecast. Recent studies highlighted that the coupled models with a one–tier approach could enhance the predictability of the ISMR. A fully coupled model will be adequate to capture the observed monsoon intra–seasonal variability better and thus will be able to predict the active break cycle of monsoon more accurately.

Long–Range Forecasting (LRF)

Statistical model

The monsoon prediction in this time scale is accomplished by using statistical and dynamical models. Sir H.F. Blanford, the first Chief Reporter of the Indian Meteorological Department (IMD), attempted to estimate the prospective rains. Indian Meteorological Department & Blanford (1886) issued tentative forecasts from 1882 to 1885 utilizing the indications provided by the snowfall in the Himalayas. The first regular series of forecasts of seasonal monsoon rainfall from June to September was provided on 4th June 1886. Since then, the long–range forecasting of monsoon has witnessed

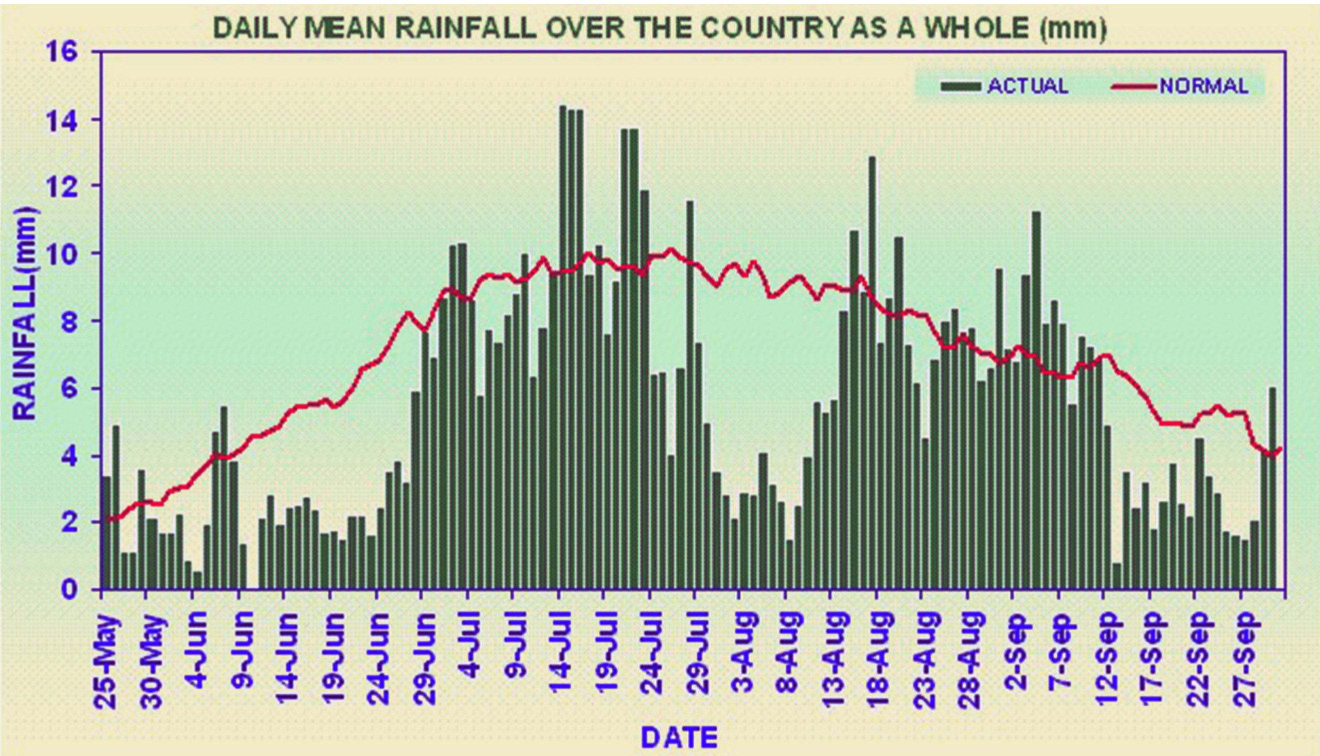


Fig. 5—All India daily rainfall from 25 May to 30 September, 2009.

many modifications. The efforts for better forecasts continued during (1904–1924) under the direction of Sir G. T. Walker, who took over as the Director–General of IMD. Walker started the forecasts based on objective techniques. He introduced correlation and regression techniques for preparing long–range forecasts. Walker was well aware that seasonal prediction can be put on a scientific footing only based on an accepted general circulation theory. In his quest to identify potential predictors for the long–range forecasting of monsoon rainfall over India, Walker discovered significant large–scale see–saw variations in global pressure patterns known as the Southern Oscillation, which profoundly influences monsoon. In 1988, IMD introduced the 16 parameters power regression and parametric models and started issuing forecasts for the ISMR over the country as a whole. The quantitative forecasts were prepared by using the power regression model. After the failure of forecast in 2002, IMD introduced a new two–stage forecast strategy in 2003, according to which the first stage forecast for the seasonal (June to September) rainfall over the country is issued in April and the update for the April forecasts is issued in June. Along with the updated forecast, forecasts for seasonal rainfall over broad homogeneous rainfall regions of India and July rainfall over the country are also issued. During the period 2003–2006, the first stage quantitative and five categories probabilistic forecast for the season rainfall over the country as a whole were issued using 8–parameter power regression (PR) model and Linear Discriminant Analysis (LDA) model respectively. Update for the first stage forecasts was issued using 10 Parameter PR and LDA models. In 2007, IMD introduced new statistical forecasting system based on ensemble technique for the ISM (June to September) rainfall over the country as a whole.

Problems of statistical model and use of dynamical models

The IMD's statistical forecasting approach has had variable degrees of effectiveness, but there has been no growth in prediction skill over a lengthy period of time. This technique has limitations that it does not anticipate rainfall based on its geographical distribution or on sub–seasonal time scales. There are more basic issues with using a small quantity of data and selecting predictors. On the other hand, the dynamical prediction has evolved over the years to a stage where coupled GCMs are now employed for routine seasonal climate prediction by operational forecasting centres. Earlier studies of dynamical prediction of the ISM relied on atmospheric GCMs using observed SST as boundary forcing. However, the inter–annual variability of the seasonal rainfall in the models showed poor correlation with observations, although SST seems to have a strong influence. Although this two–tier approach has served useful purposes, the observed lagged correlation between SST and rainfall was correctly simulated by a coupled GCM but not by an atmospheric GCM forced with observed SST. These results highlight the significance of the coupled ocean–atmosphere interaction in the monsoon region and the need to use coupled GCMs for more reliable forecasts. The prediction skill of the monsoon was found to be better with a coupled model than that using an atmospheric model. A precise coupling of the fast atmosphere to the slow ocean (with long memory) is essential to simulate the ENSO (El Nino–Southern Oscillation), a dominating factor in inter–annual monsoon fluctuation rainfall.

Monsoon Mission

Ministry of Earth Sciences, Government of India, through the "National Mission of Monsoon," involved all relevant organizations and research institutes to improve monsoon's dynamical prediction. The first phase of this mission was for five years from 2012. The Indian Institute of Tropical Meteorology (IITM), Pune, is coordinating this program. IMD is responsible for operationalizing the monsoon forecast in all time scales achieved through this "Monsoon Mission Programme." For the mission, the NCEP CFS coupled model has been chosen as the core model. The main objectives of the Monsoon Mission are:

a) To build a working partnership between the Academic Research and Development Organizations and Operational Agencies to improve the monsoon forecast skill

b) To set up a state–of–the–art dynamical modelling framework for improving the prediction skill of (i) Seasonal and Extended range prediction system; and (ii) Short and Medium range prediction system

c) To set up the infrastructure and workforce required to improve the prediction skill at all–time scales

This program is aimed at enhancing the forecasting capability of monsoon in short, medium, extended range and long–range time scales. To improve the monsoon prediction in the short and medium–range time scale, data assimilation from satellites (INSAT–3D Radiance), wind profilers, GPS sonde, meso–network (Automatic Weather Stations), buoys, aircraft, etc. in the real–time mode will be very crucial. Thus, the IMD will also implement the latest assimilation modules of GFS and high–resolution WRF. This will also help in the prediction of meso–scale heavy rainfall events associated with monsoon system. During recent years, Ensemble Prediction System (EPS) has emerged as a powerful tool for improving medium–range weather forecasts. In the EPS, a single model with multiple sets of initial conditions is used to obtain the final forecast. While Singular Vector and Bred Vector (BV) methods are still widely used in generating initial perturbations, Ensemble Transform of BV, Ensemble Transform Kalman Filter and Ensemble Data Assimilation are also implemented in various centres. This would allow IMD to access EPS outputs of other global centres and provide an opportunity to develop and implement a Probabilistic Forecast System (PFS) using EPS outputs of all available centres for better forecasting of monsoon rainfall in short to extended range time scale. IMD will coordinate with NCMRWF for the implementation of EPS in IMD. As the forecast of ISMR in the extended and seasonal range requires a good coupled model. IITM Pune is working on the coupled model NCEP CFS considered as the core model under this mission. IMD will use these efforts in IITM to operationalize the same in IMD to enhance its forecasting capability of monsoon in the extended range and seasonal scale. IMD has the mandate to provide multi–scale weather forecasts ranging from now casting to seasonal forecasting. While India's present weather and climate forecasting system is designed to provide prediction services on short and medium time periods, there is a deficit on long time scales.

Current Status of Monsoon Forecasting in IMD

Short and Medium Range Forecast

With the commissioning of the High–Performance Computing System (HPCS) in 2009, NCEP based Global Forecast System (GFS T382) at the IMD Delhi became operational, using the Global Statistical Interpolation (GSI) scheme in the Global Data Assimilation System (GDAS). The Global model currently runs twice a day (00 UTC and 12 UTC) and generates the forecast for seven days. IMD began utilizing the higher–resolution global model GFS T574 (about 25 km horizontal resolution) from 2012 and GFS T1534 (about 12 km horizontal resolution) from 2016. In addition, the global ensemble forecast system (GFES at T574 resolution) model with 20 ensemble members is also implemented in IMD for medium–range weather forecasting in operational mode from 2017. Under the monsoon mission, these modelling systems were implemented at IMD with the help of IITM and NCMRWF.

Furthermore, for the short–range weather forecasting, the meso–scale forecast system Weather Research Forecast (WRF) with 3D–VAR data assimilation is used twice daily, at 27 km, 9 km and 3 km horizontal resolutions for the forecast up to three days using initial and boundary conditions from the IMD global model. In addition, at the other ten regional centres, very high–resolution meso–scale models (WRF at 3 km resolution) are operational.

