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# Impact of Indian Summer Monsoon Change on Ancient Indian Civilizations During the Holocene

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A large part of South Asia receives rainfall mainly during the Indian Summer Monsoon (ISM) season of the year (Jun–Sep). The socioeconomic conditions of most of the developing countries in this region largely depend on the ISM rains. It also played important roles in rise and collapse of ancient civilizations in this region. However, the influence of the ISM on Indian ancient civilizations has not yet been fully explored though there were some attempts to correlate monsoon variation with their rise and fall. For example, in the mid to late Holocene period, Indus Valley or Harappan Civilization flourished in the western part of India from its early development, through its urbanization and eventual transformation into a rural society. Probably a prolonged decrease in the ISM rainfall caused the decline in the urban phase of the Indus Civilization around the 4.2 kyr BP global climate event. Another well-recorded early Holocene global climate event is the 8.2 kyr BP cooling event which also reportedly influenced ISM significantly, but its impact on human settlement is not clear in this region. The present study is a comprehensive review of the archaeological and climatological researches carried out on the role of ISM variability on the rise and fall of ancient Indian civilizations for the most part of the ongoing interglacial period, the Holocene. The review covers the studies on the period of the last 10 kyr as evidence suggests that human settlement and cultural developments in this region started around the beginning of this period. We have noted that the existing studies are mostly restricted to vague qualitative analysis of the weakening/strengthening of the ISM, and researches related to quantitative estimations of changes of the monsoon strengths and durations of drought events that caused collapse of civilizations are limited. Therefore, in the present analysis, emphasis has also been given on the requirement of estimating the absolute changes that might have caused cultural shifts. Some possible ways to quantitatively estimate the changes of some climate parameters are discussed.

**Keywords: ancient civilization, Indian summer monsoon, paleoclimate records, stable isotopes, Holocene**

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## INTRODUCTION

### A Brief History of Ancient Civilizations in the Indian Subcontinent

There is a long history of rise and fall of civilizations in the Indian subcontinent. The existing records indicate that there was human occupation in North India about 30 kyr BP (Singh et al., 1999) though settled life probably started around early Holocene time. The old Indian civilizations were mostly developed on alluvium (Giosan et al., 2012; Macklin and Lewin, 2015), in dry environments with their farming dependent on natural inundation or controlled irrigation from river water. These early civilizations were vulnerable to political as well as environmental stresses, and the factors responsible for the decline and collapse of many of them have been debated (McAnany and Yoffee, 2010; Butzer, 2012). From the climatological point of view, some major causes of cultural abandonment were prolonged drought, e.g., the Indus (Staubwasser et al., 2003; Giosan et al., 2012; Kathayat et al., 2017), destructive floods, e.g., Huang He (Kidder et al., 2012), abrupt reductions in river flow and river water availability, e.g., Nile in Nubia (Macklin et al., 2013), and prolonged salinization of soil, e.g., Euphrates (Jacobsen and Adams, 1958). Available studies mostly point to climate change or, more precisely, significantly low ISM rainfall for a prolonged period of many years as the cause of the collapse of the ancient Indian civilizations.

Agricultural practices in Central India probably started around early Holocene. Based on pollen analysis, Quade et al. (2013) suggested that the agricultural activity in Madhya Pradesh, India, started about 9 kyr BP. The authors also observed humid conditions and increased agricultural activities between 7 and 4 kyr. Evidence of transformation from hunter-gathering to communities with settled agriculture and domestication of animals was reported at Mehrgarh (now in Pakistan) around the early phase of Holocene. The earliest available settlement at Mehrgarh dates back to ~ 9 kyr BP (Jarrige and Lechevallier, 1979; Jarrig, 1981; Jarrig, 1993) which coincides with a humid phase of the ISM (Fleitmann et al., 2003; Gupta, 2004). Existence of agricultural activity in central India about 7 kyr BP was also reported by Yadava et al. (2007) based on earth burns, charcoals, and plant remains observed in a limestone cave located in Chhattisgarh, India. Archaeological evidence of cultivation of grains in southern Asia around 9 kyr BP was reported by Kulke and Rothermund (2004). Therefore, settled life at least in some parts of India and transition from foraging to farming and pastoralism started in early Holocene time. However, it is very complex to identify the transition time from foraging to farming in south Asia as pointed out by BarkerRichards et al. (2013) particularly due to scarcity of archaeological data. Relatively more proxy data and extensive analysis are available from the mid Holocene onward during which the region witnessed many interesting phenomena related to both climate change and archaeology as discussed below.

