Monsoon in history and present


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ABSTRACT


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 has 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 literature (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 6th–5th 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
(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 (Shamaasra, 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)" (Sasti & 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. KahanGhag 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 been imagined as the poets and artists. The most celebrated classical Sanskrit poet Kalidasa in his elegiac poem Meghdhoottam, 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 Erythrean 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 “Mausami” (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...
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 southern 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 typhoides), ragi (Eleusine coracana), little millet ( Panicum miliare) and Italian millet (Setaria italic) 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 Ghaggar–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 landscape 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 during 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 & Sunethi, 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 Mehargarh, 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 paleoclimate 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. sphaeroccum*), 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 Lunakarsar 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 ~6000 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, Gulkral) 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 Anchur (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 delta's 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 insulation-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 monsoon 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, Didwan, Lunarkarsar 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. 2I). 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 δ¹⁸O values at 3500 yr BP (Bar–Matthews et al., 2003) and a higher amplitude peak at 3400 yr BP (Fleitmann et al., 2007), indicating declining 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 δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O 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 fluviolacustrine 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 (Martin–Puertas et al., 2009), synchronous with intense solar insolation and associated with the northward shift of the ITCC (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 southwestward 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 Ghats indicate wet conditions during LIA (Borgaonkar et al., 2010). A negative δ18O excursion in the speleothem records from Wadh 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 Wadh Shikhar Cave, NE India, 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 δ18O 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; Tiemey 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 Akalagavi 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 westlerlies 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 (%).
monsoon rainfall in inter–annual and intra–seasonal time scales is very crucial.

Monsoon variability and Indian economy

The Indian Summer Monsoon Rain (ISM) 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 DJAS 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.
(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 the monsoon season in 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
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 Value 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
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 & Achuthavarriar, 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**


Ashok K, Guan ZY, Saji NH & Yamagata T 2004. Individual and combined


Christian J 1891. Behar Proverbs (reprinted 1896), Delhi, Unity Book Service.


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


Dalfes HN 1997. Environmental vulnerability of early societies: some


Kennedy KAR, Lovell NC & Burrow CB 1986. Mesolithic human remains from the Gangetic Plain: Saarai Nahar Rai (Occasional Papers and Theses of the South Asia Program, Cornell University, No. 10.)
Kotlia BS, Singh AK, Joshi LM & Bhaila 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.
Holocene pollen record from the northwestern Himalayan lake Tso Moriri: implications for palaeoclimatic and archaeological research. Quaternary International 348: 93–112.