The short and medium–range forecasts are very sensitive to the initial state of the atmosphere from which the models begin the prediction. A better initial state will lead to an improved prediction. Hence, higher–resolution data are required to assimilate for success in this range. Under the ongoing modernization program of the IMD, this issue has been addressed with the expansion and digitization of its observational network to achieve smooth data flow. Furthermore, good quality dense observations (both conventional and non–conventional) are expected to be available through Doppler Weather Radar (DWR), Satellites (INSAT–3D Radiance), wind profilers, GPS sonde, meso–network (Automatic Weather Stations), buoys and aircraft in the real–time mode to ingest into the assimilation cycle of global and meso–scale NWP models, availing the advantage of the advanced telecommunication system. Considering the need for the farming sector, IMD has upgraded the Agro–Meteorological Advisory Service from agro climate zone to district level. As a significant step, IMD started issuing district–level weather forecasts from 1st June 2008 for meteorological parameters such as rainfall, maximum and minimum temperature, relative humidity, surface wind and cloud octa up to 5 days in quantitative terms. These forecasts are generated through the Multi–Model Ensemble (MME) system, using model outputs of state–of–the–art global models from the leading global NWP centres. Though the MME technique has resulted in some major improvements in the accuracy and dependability of NWP products, constraints remain, specifically in forecasting intensity and meso–scale rainfall features that cause inland flooding.

Extended Range Forecast

Weather forecasting on a longer time scale (more than seven days and up to a month) using a numerical model requiring the involvement of the ocean and necessitating the use of a linked mode. Models must accurately mimic the statistics (amplitude, phase propagation and frequency spectra) of the intra–seasonal oscillation to forecast the monsoon on this time scale (ISO). In recent years, it has been discovered that a considerable degree of air–sea interaction is associated with the summer ISOs and coupled models are also in the development stage for the precise forecast of monsoon on this time scale. Initially, in the absence of a cutting–edge dynamical prediction system in IMD for extended range prediction of active/break spells, it was generating monsoon forecasts in this time scale based on real–time coupled model outputs available from leading international centres such as the NCEP in the United States, the ECMWF in the United Kingdom and the JMA in Japan. Forecasts for three weeks were created utilising the output of these linked models for the long–term forecast (Pattanaik *et al*., 2013a, b; Pattanaik, 2014; Pattanaik & Das 2015).

Recently, in July 2016, with the Ministry of Earth Sciences (MoES) efforts, coupled model with a suite of models from CFSv2 coupled model has been operationally executed in IMD. This dynamical prediction system developed at IITM has been transferred to IMD and IMD has implemented the same for generating operational Extended Range Forecast products to different users. This suite of models at different resolutions with atmospheric and oceanic initial conditions obtained from NCMRWF and INCOIS assimilation system respectively are (i) CFSv2 at T382 (≈ 38 km), (ii) CFSv2 at T126 (≈ 100 km), (iii) GFSbc (bias–corrected SST from CFSv2) at T382 and (iv) GFSbc at T126. The operational suite is ported in ADITYA HPCS at IITM Pune for a day–to–day operational run. The multi–model ensemble (MME) out of the above 4 suites of models are run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126. The identical suites of the model are also run on hindcast mode for 13 years (2003–2016). The average ensemble forecast anomaly of all the 4 sets of model runs of 4 members is calculated by subtracting corresponding 13–years model hindcast climatology. For the preparation of mean and anomaly forecast is prepared every Thursday, which is valid for 4 weeks for days 3–9 (week1; Friday to Thursday), days 10–16 (week2; Friday to Thursday), days 17–23 (week3; Friday to Thursday) and days 24–30 (week4; Friday to Thursday).

Long–Range Forecasting

IMD has been providing long–range operational forecasts based on statistical techniques. The statistical approach has shown exemplary skill in generating forecasts for the seasonal rainfall over the country as a whole and four geographical regions (Northwest India, Central India, Northeast India and South Peninsula) and that for the monthly rainfall over the country as a whole for July, August and September. IMD also generates an operational forecast for the rainfall during the second half of the monsoon season over the country as a whole. However, the statistical approach has been found to have limited skill for monthly and seasonal forecasts for smaller spatial scales such as state, subdivision, district, etc. In addition to a statistical operational forecasting system, IMD has also established an experimental dynamical forecasting system for the long–range forecasting of ISMR at IMD Pune. The dynamical forecasting system is based on Experimental Climate Prediction Center (ECPC) seasonal forecasting model (SFM). SFM model (AGCM) is used to prepare monthly and seasonal forecasts during the monsoon season using persistent and forecasted SSTs as boundary forcing. The experimental forecasting system demonstrated some useful predicting abilities. However, further work is required before the dynamical forecasting system may be employed for operational reasons. Through Monsoon Mission efforts, IMD has recently adopted the fully coupled model (CFSv2) for seasonal forecasting. The predicted variables from the coupled model, a hybrid dynamical–empirical model, have been constructed for real–time prediction of seasonal monsoon rainfall and their skill is significantly greater than the coupled model's raw skill. This model is being tested and is useful for monsoon predictions (Pattanaik & Kumar, 2015).

Indian Summer Monsoon–variability and changes in the recent period

The ISM develops as a response to the intense heating of the subcontinent during the spring–summer season when the maximum solar insolation moves north from the equator. The land gets warmer relative to the adjoining ocean during this time, resulting in a tropospheric meridional temperature gradient. The heating over the high altitudes of the Himalaya and the Tibetan Plateau ensures that the temperature gradient is functional throughout the troposphere. This results in the build–up of a low pressure zone over northern India in late spring, parallel to the Himalayas in a west to east direction, known as the "monsoon trough". The resultant meridional pressure gradient induces a cross–equatorial surface flow and a return flow in the upper troposphere. These monsoon winds carry the moisture from the adjoining Indian Ocean during the northern summer, which pours as the ISMR over the Indian subcontinent from June to September (Webster *et al*., 1998; Turner & Annamalai 2012). Though the land surface cools with the onset of the monsoon rainfall, the latent heat released into the atmosphere keeps the troposphere warm and maintains the meridional temperature gradient throughout the summer. With the intense solar insolation during summer, the thermodynamic conditions are also favourable in maintaining seasonal ITCZ migration, which positively enhances the monsoon trough. India receives more than 80% of the annual rainfall during the ISM. Around the end of September, with the fast retreat of the Sun to the south, the land cools rapidly and the ocean gets warmer, leading to a reversal of the thermal and pressure gradients, relocating the ITCZ towards the equator. The northeast monsoon winds follow as a response, picking up moisture from the Bay of Bengal, bringing rainfall to the southeastern regions of India. The ISM exhibits variability on diurnal, intra–seasonal, seasonal, inter–annual and decadal time scales. On inter–annual time scales, ENSO is the dominant mode of variability of the ISM and is the major driver of monsoon variability (Rasmusson & Carpenter, 1983). An El Niño event, characterized by warmer–than–average ocean waters in the central and eastern Pacific, modulates tropical atmospheric circulation, thereby dampening the monsoon winds and rainfall over land. Hence typically, an El Niño year may be characterized by a dry monsoon for a large region over the subcontinent, while a La Niña may denote a wet monsoon year.

However, only about 50% of monsoon droughts or floods may be linked to the ENSO in the Pacific (Roxy, 2017) and other modes of climate variability contribute to the rest of the monsoon variability. For example, the Indian Ocean Dipole (IOD), a periodic oscillation of SST anomalies and convection between the west and eastern parts of the Indian Ocean (Murtugudde *et al*., 1998; Saji *et al*., 1999; Webster *et* *al*., 1999), occasionally impacts the monsoon conditions when it is active (Ashok *et al*., 2001, 2004). A positive phase of IOD is characterized by warm SST anomalies in the western Indian Ocean with enhanced local convection, cool SST anomalies in the eastern Indian Ocean and suppressed convection. Such a positive IOD enhances the meridional monsoon circulation, resulting in increased convection and rainfall over the Indian subcontinent and vice–versa for the negative phase. In 1997, there were cases when a strong El Niño was evolving in the Pacific, potentially weakening the ISM, but coincided with the positive IOD, which suppressed the impact of the El Niño, thereby ensuring an average rainfall year for the ISM. Other than ENSO and IOD, Wang *et al.* (2015a) suggested that the Indo–Pacific monsoon–ocean coupled system acts as a dominant mode influencing the monsoon variability. They also suggested that as a response to the Indo–Pacific warm pool–atmosphere coupled system, the rainfall anomaly exhibits enhanced rainfall in the equatorial western Pacific, while the rainfall over India is largely suppressed except over the Western Ghats. In recent decades, the global warming trend, especially in the tropical Indian and Pacific oceans, has emerged as a dominant mode regulating the monsoon variability (Wang *et al*., 2015a). On a large scale, the Northern Hemisphere ISM and the Hadley and Walker circulations have shown substantial intensification during 1979–2011, with a striking increase of rainfall by 9.5% per degree of global warming (Wang *et al*., 2013). However, the ISMR, especially over the central and northern regions, has exhibited a statistically significant weakening since the 1950s (Roxy *et al*., 2015). This secular decline in the mean rainfall is consistent with a dampening of the local Hadley circulation. Research using models and observations attributed the weakening of the ISM to a combination of factors, including the rapid warming of the Indian Ocean (Roxy *et al.*, 2015), land use–land cover changes (Paul *et al*., 2016) and increased aerosol content in the atmosphere (Bollasina *et al*., 2011). A recent analysis by Wang *et al.* (2015b) points out that the state–of–the–art numerical models fail to represent the warming trend in the Indo–Pacific region accurately, a reason for the monsoon seasonal prediction skills to go down in recent decades.

The ISM also exhibits pronounced intra–seasonal variability, on a roughly 10–90 days' time–scale, manifested as the wet (active) and dry (break) spells of the monsoon (Krishnamurthy & Achuthavarier, 2012). MISO originates in the Indian Ocean and propagates northward as an ocean–atmospheric coupled evolution of SST, winds and convection (Jiang *et al*., 2004; Roxy & Tanimoto, 2007). Since the initiation and propagation of MISO tied to the SSTs, the basin–wide warming in the Indian Ocean has impacted its characteristics in recent decades. Sabeerali *et al*. (2014) indicate that the SST warming in the Indian Ocean during the past decade (2001–2011) has changed the space–time characteristics of the northward–propagating monsoon intraseasonal oscillations, compared to that during 1978–1988. In recent years, they found that the excess warming triggers stationary convection over the equatorial Indian Ocean, stalling the northward propagation.