One of the most well-documented advanced civilizations in the subcontinent is the Harappan or Indus Valley Civilization (Kenoyer, 1997; Kenoyer, 1998; Possehl, 2002a; Madella and Fuller, 2006; Wright, 2009; Gangal et al., 2010; MacDonald, 2011; Giosan et al., 2012; Sarkar et al., 2016; Sengupta et al., 2019) which developed at the arid outer belt of ISM dominated region (**Figure 1**). The Harappan Civilization that flourished in the north western part of the Indian subcontinent was probably the largest among the 10 kyr Bronze Age Civilizations. The Harappan culture started evolving from ~5.5 kyr BP from preceding agricultural communities in the Indus alluvial plain and reached to its urban peak, i.e., mature phase during 4.5–3.9 kyr BP (Sengupta et al., 2019). The Harappans were agrarian though they were advanced in trading and architecture and designed sophisticated materials including weapons. Unlike other contemporary civilizations, Harappans probably did not attempt to control water resources by large-scale canal irrigation (Schumm, 2007). Deurbanization of Harappa or dispersion into smaller groups happened after ~3.9 kyr BP, indicated by disappearance of the special Harappan script and appearance of regional artefact and trading activities (Kenoyer, 1998; Possehl, 2002a; Kenoyer, 2006; Wright, 2009; Sengupta et al., 2019). This is often referred to as the collapse of the Harappan Civilization. The Harappan Civilization perhaps flourished on the bank of the mythological river Saraswati. The existence of the Saraswati/Ghaggar has been established recently by Chatterjee et al. (2019) using geochemical and isotopic proxies. The authors inferred that the river was active in the region for two periods in the past, namely, 80–20 and 9.4–4.5 kyr, the timing of the ultimate decline of the river coincides with the collapse of the Harappan Civilization around the beginning of the Meghalayan Stage. Causes of decline of civilizations are elaborated in *Influences of ISM on the Ancient Civilizations in Indian Subcontinent*.

After Harappa or contemporary to it, another civilization flourished in the Indian subcontinent called the Vedic Civilization approximately between 4 and 2.5 kyr BP (Pruti, 2004). Some researchers argued that the Vedic Civilization also existed in the banks of the mythological river Saraswati that was flowing in the region between Indus River in the west and Aravalli Mountain range (Singhvi and Kar, 1992; Chauhan, 1999) and claimed to be even older than the Harappa (e.g., Radhakrishna and Merh, 1999; Paliwal, 2011). However, most consensus is that the Vedic Civilization flourished between 3.5 and 2.5 kyr BP (Samanta et al., 2011). Vedic is the first historic civilization which has some written records and the name Vedic came from *Vedas*, the early literature of Vedic people. Unfortunately, its relation with Harappan is not well established. Initial Vedic culture was nomadic in nature with cattle rearing as their main occupation along with cropping practices. The later phase was dominated by agricultural activities governing the economy with decline in cattle rearing and emergence of relatively large kingdoms (Pruti, 2004).

## Indian Summer Monsson, Its Importance, Causes, and Consequences of Its Variation

The Indian Summer Monsoon (ISM) is a synoptic scale weather system and strongly impacts and contributes to shaping the socioeconomic and cultural advancement in South Asia. It is a manifestation of the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Webster et al., 1998; Gadgil, 2018). It strongly affects the hydroclimatic conditions which in turn strongly impacts the food-grain production and the Gross Domestic Product (Gadgil and Gadgil, 2006) of nearly a quarter of the global human population living in this region. Slight variations in ISM strength or its delay in the historic past caused many serious impacts on humans in economic as well as ecological aspects caused by floods and droughts (Shewale and Kumar, 2005; Cook et al., 2010; Laskar et al., 2010, Laskar A. et al., 2013a; Sridhar et al., 2015; Dutt et al., 2018; Dutt et al., 2019; Kotlia et al., 2018; Gupta et al., 2020). In the Holocene, the region experienced many droughts, mega droughts, and extreme