CONCLUSIONS

Based on the evaluation and evolution of ISM's trajectory in history, the recent past and the present–it is obvious that it impacts human life, society, civilization in unmistakable ways. There are spheres where nomads have made their life centered on the monsoon life cycle and remained dependent both on its mercy and vagaries. In ancient time it is supposed to be the harbinger of good omen as it provisioned the lives of the population. Societal dependence on it, till present, remains a lifeline for societal well–being and uplift and for the health and the wealth of the nation.

In the present work–a connecting thread of ISM and its evolution in the historical perspective has been attempted to understand the internal variability and possibly to obtain insights on its future trajectory. This approach provides perspectives of the monsoon on millennial timescale, in history, in the recent past; and the way in which modern civilization is attempting to understand it through the adoption of advanced technology–supported observational platforms, modelling and computational methods. Considerable progress has been made by several national agencies for the delivery of improved forecasts on different time ranges.

REFERENCES

Agrawal DP 1982. The Archaeology of India, Copenhagen: Scandinavian Institute of Asian Studies Monograph Series No.46, Curzon Press, London.

Ali SN, Agrawal S, Quamar MF, Dubey J, Chauhan N, Bisht P, Pandey P, Arif M, Shekhar M & Morthekai P 2020a. Climate variability in the Central Himalaya during the last ~ 15 kyr: Evidence of precipitation variability from multiproxy studies. Journal of Palaeontological Society of India 65: 36–54.

Ali SN, Agrawal S, Sharma A, Phartiyal B, Morthekai P, Govil P, Bhushan R, Farooqui S, Jena PS & Shivam A 2020b. Holocene hydroclimatic variability in the Zanskar Valley, Northwestern Himalaya, India. Quaternary Research: 1–7.

Ali SN, Dubey J, Ghosh R, Quamar MF, Sharma A, Morthekai P, Dimri AP, Shekhar M, Arif Md. & Agarwal S 2018. High frequency abrupt shifts in the Indian Summer Monsoon since Younger Dryas in the Himalaya. Scientific Reports: 8: 9287.

Allchin B & Allchin R 1982. The Rise of Civilization in India and Pakistan. Cambridge University Press.

Allchin B, Goudie A & Hegde KTM 1978. Prehistory and Palaeogeography of the Great Indian Desert, London Academic Press.

Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC & Clark PU 1997. Holocene climatic instability: a prominent widespread event 8200 yr ago. Geology 25: 438–486.

An Z, Colman SM, Zhou W, Li X, Brown ET, Jull AT, Cai Y, Huang Y, Lu X, Chang H & Song Y 2012. Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka. Scientific Reports 2(1): 1–7.

Anderson DM, Overpeck JT & Gupta AK 2002. Increase in the Asian Southwest Monsoon during the past four centuries. Science 297: 596–599.

Ashok K, Guan ZY, Saji NH & Yamagata T 2004. Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian Summer Monsoon. Journal of Climate 17(16): 3141–3155.

Ashok K, Guan ZY & Yamagata T 2001. Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophysical Research Letters 28(23): 4499–4502.

Bali R, Chauhan MS, Mishra AK, Ali SN, Tomar A, Khan I, Singh DS & Srivastava P 2016. Vegetation and climate change in the temperate–subalpine belt of Himachal Pradesh since 6300 cal. yrs. BP, inferred from pollen evidence of Triloknath palaeolake. Quaternary International 444: 11–23. http: //dx.doi.org/10.1016/j.quaint.2016.07.057.

Bar–Matthews M, Ayalon A, Gilmour M, Matthews A & Hawkesworth CJ 2003. Sea–land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. Geochimica et Cosmochimica Acta 67(17): 3181–3199.

Bell B 1971. The dark ages in ancient history. I. The first dark age in Egypt. American Journal of Archaeology 75(1): 1–26.

Benn DI & Owen LA 1998. The role of the Indian Summer Monsoon and the mid–latitude westerlies in Himalayan glaciation: review and speculative discussion. Journal of Geological Society of India 155: 353–363.

Berkelhammer M, Sinha A, Mudelsee M, Cheng H, Edwards RL & Cannariato K 2010. Persistent multidecadel power of the Indian Summer Monsoon. Earth and Planetary Science Letters 290: 166–172.

Berkelhammer M, Sinha A, Stott L, Cheng H, Pausata FS & Yoshimura K 2012. An abrupt shift in the Indian monsoon 4000 years ago. Geophysical Monograph Series 198: 75–87.

Bhattacharayya A, Ranhotra PS & Gergan JT 2011. Vegetation vis–a–vis climate and glacier history during 12,400 to 5,400 yr BP from Dokriani Valley, Garhwal Himalaya, India. Journal of Geological Society of India 77: 401–408.

Bhattacharyya A, Sharma J, Shah SK & Chaudhary V 2007. Climatic changes during the last 1800 yrs BP from paradise lake, Sela Pass, Arunachal Pradesh, Northeast Himalaya. Current Science 93: 983–987.

Björck S, Muscheler R, Kromer B andersen CS, Heinemeier J, Johnsen S, Conley D., Koc N, Spurk M & Veski S 2001. High–resolution analysis of an early Holocene climate event may imply decreased solar forcing as an important climate trigger. Geology 12: 1107–1110.

Bollasina MA, Ming Y & Ramaswamy V 2011. Anthropogenic aerosols and the weakening of the South Asian Summer Monsoon. Science 334: 502–505.

Bond G, Kromer B, Beer J, Muscheler R, Evans MN, Shower W, Hoffman S, Lotti–Bond R, Hajdas I & Bonani G 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294: 2130–2136.

Bond G, Showers W, Chesesby M, Lotti R, Almasi P, DeMenocal P, Priore P, Cullen H, Hajdas I & Bonani G 1997. A pervasive millennial scale cycle in North Atlantic Holocene and glacial climates. Science 278: 1257–1266.

Borgaonkar HP, Sikder AB, Ram S & Pant GB 2010. El Niño and related monsoon drought signals in 523–year–long ring width records of teak (*Tectona grandis* LF) trees from south India. Palaeogeography, Palaeoclimatology, Palaeoecology 285(1–2): 74–84.

Bradley RS 1999. Paleoclimatology: reconstructing climates of the Quaternary. Elsevier.

Bradley RS & Jones PD 1993. 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. The Holocene 3(4): 367–376.

Breitenbach SFM, Adkins JF, Meyer H, Marwan N, Kumar KK & Haug GH 2010. Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in Southern Meghalaya, NE India. Earth and Planetary Science Letter 292(1–2): 212–220.

Broecker WS 2001. Was the medieval warm period global? Science 291: 1497–1499.

Brown ET, Bendick R, Bourles DL, Gaur V, Molnar P, Raisbeck GM & Yiou F 2003. Early Holocene climate recorded in geomorphological features in western Tibet. Palaeogeography, Palaeoclimatology, Palaeoecology 199(1–2): 141–151.

Bryson RA & Swain AM 1981. Holocene variations of monsoon rainfall in Rajasthan. Quaternary Research 16: 135–145.

Buckley BM, Anchukaitis KJ, Penny D, Fletcher R, Cook ER, Sano M, Wichienkeeo A, Minh TT & Hong TM 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. Proceedings of the National Academy of Sciences 107(15): 6748–6752.

Chauhan MS & Chatterjee S 2008. Holocene vegetation, climate and human habitation in the Central Ganga Plain, based on pollen records from the lake deposits. Journal of Palaeosciences 57: 1–3.

Chauhan MS, Pokharia AK & Singh IB 2009. Pollen record of vegetation, climate change and human habitation from Lahuradewa Lake, Sant Kabir Nagar District, Uttar Pradesh, India. Man and Environment 34: 88–100.

Chauhan MS, Pokharia AK & Srivastava RK 2015. Late Quaternary vegetation history, climate variability and human activity in Central Ganga Plain, deduced from pollen proxy records from Karela Jheel, India. Quaternary International 371: 144–156.

Chauhan MS & Sharma C 2000. Late Holocene vegetation and climate in Dewar Tal area, Inner Lesser Garhwal Himalaya. Palaeobotanist 49: 509–514.

Chauhan OS 2003. Past 20,000–year history of Himalayan aridity: Evidence from oxygen isotope records in the Bay of Bengal. Indian Academy of Sciences 84: 90–93.

Chauhan OS, Patil SK & Suneethi J 2004. Fluvial influx and weathering history of the Himalayas since Last Glacial Maxima–isotopic, sedimentological and magnetic records from the Bay of Bengal. Current Science 87: 509–515.

Chauhan OS & Suneethi J 2001. 18 Ka BP records of climatic changes, Bay of Bengal: Isotopic and sedimentological evidences. Current Science 89: 1231–1234.

Chen J, Wan G, Zhang DD, Chen Z, Xu J, Xiao T & Huang R 2005. The 'Little Ice Age' recorded by sediment chemistry in lake Erhai, southwest China. The Holocene 15: 925–931.

Cheng H, Fleitmann D, Edwards RL, Wang X, Cruz FW, Auler AS, Mangini A, Wang Y, Kong X, Burns SJ & Matter A 2009. Timing and structure of the 8.2 kyr BP event inferred from $\delta^{18}O$ records of stalagmites from China, Oman and Brazil. Geology 37(11): 1007–1010.

Childe VG 1936. Man Makes Himself (The Library of Science and Culture.) Pp. xii + 275. (London: Watts and Co., 1936.) 7s. 6d. net.

Christian J 1891. Behar Proverbs (reprint 1986), Delhi, Unity Book Service.

Chu G, Liu J, Sun Q, Lu H, Gu Z, Wang W & Liu T 2002. The 'Mediaeval Warm Period' drought recorded in lake Huguangyan, tropical South China. The Holocene 12: 511–516.

Cook ER, Anchukaitis KJ, Buckley BM, D'Arrigo RD, Jacoby GC & Wright WE 2010. Asian monsoon failure and megadrought during the last millennium. Science 328: 486–489.

Cook ER, Seager R, Cane MA & Stahle DW 2007. North American drought: reconstructions, causes and consequences. Earth–Science Reviews 81: 93–134.

Cookson E, Hill DJ & Lawrence D 2019. Impacts of long term climate change during the collapse of the Akkadian Empire. Journal of Archaeological Science 106: 1–9.

Costantini L 1983. The beginning of agriculture in Kachi Plain: the evidence of Mehargarh: *In:* Allchin B (Editor)–South Asian Archaeology 1981: 29–33.

Costantini L 1984. The beginning of agriculture in the Kachi Plain: the evidence of Mehrgarh. *In:* Allchin B (Editor)–South Asian Archaeology 1981. Cambridge University Press, Cambridge: 29−33.

Costantini L & Biasini LC 1985. Agriculture in Baluchistan between the 7th and the 3rd millennium BC. Newsletter of Baluchistan Studies 2: 16−30.

Crindle Mc 1921. Ancient India as described by Megasthenes and Arrian, trans. Calcutta, Chakravarti & Chatterjee.

Cronin TM, Hayo K, Thunell RC, Dwyer GS, Saenger C & Willard DA 2010. The medieval climate anomaly and little ice age in Chesapeake Bay and the North Atlantic Ocean. Palaeogeography, Palaeoclimatology, Palaeoecology 297(2): 299–310.

Cullen HM, Demenocal PB, Hemming S, Hemming G, Brown FH, Guilderson T & Sirocko F 2000. Climate change and the collapse of the Akkadian empire: Evidence from the deep sea. Geology 28(4): 379–382.

Dalfes HN 1997. Environmental vulnerability of early societies: some

reflections on modelling issues. In Third millennium BC climate change and Old World collapse. Springer, Berlin, Heidelberg: 691–697.
Danino M 2008. New insights into Harappan town planning, proportion and units with special reference to Dholavira. Man and Environment 33(1): 66–79.
Das PK 1968. The Monsoon, National Book Trust, New Delhi: 32 pp.
Paddayya K 1994. Investigation of man–environment relationship in Indian Archaeology: some theoretical considerations. Man and Environment 19: 1–28.
Davids TWR & Oldenberg H 1881.Vinaya Texts, Part I, The Clarendon Press. Oxford.
DeMenocal PB 2001. Cultural responses to climate change during the Late Holocene. Science 292: 667–673.
Demske D, Tarasov PE, Wünnemann B & Riedel F 2009. Late glacial and Holocene vegetation, Indian monsoon and westerly circulation in the Trans–Himalaya recorded in the lacustrine pollen sequence from Tso Kar, Ladakh, NW India. Palaeogeography, Palaeoclimatology, Palaeoecology 279(3–4): 172–185.
Denniston RF, González LA, Asmerom Y, Sharma RH & Reagan MK 2000. Speleothem evidence for changes in Indian Summer Monsoon precipitation over the last~ 2300 years. Quaternary Research 53(2): 196–202.
Deotare BC, Kajale MD, Kshirsagar AA & Rajaguru SN 1998. Geoarchaeological and palaeoenvironmental studies around Bap–Malar playa, district Jodhpur, Rajasthan. Current Science 75: 316–320.
Deotare BC, Kajale MD, Rajaguru SN, Kusumgar S, Jull AJT & Donahue JD 2004. Palaeoenvironmental history of Bap–Malar and Kanod playas of western Rajasthan, Thar Desert. Journal of Earth System Science 113(3): 403–425.
Dixit S & Bera SK 2013. Pollen–inferred vegetation vis–à–vis climate dynamics since Late Quaternary from western Assam, northeast India: Signal of global climatic events. Quaternary International 286: 56–68.
Dixit Y, Hodell DA & Petrie CA 2014. Abrupt weakening of the summer monsoon in northwest India ~ 4100 yr ago. Geology 42(4): 339–342.
Dixit Y, Hodell DA, Giesche A, Tandon SK, Gázquez F, Saini HS, Skinner LC, Mujtaba SA, Pawar V, Singh RN & Petrie CA 2018. Intensified summer monsoon and the urbanization of Indus Civilization in northwest India. Scientific Reports 8(1): 1–8.
Dixit Y, Hodell DA, Sinha R & Petrie CA 2015. Oxygen isotope analysis of multiple, single ostracod valves as a proxy for combined variability in seasonal temperature and lake water oxygen isotopes. Journal of Paleolimnology 53(1): 35–45.
Dixit Y & Tandon SK 2016. Hydroclimatic variability on the Indian subcontinent in the past millennium: review and assessment. Earth–Science Reviews 161: 1–15.
Dutt S, Gupta AK, Cheng H, Clemens SC, Singh RK & Tewari VC 2021. Indian Summer Monsoon variability in northeastern India during the last two millennia. Quaternary International 571: 73–80.
Dutt S, Gupta AK, Clemens SC, Cheng H, Singh RK, Kathayat G & Edwards RL 2015. Abrupt changes in Indian Summer Monsoon strength during 33,800 to 5500 years BP. Geophysical Research Letters 42(13): 5526–5532.
Dutt S, Gupta AK, Singh M, Jaglan S, Saravanan P, Balachandiran P & Singh A 2019. Climate variability and evolution of the Indus Civilization. Quaternary International 507: 15–23.
Dykoski CA, Edwards RL, Cheng H, Yuan D, Cai Y, Zhang M, Lin Y, Qing J, An Z & Revenaugh J 2005. A high–resolution, absolute–dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth and Planetary Science Letters 233(1–2): 71–86.
Ehrhardt S & Kennedy KAR 1965. Excavations at Langhnaj: 1944–1963, Part III: The Human Remains. Deccan College, Pune.
Enzel Y, Ely LL, Mishra S, Ramesh R, Amit R, Lazar B, Rajaguru SN, Baker VR & Sandler A 1999. High–resolution Holocene environmental changes in the Thar Desert, northwestern India. Science 284: 125–128.
Feng S & Hu Q 2008. How the North Atlantic multidecadal oscillation may have influenced the Indian summer monsoon during the past two millennia. Geophysical Research Letter 35. L01707, doi: 10.1029/2007GL032484.
Fleitmann D, Burns SJ, Mangini A, Mudelsee M, Kramers J, Villa I, Neff U, Al–Subbary AA, Buettner A, Hippler D & Matter A 2007. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quaternary Science Reviews 26(1–2): 170–188.
Fleitmann D, Burns SJ, Mudelsee M, Neff U, Kramers J, Mangini A & Matter A 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. Science 300(5626): 1737–1739.
Fontes JC, Gasse F & Gibert E 1996. Holocene environmental changes in Lake Bangong Basin (western Tibet). Part 1: Chronology and stable isotopes of carbonates of a Holocene lacustrine core. Palaeogeography, Palaeoclimatology, Palaeoecology 120(1–2): 25–47.
Fuller DQ 2002. Fifty Years of Archaeobotanical Studies in India: Laying a Solid Foundation. *In:* Settar S & Korisettar R (Editors)–Indian Archaeology in Retrospect, Volume III. Archaeology and Interactive Disciplines, Publications of the Indian Council for Historical Research. New Dehli, Manohar: 247–364.
Fuller DQ 2006. Agricultural Origins and Frontiers in South Asia: A Working Synthesis. Journal of World Prehistory 20: 1−86.
Fuller DQ 2011. Finding plant domestication in the Indian subcontinent. Current Anthropology 52: S347–S362.
Fuller DQ, Korisettar R, Venkatasubbaiah PC & Jones MK 2004. Early plant domestication in southern India: some preliminary archaeobotanical results. Vegetation History and Archaeobotany 13: 115−129.
Fuller DQ & Madella M 2001. Issues in Harappan Archaeobotany: Retrospect and Prospect: *In:* Settar S & Korisettar R (Editors)–Indian Archaeology in Retrospect, Volume II. Protohistory Publications of the Indian Council for Historical Research. New Dehli, Manohar: 317–390.
Gadgil S 2003. The Indian monsoon and its variability. American Review of Earth and Planetary Sciences 31: 429–467.
Gadgil S & Gadgil S 2006. The Indian monsoon, GDP and agriculture. Economic and Political Weekly 41: 4887–4895.
Gasse F, Arnold M, Fontes JC, Fort M, Gibert E, Huc A, Bingyan L, Yuanfang L, Qing L, Melieres F & Van Campo E 1991. A 13,000–year climate record from western Tibet. Nature 353(6346): 742–745.
Gasse F & Van Campo E 1994. Abrupt post–glacial climate events in West Asia and North Africa monsoon domains. Earth and Planetary Science Letters 126(4): 435–456.
Gautama V & Vajracharya 2013. Frog hymns and Rain Babies: Monsoon Culture and the Art of Ancient South Asia, Marg Foundation, Mumbai.
Ghosh S, Sanyal P, Roy S, Bhushan R., Sati SP, Philippe A & Juyal N 2020. Early Holocene Indian Summer Monsoon and its impact on vegetation in the Central Himalaya: Insight from δD and δ13C values of leaf wax lipid. The Holocene 30(7): 1063–1074.
Giosan L, Clift PD, Macklin MG, Fuller DQ, Constantinescu S, Durcan JA, Stevens T, Duller GAT, Tabrez A, Adhikari R, Gangal K, Alizai A, Filip F, VanLaningham S & Syvitski JPM 2012. Fluvial landscapes of the Harappan Civilization. Proceedings of National Academy of Sciences 109: 1688–1694
Giosan L, Orsi WD, Coolen M, Wuchter C, Dunlea AG, Thirumalai K, Munoz SE, Clift PD, Donnelly JP, Galy V & Fuller DQ 2018. Neoglacial climate anomalies and the Harappan metamorphosis. Climate of the Past 14(11): 1669–1686.
Goodbred JrSL & Kuehl SA 2000. Enormous Ganges–Brahmaputra sediment discharge during strengthened early Holocene Monsoon. Geology 28(12): 1083–1086.
Gourlan AT, Albarede F, Achyuthan H & Campillo S 2020. The marine record of the onset of farming around the Arabian Sea at the dawn of the Bronze Age. The Holocene 30(6): 878–887.
Govil P & Naidu PD 2010. Evaporation-precipitation changes in the eastern Arabian Sea for the last 68 ka: Implications on monsoon variability. Palaeoceanography 25(1).
Goyal P, Pokharia AK, Kharakwal JS, Joglekar P, Rawat YS & Osada T 2013. Subsistence system, palaeoecology and ^{14}C chronology at Kanmer, a Harappan site in Gujarat, India. Radiocarbon 55(1): 141−150.
Graham NE, Ammann CM, Fleitmann D, Cobb KM & Luterbacher J 2011. Support for global climate reorganization during the "Medieval Climate Anomaly". Climate Dynamics 37(5): 1217–1245.