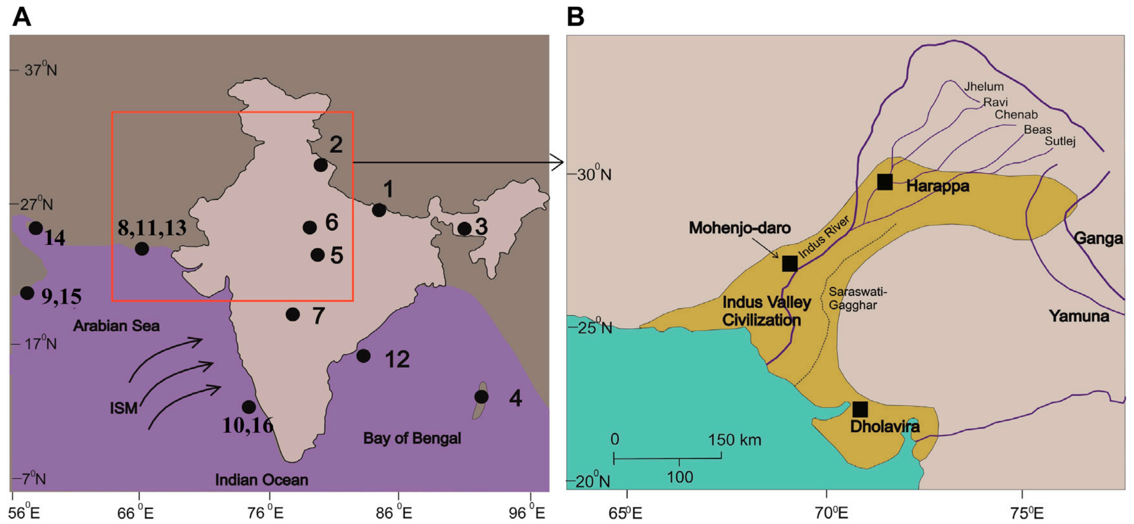

**FIGURE 1 | (A)** Map of India and its surroundings with filled circles showing the approximate locations of the sites from which the data of the proxy records are presented in **Figures 2**, **3**: 1) Ali et al. (2018), 2) Kathayat et al. (2016), 3) Berkelhammer et al. (2012), 4) Laskar A. H. et al. (2013b), 5) Dixit et al. (2014a), 6) Dixit et al. (2014b), 7) Prasad et al. (2014), 8) Staubwasser et al. (2002), 9) Gupta et al. (2003), 10) Tiwari et al. (2015), 11) von Rad et al. (1999), 12) Ponton et al. (2012), 13) Pichevin et al. (2007), 14) Sirocko et al. (1993), 15) (Altabet et al., 2002), and 16) Saraswat et al. (2013). **(B)** Regions showing the Indus Valley Civilization settlement along with major rivers. Some major excavation sites are shown by filled squares. Redrawn following Green (2021).

flooding observed by many paleoclimate researchers (Berkelhammer et al., 2010; Buckley et al., 2010; Cook et al., 2010; Sinha et al., 2011; Dixit and Tandon, 2016; Kathayat et al., 2018; Sharma et al., 2021). Many of these major climatic events are believed to cause collapse of ancient civilizations. Even in the last decade many such extreme events such as the Kedarnath flood in 2013; Kerala flood in 2019; and floods in Assam, Maharashtra, and Gujarat and glacier burst in Uttarakhand in 2021 caused severe human and financial loss (Dobhal et al., 2013; Singh et al., 2014; Rana et al., 2021). These extreme events may further intensify with greater magnitude in different geographical localities in the future with global warming (IPCC, 2013), thus jeopardizing planning strategies. Therefore, detailed analyses of the ISM in the past and how it influenced ancient inhabitants are required to understand its possible impacts. Though model forecasting and better technology would help to take preparation and minimization of loss in case any such situation arises in future, still a better understanding of the past may help to handle possible impacts in the future.