Grove JM 1988. The Little Ice Age. Methuen, London: 498pp.
Grove JM 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Climatic change 48(1): 53–82.
Gunnell Y, Anupama K & Sultan B 2007. Response of the South Indian runoff–harvesting civilization to northeast monsoon rainfall variability during the last 2000 years: instrumental records and indirect evidence. The Holocene 17(2): 207–215.
Gupta AK 2004. Origin of agriculture and domestication of plants and animals linked to early Holocene climate amelioration. Current Science 87: 54–59.
Gupta AK, Anderson DM & Overpeck JT 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature 421(6921): 354–357.
Gupta AK, Anderson DM, Pandey DN & Singhvi AK 2006. Adaptation and human migration and evidence of agriculture coincident with change in the Indian summer monsoon during the Holocene. Current Science 90(8): 1082–1090.
Gupta AK, Das M & Anderson DM 2005. Solar influence on the Indian summer during Holocene. Geophysical Research Letters 12: 17703.
Gupta AK, Dutt S, Cheng H & Singh RK 2019. Abrupt changes in Indian Summer Monsoon strength during the last~ 900 years and their linkages to socio–economic conditions in the Indian subcontinent. Palaeogeography, Palaeoclimatology, Palaeoecology 536: 109347.
Hait AK & Behling H 2009. Holocene mangrove and coastal environmental changes in the western Ganga–Brahmaputra Delta, India. Vegetation History and Archaeobotany 18(2): 159–169.
Haq Z & Choudhary G 2014. Why Monsoon is the Life Blood of Indian Economy. New Delhi: Hindustan Times. Available from: http: //www.hindustantimes.com/business–news/why–monsoon–is–the–life–blood–of–indianeconomy/article–1193815.aspx
Harris D 2010. Origins of Agriculture in Western Central Asia: An Environmental Archaeological Study. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. https: //doi.org/10.9783/9781934536513.
Hassan FA 1981. Demographic archaeology. In Advances in archaeological method and theory Academic Press: 225–279.
Hassan FA & Stucki BR 1987. Nile floods and climatic change: *In:* Rampino MR, Sanders JE, Newman WS & Konigsson LK (Editors)–Climate: History, Periodicity and Predictability Van Nostrand Reinhold Company: 37–46.
Haug GH, Hughen KA, Sigman DM, Peterson LC & Röhl U 2001. Southward migration of the intertropical convergence zone through the Holocene. Science 293(5533): 1304–1308.
Indian Meteorological Department & Blanford HF 1886. Report on the Meteorology of India in 1884. Superintendent of Government Printing.
Ivory SJ & Lézine AM 2009. Climate and environmental change at the end of the Holocene Humid Period: A pollen record off Pakistan. Comptes Rendus Geoscience 341(8–9): 760–769.
Jain M & Tandon SK 2003. Fluvial response to Late Quaternary climate changes, western India. Quaternary Science Reviews 22(20): 2223–2235.
Jain M, Tandon SK & Bhatt SC 2004. Late Quaternary stratigraphic development in the lower Luni, Mahi and Sabarmati river basins, western India. Journal of Earth System Science 113(3): 453–471.
Jarrige JF 1990. Excavations at Nausharo 1988–1989. Pakistan Archaeology 25: 193–240.
Jarrige JF 2008. Mehrgarh neolithic. Pragdhara 18: 136–154.
Jiang XN, Li T & Wang B 2004. Structures and mechanisms of the northward propagating boreal summer intraseasonal oscillation. Journal of Climate 17(5): 1022–1039.
Joshi LM, Kotlia BS, Ahmad SM, Wu CC, Sanwal J, Raza W, Singh AK, Shen CC, Long T & Sharma AK 2017. Reconstruction of Indian monsoon precipitation variability between 4.0 and 1.6 ka BP using speleothem $\delta^{18}O$ records from the Central Lesser Himalaya, India. Arabian Journal of Geosciences 10(16): 1–16.
Joshi RV 1978. Stone Age Cultures of Central India: Report on the Excavations of Rock Shelters at Adamgarh, Madhya Pradesh: Deccan College Post–graduate and Research.
Kajale MD & Deotare BC 1997. Late Quaternary environmental studies on salt lakes in western Rajasthan, India: a summarized view. Journal of Quaternary Science 12(5): 405–412.
Kale VS & Baker VR 2006. An extraordinary period of low–magnitude floods coinciding with the Little Ice Age: palaeoflood evidence from central and western India. Journal of Geological Society of India 68(3): 477.
Kar R, Ranhotra PS, Bhattacharyya A & Sekar B 2002. Vegetation vis–à–vis climate and glacial fluctuations of the Gangotri Glacier since the last 2000 years. Current Science 82(3): 347–351.
Kathayat G, Cheng H, Sinha A, Yi L, Li X, Zhang H, Li H, Ning Y & Edwards RL 2017. The Indian monsoon variability and civilization changes in the Indian subcontinent. Science advances 3(12): p.e1701296.
Kennedy KAR, Lovell NC & Burrow CB 1986. Mesolithic human remains from the Gangetic Plain: Sarai Nahar Rai (Occasional Papers and Theses of the South Asia Program, Cornell University, No. 10.)
Kennedy KAR, Lukacs JR, Pastor RF, Johnston TL, Lovell NC, Pal JN & Burrow CB 1992. Human skeletal remains from Mahadaha: A Gangetic Mesolithic Site (Occasional Papers and Theses of the South Asia Program, Cornell University, No. 11)
Kenoyer JM 1998. Ancient cities of the Indus Valley Civilization. Oxford University Press and American Institute of Pakistan Studies, Karachi and Islamabad.
Kessarkar PM, Purnachadra Rao V, Naqvi SWA & Karapurkar SG 2013. Variation in the Indian Summer Monsoon intensity during the Bølling-Ållerød and Holocene. Palaeoceanography 28(3): 413–425.
Kotlia BS, Ahmad SM, Zhao JX, Raza W, Collerson KD, Joshi LM & Sanwal J 2012. Climatic fluctuations during the LIA and post–LIA in the Kumaun Lesser Himalaya, India: evidence from a 400 y old stalagmite record. Quaternary International 263: 129–138.
Kotlia BS & Joshi LM 2013. Late Holocene climatic changes in Garhwal Himalaya. Current Science 104(7): 911–919.
Kotlia BS, Sanwal J, Phartiyal B, Joshi LM, Trivedi A & Sharma C 2010. Late Quaternary climatic changes in the eastern Kumaun Himalaya, India, as deduced from multi–proxy studies. Quarternary International 213: 44–55.
Kotlia BS, Singh AK, Joshi LM & Dhaila BS 2015. Rainfall variability in the Indian Central Himalaya during last ca. 4,000 years inferred from a speleothem record: Impact of Indian Summer Monsoon (ISM) and Westerlies. Quaternary International 371: 244–253.
Kotlia BS, Singh AK, Zhao JX, Duan W, Tan M, Sharma AK & Raza W 2017. Stalagmite based high resolution precipitation variability for past four centuries in the Indian Central Himalaya: Chulerasim cave re–visited and data re–interpretation. Quaternary International 444: 35–43.
Krishnamurthy V & Achuthavarier D 2012. Intraseasonal oscillations of the monsoon circulation over South Asia. Climate dynamics 38(11): 2335–2353.
Krishnan KG 1980. Uttankita Vidyaranya Sanskrit Epigraphs, Vol–II, Uttankita Vidyaranya Trust, Mysore.
Kumar KK, Rajagopalan B & Cane MA 1999. On the weakening relationship between the Indian monsoon and ENSO. Science 284(5423): 2156–2159.
Kumar P, Sanwal J, Dimri AP & Ramesh R 2019. Contribution of diverse monsoon precipitation over Central and Northern India during mid to Late Holocene. Quaternary International 507: 217–223.
Kuper R & Kröpelin S 2006. Climate–controlled Holocene occupation in the Sahara: motor of Africa's evolution. Science 313(5788): 803–807.
Lau WK, Waliser DE & Hsu HH 2012. Intraseasonal variability of the atmosphere–ocean–climate system: East Asian Monsoon. In Intraseasonal Variability in the Atmosphere Ocean Climate System. Springer, Berlin, Heidelberg: 73–110.
Lawrence D, Palmisano A & de Gruchy MW 2021. Collapse and continuity: A multi–proxy reconstruction of settlement organization and population trajectories in the Northern Fertile Crescent during the 4.2 kya Rapid Climate Change event. PloS one 16: p.e0244871.
Lefeber Rosalind trans. 1994/ 2000. The Ramayana of Valmiki, An Epic of Ancient India, Vol IV, Kishkindhakanda, Princeton University Press, Princeton.
Leick G 2009. Historical Dictionary of Mesopotamia (Vol. 26). Scarecrow Press.
Leipe C, Demske D, Tarasov PE & HIMPAC Project Members 2014. A

Holocene pollen record from the northwestern Himalayan lake Tso Moriri: implications for palaeoclimatic and archaeological research. Quaternary International 348: 93–112.

Liang F, Brook GA, Kotlia BS, Railsback LB, Hardt B, Cheng H, Edwards RL & Kandasamy S 2015. Panigarh Cave stalagmite evidence of climate change in the Indian Central Himalaya since AD 1256: Monsoon breaks and winter southern jet depressions. Quaternary Science Reviews 124: 145–161.

Limaye RB, Kumaran KPN & Padmalal D 2014. Mangrove habitat dynamics in response to Holocene sea level and climate changes along Southwest Coast of India. Quaternary International 325: 116–125.

Liu XQ, Dong HL, Rech JA, Matsumoto R, Yang B & Wang YB 2008. Evolution of Chaka Salt Lake in NW China in response to climate change during the latest Pleistocene–Holocene. Quaternary Science Reviews 27: 867–879.

Lone AM, Achyuthan H, Shah RA, Sangode SJ, Kumar P, Chopra S & Sharma R 2020. Palaeoenvironmental shifts spanning the last~ 6000 years and recent anthropogenic controls inferred from a high–altitude temperate lake: Anchar Lake, NW Himalaya. The Holocene 30(1): 23–36.

Lukacs JR, Misra VN & Kennedy KAR 1982. Bagor and Tilwara: Late Mesolithic Cultures of Northwest India, vol. I, The Human skeletal remains. Deccan College, Pune.

MacDonald G 2011. Potential influence of the Pacific Ocean on the Indian Summer Monsoon and Harappan decline. Quaternary International 229: 140–148.

Madella M & Fuller DQ 2006. Palaeoecology and the Harappan Civilisation of South Asia: a reconsideration. Quaternary Science Reviews 25: 1283–1301.

Malhotra KC, Khomine SB & Gadgil M 1983. Hunting strategies among three non–pastoral nomadic groups of Maharashtra. Man India 63: 21–39.

Manoj MC, Thakur B & Uddandam PR 2021. Controls on rare earth elements distribution from Kerala Coast, southwest India over the past 2000 years. Environmental Forensics: 1–16.

Margaritelli G, Cacho I, Català A, Barra M, Bellucci LG, Lubritto C, Rettori R & Lirer F 2020. Persistent warm Mediterranean surface waters during the Roman Period. Scientific Reports 10(1): 1–10.

Marshall MH, Lamb HF, Huws D, Davies SJ, Bates R, Bloemendal J, Boyle J, Leng MJ, Umer M & Bryant C 2011. Late Pleistocene and Holocene drought events at Lake Tana, the source of the Blue Nile. Global and Planetary Change 78: 147–161.

Martín–Puertas C, Valero–Garcés BL, Brauer A, Mata MP, Delgado–Huertas A & Dulski P 2009. The Iberian–Roman Humid Period (2600–1600 cal yr BP) in the Zoñar Lake varve record (Andalucía, southern Spain). Quaternary Research 71(2): 108–120.

Matthews JA & Briffa KR 2005. The 'Little Ice Age': re-evaluation of an evolving concept. Geografiska Annaler: Series A Physical Geography 87(1): 17–36.

McConnell John A 1990. The Rohini Conflict and the Buddha's Intervention. *In:* Sulak Sivaraksa (Editor)–Radical Conservatism: Buddhism in the Contemporary World. Bangkok: Thai Inter–religious Commission for Development and the International Network for Engaged Buddhists: 200 pp.

McGhee R 1981. Archaeological evidence for climatic change during the last 5000 years: *In:* Wigley TML, Ingram MJ & Farmer G (Editors)–Climate and History: Studies in past climates and their impact on Man. Cambridge University Press, Cambridge: 162–179.

Mishra PK, Anoop A, Schettler G, Prasad S, Jehangir A, Menzel P, Naumann R, Yousuf AR, Basavaiah N, Deenadayalan K & Wiesner MG 2015. Reconstructed late Quaternary hydrological changes from Lake Tso Moriri, NW Himalaya. Quaternary International 371: 76–86.

Misra VN 1973. Bagor: A late Mesolithic settlement in northwest India. World Archaeology 5: 92–100.

Misra VN 1976. Ecological adaptations during the terminal stone age in western and central India: *In:* Kennedy KAR & Possehl GL (Editors)–Ecological Backgrounds of South Asian Prehistory (Ithaca: Cornell University): 28–51.

Misra VN 1984. Climate, a factor in the rise and fall of the Indus Civilization— Evidence from Rajasthan and Beyond: *In:* Lal BB & Gupta SP (Editors)–Frontiers of the Indus Civilization, New Delhi: 461–489.

Misra VN 1997. Mesolithic India: history and current status of research; in Colloquia of the International Congress of Prehistoric and Protohistoric Sciences 1996 (Forli: ABACO Edizioni) 16: 321–328.

Misra VN 2001. Prehistoric human colonization of India. Journal of Biosciences 26(4): 491–531.

Misra VN & Rajaguru SN 1986. Environment et culture de l' homme prehistorique dans le desert du Thar, Rajasthan, Inde.

Molnar P, Boos WR & Battisti DS 2010. Orographic controls on climate and paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau. Annual Review of Earth and Planetary Sciences 38: 77–102.

Montgomery DR, Hallet B, Yuping L, Finnegan N anders A, Gillespie A & Greenberg HM 2004. Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. Quaternary Research 62(2): 201–207.

Motuzaite MG, Tabaldiev K, Hermes T, Ananyevskaya E, Grikpedis M, Luneau E, Merkyte I & Rouse LM 2020. High–altitude agro–pastoralism in the Kyrgyz Tien Shan: New excavations of the chap farmstead (1065–825 cal bc). Journal of Field Archaeology 45(1): 29–45.

Mughal 1997. Ancient Cholistan: Archaeology and Architecture. Lahore, Ferozsons (Pvt.) Ltd.

Murtugudde R, Goswami BN & Busalacchi AJ 1998. April. Air–sea interaction in the southern tropical Indian Ocean and its relations to interannual variability of the monsoon over India. *In:* Proceedings of the International Conference on Monsoon and Hydrologic Cycle. Korean Meteorological Agency: 184–188.

Nagar M & Misra VN 1989. Hunter–gatherers in an agrarian setting: the nineteenth century situation in the Ganga plains. Man Environment 13: 65–78.

Nagar M & Misra VN 1990. The Kanjars: a hunting–gathering community of the Ganga Valley, Uttar Pradesh. Man Environment 15: 71–88.

Nagar M & Misra VN 1993. The Pardhis: a hunting–gathering community of central and western India. Man Environment 18: 115–144.

Naidu PD 2006. Link between western Arabian Sea surface temperature and summer monsoon strength and high–latitude abrupt climate events. http: //drs.nio.org/drs/handle/2264/467

Naidu PD & Malmgren BA 1996. A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera. Paleoceanography 11(1): 129–140.

Nair KM, Padmalal D, Kumaran KPN, Sreeja R, Limaye RB & Srinivas R 2010. Late Quaternary evolution of Ashtamudi–Sasthamkotta Lake systems of Kerala, Southwest India. Journal of Asian Earth Science 37: 361–372.

Neff U, Burns SJ, Mangini A, Mudelsee M, Fleitmann D & Matter A 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. Nature 411(6835): 290–293.

Newton A, Thunell R & Stott L 2006. Climate and hydrographic variability in the Indo–Pacific Warm Pool during the last millennium. Geophysical Research Letters 33: doi: 10.1029/2006GL027234. ISSN: 0094–8276.

Oppo DW, Rosenthal Y & Linsley BK 2009. 2,000–year–long temperature and hydrology reconstructions from the Indo–Pacific warm pool. Nature 460: 1113–1116.

Overpeck J anderson D, Trumbore S & Prell W 1996. The southwest Indian monsoon over the last 18,000 years. Climate Dynamics 12: 213–225.

Pal JN 1992. Mesolithic human burials in the Gangetic plain, north India. Man Environment 17: 35–44.

Pandey DN, Gupta AK & Anderson DM 2003. Rainwater harvesting as an adaptation to climate change. Current Science 85: 46−59.

Pant GB & Parthasarathy SB 1981. Some aspects of an association between the southern oscillation and Indian Summer Monsoon. Archives for Meteorology, Geophysics And Bioclimatology 29(3): 245–252.

Pattanaik DR 2012. Indian monsoon variability. Monsoon Monograph 2: 35–77.

Pattanaik DR 2014. Meteorological subdivisional–level extended range forecast over India during southwest monsoon 2012. Meteorology and Atmospheric Physics 124(3): 167–182.

Pattanaik DR & Das AK 2015. Prospect of application of extended range forecast in water resource management: a case study over the Mahanadi River Basin. Natural Hazards: 77. doi: 10.1007/s11069–015–1610–4.
Pattanaik DR & Kumar A 2015. A hybrid model based on latest version of NCEP CFS coupled model for Indian monsoon rainfall forecast. Atmospheric Science Letters 16(1): 10–21.
Pattanaik DR, Mohapatra M, Mukhopadhyay B & Tyagi A 2013a. A preliminary study about the prospects of extended range forecast of tropical cyclogenesis over the north Indian Ocean during 2010 post–monsoon season. Mausam 64(1): 171–188.
Pattanaik DR, Rathore LS & Kumar A 2013b. Observed and forecasted intraseasonal activity of southwest monsoon rainfall over India during 2010, 2011 and 2012. Pure and Applied Geophysics 170(12): 2305–2328.
Paul S, Ghosh S, Oglesby R, Pathak A, Chandrasekharan A & Ramsankaran RAAJ 2016. Weakening of Indian Summer Monsoon rainfall due to changes in land use land cover. Scientific Reports 6(1): 1–10.
Petraglia MD & Allchin B 2007. Human evolution and culture change in the Indian subcontinent. In The Evolution and History of Human Populations in South Asia, Springer, Dordrecht: 1–20.
Phadtare NR 2000. Sharp decrease in summer monsoon strength 4000–3500 cal BP in the central higher Himalayas of India based on pollen evidences from alpine peat. Quaternary Research 53: 122–129.
Phadtare NR & Pant RK 2006. A century–scale pollen record of vegetation and climate history during the past 3500 years in the Pinder Valley, Kumaon Higher Himalaya, India. Journal of Geological Society of India 68: 495–506.
Pokharia AK 2008. Record of macrobotanical remains from the Aravalli Hill, Ojiyana, Rajasthan: Evidence for agriculture–based subsistence economy. Current Science 94(5): 612−623.
Pokharia AK 2011. Palaeoethnobotany at Lahuradewa: A contribution to the 2nd Millennium BC agriculture of the Ganga Plain, India. Current Science 101(12): 1569−1578.
Pokharia AK, Agnihotri R, Sharma S, Bajpai S, Nath J, Kumaran RN & Negi BC 2017b. Altered cropping pattern and cultural continuation with declined prosperity and extreme arid event at ~4.2ka BP: Evidence from an Indus archaeological site Khirsara, Gujarat, western India. PLos One 12(10): p.e0185684.
Pokharia AK, Kharakwal JS & Srivastava A 2014. Archaeobotanical evidence of millets in the Indian subcontinent with some observations on their role in the Indus civilization. Journal of Archaeological Sciences 42: 442–455.
Pokharia AK, Mani BR, Michael Spate, Betts A & Srivastava A 2017a. Early Neolithic agriculture (2700–2000 BC) and Kushan Period developments (AD 100–300): Macrobotanical evidence from Kanispur in Kashmir, India. Vegetation History and Archaeobotany 27(3): 477–491
Pokharia AK, Pal JN & Srivastava A 2009. Plant macro–remains from Neolithic Jhusi in Ganga Plain: evidence for grain–based agriculture. Current Science 97: 564−571.
Pokharia AK, Sharma S, Tripathi D, Misra N, Pal JN, Ram Vinay & Srivastava A 2016. Neolithic–Early Historic (2500–200 BC) plant use: the archaeobotany of Ganga Plain. Quaternary International 443: 223–237.
Ponton C, Giosan L, Eglinton TI, Fuller DQ, Johnson JE, Kumar P & Collett TS 2012. Holocene aridification of India. Geophysical Research Letters 39(3): L03704.
Possehl GL 1997a. Climate and the eclipse of the ancient cities of the Indus. *In:* Dalfes HN, Kukla G & Weiss H (Editors)–Third Millennium BC Climate Changes and Old World Collapse. Springer, Heidelberg 49: 193–243.
Possehl GL 1997b. The transformation of the Indus Civilization. Journal of World Prehistory 11: 425–472.
Possehl GL 2002. The Indus Civilization: A Contemporary Perspective. Rowman Altamira.
Possehl GL & Gullapalli P 1999. The early iron age in South Asia. The archaeometallurgy of the Asian old world 16: 153.
Possehl GL & Kennedy KA 1979. Hunter–gatherer/agriculturalist exchange in prehistory: An Indian example. Current Anthropology 20(3): 592–593.
Prasad S, Anoop A, Riedel N, Sarkar S, Menzel P, Basavaiah N, Krishnan R, Fuller D, Plessen B, Gaye B, Rohl U, Wilkes H, Sachse D, Swant R, Wiesner MG & Stebich M 2014. Prolonged monsoon droughts and links to Indo–Pacific warm pool: A Holocene record from Lonar Lake, central India. Earth and Planetary Science Letters 391: 171–182.
Prasad S & Enzel Y 2006. Holocene palaeoclimates of India. Quaternary Research 66: 442–453.
Prasad V, Farooqui A, Sharma A, Phartiyal B, Chakraborty S, Bhandari S, Raj R & Singh A 2014. Mid–late Holocene monsoonal variations from mainland Gujarat, India: A multi–proxy study for evaluating climate culture relationship. Palaeogeography, Palaeoclimatology, Palaeoecology 397: 38–51.
Prasad V, Phartiyal B & Sharma A 2007. Evidence of enhanced winter rainfall and the prevalence of a cool and dry climate during the mid to late Holocene in mainland Gujarat, India. The Holocene 17(7): 889–896.
Prasanna V 2014. Impact of monsoon rainfall on the total food grain yield over India. Journal of Earth System 123(5): 1129–1145.
Puri VMK 2008. Vedic Sarasvati: Scientific signatures on its origin from Himalaya. *In:* Kalyanaraman S (Editor)–Vedic Sarasvati and Hindu Civilization, Aryan Books International, New Delhi: 14–15.
Quamar MF & Chauhan MS 2012. Late Quaternary vegetation, climate as well as lake–level changes and human occupation from Nitaya area in Hoshangabad District, southwestern Madhya Pradesh (India), based on pollen evidence. Quaternary International 263(14): 104–113.
Quamar MF & Chauhan MS 2014. Signals of medieval warm period and little ice age from southwestern Madhya Pradesh (India): a pollen–inferred Late–Holocene vegetation and climate change. Quaternary International 325: 74–82.
Rajmanickam V, Achyuthan H, Eastoe C & Farooqui A 2016. Early–Holocene to present palaeoenvironmental shifts and short climate events from the tropical wetland and lake sediments, Kukkal Lake, southern India: Geochemistry and palynology. The Holocene 27(3): 404–417.
Rao MP, Cook ER, Cook BI, D'Arrigo RD, Palmer JG, Lall U, Woodhouse CA, Buckley BM, Uriarte M, Bishop DA & Jian J 2020. Seven centuries of reconstructed Brahmaputra River discharge demonstrate underestimated high discharge and flood hazard frequency. Nature communications 11(1): 1–10.
Rao YP 1976. Southwest Monsoon. Synop. Met. No. 1 /1976, Met. Mono. India Met. Dept. 107, Riehl, H., 1979: Climate and weather in the tropics. Academic Press: 367–369.
Rao VP, Kessarkar PM, Thamban M & Patil SK 2010. Palaeoclimatic and diagenetic history of the late quaternary sediments in a core from the Southeastern Arabian Sea: Geochemical and magnetic signals. Journal of Oceanography 66(1): 133–146.
Rasmusson EM & Carpenter TH 1983. The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. Monthly Weather Review 111(3): 517–528.
Ratnagar S 1987. Pastoralists in the prehistory of Baluchistan. Studies in History 3: 137–154.
Ratnagar S 2000. The end of the great Harappan tradition. Manohar Publishers, New Delhi: 163 pp.
Rawat S, Gupta AK, Sangode SJ, Srivastava P & Nainwal HC 2015. Late Pleistocene–Holocene vegetation and Indian Summer Monsoon record from the Lahaul, Northwest Himalaya, India. Quaternary Science Reviews 114: 167–181.
Reddy SN 1994. Plant usage and subsistence modelling: An ethnoarchaeological approach to the Late Harappan of northwest India. Ph.D Dissertation, University of Wisconsin, University Microfilm, Ann. Arbor.
Roxy M & Tanimoto Y 2007. Role of SST over the Indian Ocean in Influencing the Intraseasonal Variability of the Indian Summer Monsoon. Journal of the Meteorological Society of Japan 85(3): 349–358. doi: 10.2151/jmsj.85.349.
Roxy MK 2017. Land warming revives monsoon. Nature Climate Change 7: 549–550.
Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K & Goswami BN 2015. Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land–sea thermal gradient. Nature Communications 6(1): 1–10.
Roy TN 1983. The Ganges Civilization: a critical archaeological study of the painted grey ware and northern black polished ware periods of the Ganga