The Holocene is the current warm geological epoch, established around 11.5 kyr BP after the last glacial period. Warming during the Holocene has been associated with the increased solar insolation also termed as the Holocene Thermal Maxima (HTM). However, the temperature increase was punctured by some global cooling events. For example, events at 8.2 and 4.2 ka are identified as globally dry cool climates (Staubwasser et al., 2003; Liu et al., 2013; Dixit et al., 2014a; Dixit et al., 2014b; Banerji et al., 2020) though the exact reason for these relatively abrupt climate events remain elusive. The 8.2 kyr even was probably caused by weakening of the North Atlantic Deep Water formation resulting in the change in the Atlantic Meridional Overturn Circulation (Barber et al., 1999). The driving force behind the weakening of the North Atlantic Deep water formation was probably the glacial outburst of freshwater from Lake Agassiz into the North Atlantic (Bauer et al., 2004). The 4.2 kyr event, a multidecadal to century scale event over an extensive region (e.g., Cullen et al., 2000; Drysdale et al., 2006; Dixit et al., 2014a; Mehrotra et al., 2018), points to a global megadrought (Weiss, 2016). This event has been accepted as the formal boundary of late and middle Holocene at the global scale and the period after 4.2 kyr is called the Meghalayan age. Despite its wide spread recognition, the timing, duration, its origin in terms of changes in ocean and atmospheric circulation remain intangible. Moreover, many of the paleoclimate records do not show the evidence of the 4.2 ka event, at least as a major event of the mid-late Holocene (e.g., Seppa et al., 2009; Roland et al., 2014) and not necessarily as a cold and dry event (e.g., Railsback et al., 2018) indicating spatial variation in its impact. For example, in the regions affected by ISM, the 4.2 kyr event is not obvious in all proxy records and in the records where it is observed is mostly shown as weak ISM rather than cooling (e.g., Siroko et al., 1993). Some researchers suggested that this event is not just a single long dry event but a complex succession of dry/wet events, (Magny et al., 2009; Railsback et al., 2018). In the Mediterranean region, it is mostly considered as a dry interval as observed in many proxy records in speleothems (Drysdale et al., 2006; Zanchetta et al., 2016; Finné et al., 2017), pollen (e.g., Magri and Parra, 2002; Di Rita and Magri, 2009; Kaniewski et al., 2013), lake sediments (e.g., Zanchetta et al., 2012), and marine sediments (e.g., Margaritelli et al., 2016). Moreover, the exact timing of the event differs across proxy records (Finné et al., 2011), challenging the view that it is a global period of significant drought. Other regional to global climate events observed during the late Holocene period include the Roman Warm Period, Medieval Warm Anomaly, the Little Ice Age, and the modern warm period that influenced ISM rainfall significantly (Laskar A. H. et al., 2013b; Liang et al., 2015; Kotlia et al., 2017). Some of these events are consistent in many proxy records while some others are missing in some archives indicating their variations from region to region and nonuniform effects on different proxies. These seasonal to multidecadal climate anomalies are associated with El-Nino Southern Oscillation, Indian Ocean Dipole, North Atlantic Oscillation, Pacific Decadal Oscillation, Inter Decadal Pacific Oscillation, and Indo-Pacific Warm Pool. However, the effects of most of these forces on ISM are nonstationary (e.g., Krishna Kumar et al., 2006). Though these late Holocene climatic phenomena have drastic influence on the socioeconomy of the subcontinent and south Asian countries as discussed earlier, their effect on settlement/displacement of human civilization is probably not that severe to cause collapse of a civilizations as happened in the early to mid Holocene and hence not discussed in detail here.