Plains of India. Stosius Incorporated/Advent Books Division.

Ryder AW trans 1914. Shakuntala: Kalidas, Createspace Independent Publishing Platform.

Sabeerali C, Rao SA, George G, Rao DN, Mahapatra S, Kulkarni A & Murtugudde R 2014. Modulation of monsoon intraseasonal oscillations in the recent warming period. Journal of Geophysical Research: Atmospheres 119(9): 5185–5203.

Sadhale Nalini tras. 1999. Krishi–Parashar: A text on Ancient Indian Agriculture in Sanskrit, Asian–Agri History Foundation, Hyderabad.

Saini HS, Tandon SK, Mujtaba SAI, Pant NC & Khorana RK 2009. Reconstruction of buried channel–floodplain systems of the northwestern Haryana Plains and their relation to the 'Vedic' Saraswati. Current Science 97(11): 1634–1643.

Saji NH, Goswami BN, Vinayachandran PN & Yamagata T 1999. A dipole mode in the tropical Indian Ocean. Nature 401(6751): 360–363.

Sankalia HD & Karve I 1949. Early primitive microlithic culture and people of Gujarat. American. Anthropologist 51: 28–34

Sanwal J, Kotlia BS, Rajendran C, Ahmad SM, Rajendran K & Sandiford M 2013. Climatic variability in central Indian Himalaya during the last ~1800 years: Evidence from a high resolution speleothem record. Quaternary International 304: 183–192.

Saraswat KS 1992. Archaeobotanical remains in ancient cultural and socio–economical dynamics of the Indian subcontinent. Palaeobotanist 40: 514−545.

Saraswat KS 2004. Plant economy of early farming communities: *In:* Singh BP (Editor)–Early farming communities of the Kaimur, Publication scheme, Jaipur 2: 416−535.

Saraswat KS & Pokharia AK 2002. Harappan plant economy at ancient Balu, Haryana. Pragdhara 12: 153–171.

Saraswat KS & Pokharia AK 2003. Palaeoethnobotanical investigations at Early Harappan Kunal. Pragdhara 13: 105–139.

Sarkar A, Ramesh R, Somayajulu BLK, Agnihotri R, Jull AJT & Burr GS 2000. High resolution Holocene monsoon record from the eastern Arabian Sea. Earth and Planetary Science Letters 177: 209–218.

Sastri VS & Bhat MR trans. 1943. Varahamihira's Brihat Samhita, V B Subbaiah and Sons, Bangalore.

Saxena A, Prasad V, Singh IB, Chauhan MS & Hasan R 2006. On the Holocene record of phytoliths of wild and cultivated rice from Ganga Plain: evidence for rice–based agriculture. Current Science 90(11): 1547–1551.

Saxena A & Singh DS 2017. Multiproxy records of vegetation and monsoon variability from the lacustrine sediments of eastern Ganga Plain since 1350 AD. Quaternary International 444(A): 24–34.

Schoff WH, trans. 1912. The Periplus of the Erythraean sea, Longman, Green and Co., New York.

Seager R, Graham N, Herweijer C, Gordon AL, Kushnir Y & Cook E 2007. Blueprints for medieval hydroclimate. Quaternary Science Reviews 26: 2322–2336.

Shaffer JG & Liechtenstein DA 1989. Ethnicity and change in the Indus Valley Cultural Tradition. *In:* Kenoyer JM (Editor)–Old problems and New perspectives in South Asian Archaeology. Wisconsin Archaeological Reports, Madison: 117–126.

Shah RA, Achyuthan H, Lone AM, Kumar S, Kumar P, Sharma R, Amir M, Singh AK & Dash C 2020. Holocene palaeoenvironmental records from the high–altitude Wular Lake, western Himalayas. The Holocene 30(5): 733–743.

Shamasastry R 1915. Kautilya's Arthashastra (Translated into English): 613 pp.

Shao X, Wang Y, Cheng H, Kong X, Wu J & Edwards RL 2006. Long–term trend and abrupt events of the Holocene Asian Monsoon inferred from a stalagmite $\delta^{10}O$ record from Shennongjia in central China. Chinese Science Bulletin 51(2): 221–228.

Sharma GR 1973. Mesolithic lake culture in the Ganga Valley. Proceeding of the Prehistoric Society 34: 129–146.

Sharma GR, Misra VD, Mandal D, Misra BB & Pal JN 1980. Beginnings of Agriculture (Epipalaeolithic to Neolithic): Excavations at Chopani–Mando, Mahadaha and Mahagara (Allahabad: Abinash Prakashan).

Shaw J, Sutcliffe J, Lindsay L–S, Schwenninger J–L, Chauhan MS, Misra OP & Harvey E 2007. Ancient Irrigation and Buddhist History in central India: Optically stimulated luminescence dates and pollen sequences from the Sanchi Dams. Asian Perspectoves 46(1): 166–201.

Sikka DR 1980. Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. Proceedings of the Indian Academy of Sciences–Earth and Planetary Sciences 89(2): 179–195.

Singh DS & Singh IB 2005. Facies architecture of the Gandak Megafan, Ganga Plain, India. Special Publication of the Palaeontological Society of India 2: 125–140.

Singh DS, Gupta AK, Sangode SJ, Clemens SC, Prakasam M, Srivastava P & Prajapati SK 2015. Multiproxy record of monsoon variability from the Ganga Plain during 400–1200 AD. Quaternary International 371: 157–163.

Singh G, Joshi RD, Chopra SK & Singh AB 1974. Late Quaternary history of vegetation and climate in the Rajasthan Desert, India. Philosophical Transactions of the Royal Society of London 267: 467−501.

Singh G, Wasson RJ & Agrawal DP 1990. Vegetational and seasonal climatic changes since the last full glacial in the Thar Desert, northwestern India. Review of Palaeobotany and Palynology 64: 351–358.

Singh J, Park WK & Yadav RR 2006. Tree–ring–based hydrological records for western Himalaya, India, since AD 1560. Climate Dynamics 26: 295–303.

Singh J & Yadav RR 2005. Spring precipitation variations over the western Himalaya, India, since AD 1731 as deduced from tree rings. Journal of Geophysical Research: Atmospheres 110(D1).

Singh S, Gupta AK, Dutt S, Bhaumik AK & Anderson DM 2020. Abrupt shifts in the Indian Summer Monsoon during the last three millennia. Quaternary International 558: 59–65.

Singhvi AK, Rupakumar K, Thamban M, Gupta AK, Kale VS, Yadav RR, Bhattacharyya A, Phadtare NR, Roy PD, Chauhan MS & Chauhan OS 2009. Instrumental, terrestrial and marine records of the climate of South Asia during the Holocene. In Global Environmental Changes in South Asia: 54–124.