The present work is an attempt to assess the details of the ISM variation in the last 10 kyr to understand its role on the rise and fall of civilizations in the north-western region of the Indian subcontinent. This is carried out by compiling the major available studies from the regions influenced by ISM during the Holocene. This study will serve to identify gaps in the regional coverage, to determine if coherent regional/subregional climatic patterns are present and expose aspects that should be addressed in future research on this topic. Another important purpose of the study is to explore the possibility of estimating quantitatively the variations of some of the past climate parameters using some recently developed proxies.

## PROXY CLIMATE RECORDS

There are multiple terrestrial and marine paleoclimate records, sensitive to changes in climate parameters available in the Indian subcontinent and surrounding regions. The present review is mainly focused on stable isotope-based proxy records obtained from oceanic and terrestrial sediments, alluvial deposits, and speleothems. The proxy records used in this review are selected on the basis of length, temporal resolution, dating quality, data interpretability, and geographic distribution. Preferences are given to the records with a full Holocene coverage that attempted to quantitatively estimate climate parameters (e.g., rainfall for ISM strength), better temporally resolving data with relatively better constrains in chronology, directly associated with one or more climate variables and geographical distribution. Locations of the proxy records included and analysed in this review are shown in **Figure 1**. All records that suit the foregoing requirements are not included, but this collection represents a substantial set of data that can serve as a base for furthering a focused study related to climate change and archaeology.

## RESPONSE OF INDIAN SUMMER MONSOON TO GLOBAL AND LOCAL CLIMATIC EVENTS DURING THE HOLOCENE

Although climate variability during the Holocene is smaller in amplitude compared to the large shifts of the last glacial cycle, they are large enough to play a major role in rise and collapse the human civilizations in various parts of the globe (e.g., Staubwasser et al., 2003; Prasad et al., 2014; Pokharia et al., 2014; Kathayat et al., 2017). A number of climate perturbations have been identified during the Holocene. For example, the early Holocene atmospheric warming, the 8.2 kyr event, the 4.2 kyr event, the Medieval Climate Anomaly, the Roman Warm Period, the Little Ice Age, and the current warm period are widely recognized climate phenomena observed during the Holocene (Gupta et al., 2003; Mayewski et al., 2004; Cheng et al., 2009; Buckley et al., 2010; Laskar et al., 2013b; Dixit et al., 2014a; Dixit et al., 2014b; Dutt et al., 2015; Kathayat et al., 2018; Kotlia et al., 2018). Based on major global abrupt climate events, the Holocene period has been divided into three substages, namely, Greenlandian (11.5–8.2 kyr), Northgrippian (8.2–4.2 kyr), and Meghalayan (4.2 kyr to AD 1950) (Walker et al., 2018; Walker et al., 2019). ISM rainfall during the early Holocene (11–7 kyr BP) was significantly higher than present and was linked to Himalayan snow cover and North Atlantic sea surface temperature along with the northward migration of the ITCZ (Wang et al., 2005; Fleitmann et al., 2007). ISM weakened around 8.2 kyr with retreat of the ITCZ southwards, reduction of the northern hemisphere ice sheet, and stabilization of the Thermohaline circulation. The subsequent monsoon strength was mainly controlled by solar insolation and position of the ITCZ. Different oceanic basins modulate ISM through ocean-atmosphere teleconnections. ISM rainfall exhibited a multidecadal oscillation mode with a significant coherence with that of the Atlantic Multidecadal Oscillation (Goswami et al., 2006).

The two well-documented global events at 8.2 and 4.2 kyr BP are identified as dry or cool climates, the onset of Northgrippian and Meghalayan stages, respectively (Barber et al., 1999). The cooling event at 8.2 kyr BP affected climate throughout the Northern Hemisphere and in Greenland (Thomas et al., 2007; Cheng et al., 2009; Liu et al., 2013; Banerji et al., 2020). Using $\delta^{18}O$ and Mg/Ca measurements of a speleothem, Liu et al. (2013) showed that climate was significantly drier ~8.2 kyr ago and lasted for 150 years, with 70 years of pronounced aridity. The timing and duration of the event corresponded with that observed in the Greenland ice cores, indicating a rapid atmospheric teleconnection between the North Atlantic and the ISM. Oxygen isotope ratios ($\delta^{18}O$) in speleothems from the ISM impacted regions also indicated a pronounced weakening of the Asian and Indian monsoons at 8.2 kyr BP that probably lasted for 100–150 years (Fleitmann et al., 2003; Cheng et al., 2009; Liu et al., 2013). Lake sediment biogenic carbonate $\delta^{18}O$ values from north-western India indicated weakening of the ISM around 8.2 kyr BP (Dixit et al., 2014b). This weakening was linked to the cooling of the North Atlantic (Staubwasser et al., 2002; Gupta et al., 2003; Cai et al., 2012) when temperatures fell by ~3°C within a couple of decades (Kobashi et al., 2007).

The cooling and arid event around 4.2 kyr BP has also been reported from various parts of the globe (e.g., Cullen et al., 2000; Staubwasser et al., 2003; Drysdale et al., 2006; Berkelhammer et al., 2012; Dixit et al., 2014a; Kathayat et al., 2018; Railsback et al., 2018). This event has been recognized in middle low latitude regions in many paleo climate records from North America, South America, Africa, China, and Antarctica

(Mayewski et al., 2004; Staubwasser and Weiss, 2006). Many archaeological studies also indicated that the 4.2 kyr event was associated with cultural shifts in Africa, the Mediterranean, Middle East, and South and East Asia (e.g., Weiss et al., 1993; Enzel et al., 1999; Cullen et al., 2000; Staubwasser et al., 2003; Liu and Feng, 2012; Weiss, 2016; Kathayat et al., 2017). It is believed that the 4.2 kyr event played a major role in the decline of the Bronze Age Civilizations, including the Egyptian Old Kingdom (Stanley et al., 2003; Ramsey et al., 2010), the Akkadian Empire in Mesopotamia (Weiss et al., 1993; Cullen et al., 2000; Weiss et al., 2012), Longshan culture in China (Chauhan, 1999; Liu and Feng, 2012), and Harappan Civilization in the Indian subcontinent (Staubwasser et al., 2003; Berkelhammer et al., 2012; Dixit et al., 2014a; Kathayat et al., 2017; Sengupta et al., 2019). The 4.2 kyr event from the ISM domain has been observed in speleothem $\delta^{18}O$ measurements from Mawmluh Cave, Meghalaya, and Northeast India (Berkelhammer et al., 2012). This record was used to define the period after 4.2 kyr as the Meghalayan Age (Walker et al., 2018). A number of proxy records from the Indian subcontinent suggest that a major weakening of the ISM occurred around or after the 4.2 kyr event (Staubwasser et al., 2003; Berkelhammer et al., 2012; Laskar A. H. et al., 2013b; Dixit et al., 2014a; Nakamura et al., 2016; Kathayat et al., 2017). The 4.2 ka event was generally described as drought for a duration of two to three centuries (e.g., Berkelhammer et al., 2012; Dixit et al., 2014b; Nakamura et al., 2016). The influence of 4.2 kyr event on ISM is discussed in more detail in *Discussion*.

Many other relatively smaller magnitude climate events impacted the ISM during the late Holocene (Laskar et al., 2010; Laskar et al., 2013a; Laskar et al., 2013b). For example, over the Bay of Bengal region, speleothem $\delta^{18}O$ records suggest a declining trend of ISM strength during 4–2.1 kyr BP and enhancement during 2.1–0.8 kyr BP, and during the transition from Medieval Climate Anomaly to the Little Ice Age (0.8–0.4 kyr BP) (Laskar A. H. et al., 2013b). The Central Himalayan region experienced a decline of ISM strength during 4–3 kyr BP and enhancement during 3–2 kyr and large fluctuations during 2.0–0.8 kyr BP and then an increase after 0.8 kyr BP (Kotlia et al., 2017; Kotlia et al., 2018). These studies suggest that the global climatic epochs have a varying degree of influence on monsoonal activity over different Indian regions. However, assessment of their influences on the human settlement/dispersion needs both high resolution archaeological and climate change data.