Sinha A, Berkelhammer M, Stott L, Mudelsee M, Cheng H & Biswas J 2011. The leading mode of Indian Summer Monsoon precipitation variability during the last millennium. Geophysical Research Letters 38(15).

Sinha A, Cannariato KG, Stott LD, Cheng H, Edwards RL, Yadava MG, Ramesh R & Singh IB 2007. A 900–year (600 to 1500 A.D.) record of the Indian Summer Monsoon precipitation from the core monsoon zone of India. Geophysical Research Letters 34.

Sirocko F, Sarnthein M, Erlenkeuser H, Lange H, Arnold M & Duplessy JC 1993. Century–scale events in monsoonal climate over the past 24,000 years. Nature 364(6435): 322–324.

Solanki SK, Usoskin IG, Kromer B, Schüssler M & Beer J 2004. Unusual activity of the Sun during recent decades compared to the previous 11,000 years. Nature 431(7012): 1084–1087.

Sontakke NA & Singh N 1996. Longest instrumental regional and all–India Summer Monsoon rainfall series using optimum observations: reconstruction and update. The Holocene 6(3): 315–331.

Spate M, Zhang G, Yatoo M & Betts A 2017. New evidence for early 4th millennium BP agriculture in the western Himalayas: Qasim Bagh, Kashmir. Journal of Archaeological Science: Reports 11: 568–577.

Srivastava A, Thomas David SG, Durcan JA & Bailey RM. 2020. Holocene palaeoenvironmental changes in the Thar Desert: An integrated assessment incorporating new insights from aeolian systems. Quaternary Science Reviews 233: 106214.

Stanley JD, Krom MD, Cliff RA & Woodward JC 2003. Short contribution: Nile flow failure at the end of the Old Kingdom, Egypt: strontium isotopic and petrologic evidence. Geoarchaeology 18(3): 395–402.

Staubwasser M, Sirocko F, Grootes PM & Erlenkeuser H 2002. South Asian monsoon climate change and radiocarbon in the Arabian Sea during early and middle Holocene. Paleoceanography 17(4): 15–1.

Staubwasser M & Weiss H 2006. Holocene climate and cultural evolution in late prehistoric–early historic West Asia. Quaternary Research 66(3): 372–387.

Staubwasser M, Sirocko F, Grootes PM & Segl M 2003. Climate change at the 4.2 ka BP termination of the Indus Valley Civilization and Holocene South Asian Monsoon variability. Geophysical Research Letters 30(8): 1425–1429.

Sukumar R, Ramesh R, Pant RK & Rajagopalan G 1993. A $\delta^{13}C$ record of late Quaternary climate change from tropical peats in southern India. Nature 364: 703–706.

Swain AM, Kutzbach JE & Hastenrath S 1983. Estimates of Holocene rainfall for Rajasthan, India, based on pollen and lake–level data. Quaternary Research 19: 1−17.

Tengberg M 1999. Crop husbandry at Miri Qalat, Makran, SW Pakistan (4000–2000 BC). Vegetation History and Archaeobotany 8: 3−12.

Tewari R, Srivastava RK, Singh KK, Saraswat KS, Singh IB, Chauhan MS, Pokharia AK, Saxena A, Prasad V & Sharma M 2006. Second preliminary report of the excavations at Lahuradewa, district Sant Kabirnagar, U.P.–2002–2003–2004 and 2005–06. Pragdhara 16: 35−68.

The Imperial Gazetteer of India, Vol I, The Clarendon Press, London, 1909: 127 pp.

Thompson LG, Mosley–Thompson E, Davis ME, Henderson KA, Brecher HH, Zagorodnov VS, Mashiotta TA, Lin PN, Mikhalenko VN, Hardy DR & Beer J 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. Science 298(5593): 589–593.

Tibbetts GR 1971. Arab navigation in the Indian Ocean before the coming of the Portuguese. Being a translation of Kitab al–Fawa'id fi usul al–bahr wa'l–qawa'id of Ahmad b. Majid al–Najid. The Royal Asiatic Society of Great Britain and Ireland, London.

Tierney JE, Oppo DW, Rosenthal Y, Russell JM & Linsley BK 2010. Coordinated hydrological regimes in the Indo–Pacific region during the past two millennia. Paleoceanography 25(PA1102): 7.

Trenberth KE, Caron JM, Stepaniak DP & Worley S 2002. Evolution of El Niño–Southern Oscillation and global atmospheric surface temperatures. Journal of Geophysical Research: Atmospheres 107(D8): AAC 5–1–AAC 5–17.

Tripathi JK, Bock B, Rajamani V & Eisenhauer A 2004. Is river Ghaggar, Saraswati? Geochemical constraints. Current Science 87: 1141–1145.

Trivedi A & Chauhan MS 2009. Holocene vegetation and climatic fluctuations in northwest Himalaya, based on pollen evidence from Surinsar Lake, Jammu region, India. Journal of Geological Society of India 74: 402–412.

Turner AG & Annamalai H 2012. Climate change and the South Asian Summer Monsoon. Nature Climate Change 2(8): 587–595.

Valdiya KS 2002. Saraswati: The River that Disappeared, University Press, Hyderabad: 116 pp.

Valdiya KS 2017. Prehistoric River Saraswati, western India: Geological Appraisal and Social Aspects. Springer International Publication 136 pp.

Varma RK 1986. The Mesolithic Age in Mirzapur (Allahabad: Paramjyoti Prakashan).

Varma RK, Misra VD, Pandey JN & Pal JN 1985. A preliminary report on the excavations at Damdama (1982–1984). Man Environment 9: 45–65.

Veena MP, Achyuthan H, Eastoe C & Farooqui A 2014. A multi–proxy reconstruction of monsoon variability in the late Holocene, south India. Quaternary International 325: 63–73.

Von Rad U, Schaaf M, Michels KH, Schulz H, Berger WH & Sirocko F 1999. A 5000–yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, Northeastern Arabian Sea. Quaternary Research 51(1): 39–53.

Wang B 2006. The Asian Monsoon. Springer, Chichester.

Wang B, Lee JY & Xiang B 2015a. Asian Summer Monsoon rainfall predictability: a predictable mode analysis. Climate Dynamics 44(1–2): 61–74.

Wang B, Liu J, Kim HJ, Webster PJ, Yim SY & Xiang B 2013. Northern Hemisphere Summer Monsoon intensified by mega–El Niño/southern oscillation and Atlantic multidecadal oscillation. Proceedings of the National Academy of Sciences 110(14): 5347–5352.

Wang B, Xiang B, Li J, Webster PJ, Rajeevan MN, Liu J & Ha KJ 2015b. Rethinking Indian monsoon rainfall prediction in the context of recent global warming. Nature communications 6.

Wang Y, Cheng H, Edwards RL, He Y, Kong X, An Z, Wu J, Kelly MJ, Dykoski, CA & Li X 2005. The Holocene Asian Monsoon: links to solar changes and North Atlantic climate. Science 308(5723): 854–857.

Wanner H, Beer J, Bütikofer J, Crowley TJ, Cubasch U, Flückiger J, Goosse H, Grosjean M, Joos F, Kaplan JO, Küttel M, Müller S, Prentice IC, Solomina O, Stocker TF, Tarasov P, Wagner M & Widmann M 2008. Mid–to late Holocene climate change: an overview. Quaternary Science Reviews 27: 1791–1828.

Wanner H, Mercolli L, Grosjean M & Ritz SP 2015. Holocene climate variability and change: a data–based review. Journal of the Geological Society 172(2): 254–263.

Wasson RJ, Smith GI & Agarwal DP 1984. Vegetation and seasonal climate changes since the last full Glacial in the Thar Desert, NW India. Palaeogeography, Palaeoclimatology, Palaeoecology 46: 345−372.

Weber SA 1991. Plants and Harappan Subsistence: An example of stability and change from Rojdi. Oxford and IBH, New Delhi.

Weber SA 2003. Archaeobotany at Harappa: indications for change: *In:* Weber SA & Belcher WR (Editors)–Indus Ethnobiology. New Perspectives from the Field. Lexington Books, Lanham: 175–198.

Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai M & Yasunari T 1998. Monsoons: Processes, predictability and the prospects for prediction. Journal of Geophysical Research–Oceans 103(C7): 14451–14510.

Webster PJ, Moore AM, Loschnigg JP & Leben RR 1999. Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. Nature 401(6751): 356–360.

Weeks L 2013. The development and expansion of a Neolithic way of life. In The Oxford Handbook of Ancient Iran. Oxford University Press.

Weeks L, Alizadeh K, Niakan L, Alamdari K, Zeidi M, Khosrowzadeh A & McCall B 2006. The Neolithic settlement of highland SW Iran: new evidence from the Mamasani District. Iran 44(1): 1–31.

Weiss H & Bradley RS 2001. What drives societal collapse? Science 291: 609–610.

Weiss H, Courtney M–A, Wetterstrom W, Guichard F, Senior L, Meadow R & Curnow A 1993. The genesis and collapse of third millennium north Mesopotamian Civilization. Science 261: 995–1004.

Weiss KJ 2017. Linus Pauling, Ph.D (1901–1994): From Chemical Bond to Civilization. American Journal of Psychiatry 174(6): 518–519.

Welc F & Marks L 2014. Climate change at the end of the Old Kingdom in Egypt around 4200 BP: new geoarchaeological evidence. Quaternary International 324: 124–133.

Winner C 2012. Rain, rivers and the fate of civilizations. Oceanus Magazine 49(3): 30.

Wright KI, Critchley P, Garrard A, Baird D, Bains R & Groom S 2008. Stone bead technologies and early craft specialization: insights from two Neolithic sites in eastern Jordan. Levant 40(2): 131–165.

Wright RP 2010. The Ancient Indus: Urbanism, Economy and Society. Cambridge, Cambridge University: 1–396.

Xie SP, Xu H, Saji NH, Wang Y & Liu WT 2006. Role of narrow mountains in large–scale organization of Asian monsoon convection. Journal of Climate 19(14): 3420–3429.

Yadava MG & Ramesh R 2005. Monsoon reconstruction from radio–carbon dated tropical Indian speleothems. Holocene 15: 48–59.

Yadava MG, Ramesh R & Pant GB 2004. Past monsoon rainfall variations in peninsular India recorded in a 331–year–old speleothem. The Holocene 14(4): 517–524.

Zhang K, Zhao Y, Zhou A & Sun H 2010. Late Holocene vegetation dynamic and human activities reconstructed from lake records in western Loess Plateau, China. Quaternary International 227: 38–45.