## INFLUENCES OF INDIAN SUMMER MONSOON ON THE ANCIENT CIVILIZATIONS IN INDIAN SUBCONTINENT

The previous perspective that Holocene climate was stable has changed with the availability of high-resolution paleoclimate records (Fleitmann et al., 2003; Gupta et al., 2003; Buckley et al., 2010; Laskar A. H. et al., 2013b). As discussed before, the Holocene witnessed many climatic events which largely impacted the human societies, vegetation, and ecology. Researchers linked many of these climatic events with the shifts of cultures in different parts of the world. However, such linkage of climate with the establishment and collapse/displacement is intensely debated due to lack of direct evidence. It is believed that abrupt and/or prolonged drought conditions led the collapse or forceful migration of many cultures mainly by affecting food and water availability (Cullen et al., 2000; Buckley et al., 2010; Liu and Feng, 2012; Dixit et al., 2014a; Kathayat et al., 2017). For example, in Tell Sabi Abyad, a Neolithic archaeological site in northern Syria, a significant cultural change was observed around 6200 BC (~8.2 kyr BP) (Balter 2010; van der Plicht et al., 2011). Evidence of many such cultural shifts has been reported in Europe and Near East associated with the aridification around the 8.2 kyr event (e.g., Migowski et al., 2006; Staubwasser and Weiss, 2006; Weninger et al., 2006; Budja, 2007; Berger and Guilaine, 2009; Gronenborn, 2009; Wicks and Mithen, 2014). However, evidence of cultural changes related to the 8.2 kyr event in the Indian subcontinent is limited by the lack of data. Though there is evidence of changes in the ISM rainfall around 8.2 kyr and some sparse evidence of human settlements in the Indian subcontinent during the early Holocene as discussed earlier, the impact of the reduction of ISM strength around the 8.2 kyr event on early Holocene human settlements is unclear.

Impacts of ISM on the mid to late Holocene Indian civilizations are generally accepted as fact. The Harappan Civilization, established around the early-mid Holocene in the Indian subcontinent, was one of the most advanced Bronze Age Civilizations. The establishment and growth of this civilization started during the phase of higher precipitation from a strong ISM. Kathayat et al. (2017), based on speleothem $\delta^{18}O$ record from Sahiya cave, showed that the mature phase of Harappan culture was the period between 4.5 and 3.9 kyr BP, occurred during a wet and warm climate. Probably the optimum climate helped in agricultural activities and urban developments for the Harappans. However, the disappearance of this civilization has been a long debated subject. Evidence suggests that the decline/displacement of the civilization started around 4.2 kyr B.P probably caused by a significant decrease in ISM precipitation resulting in insufficient moisture availability in the region to support the agricultural needs of the population (Enzel et al., 1999; Staubwasser et al., 2003; Berkelhammer et al., 2012; Dixit et al., 2014a). The deurbanization of the Harappan Civilization after the 4.2 kyr event has been discussed widely (e.g., Possehl, 2002b; Ratnagar, 2002; Kulke and Rothermund, 2004; Lawler, 2008; Wright, 2009; Petrie et al., 2017). Some initial researchers also suggested foreign invasions (e.g., Aryan invasions) into India, societal instabilities, and a decline of trade (Possehl, 2002b) as causes, but no strong evidence supporting them exists (Fitzsimons, 1970). Environmental factors such as regional aridification, hydrological changes such as reduction in water flow in the main river channel, the Ghaggar-Hakra system (Kenoyer, 1998; Radhakrishna and Merh 1999; Possehl, 2002a; Fuller and Madella, 2002; Wright et al., 2008; Sengupta et al., 2019), and land degradation due to human activity (Fairservis, 1967; Atkins et al., 1998) were also suggested to play major roles in the decline of Harappan Civilization (Kenoyer, 1998; Possehl, 2002b; MacDonald, 2011). Kathayat et al. (2017) argued that a multicentennial trend of relatively drier and cooler conditions in the Harappan region that started ~4.1 kyr ago was associated with the deurbanization phase during 3.8–3.3 kyr BP. In addition, reduced river flows in the region around this time in response to decrease in ISM rainfall over the Himalayan region were also observed (Singh et al., 1990; Phadtare, 2000). Therefore, the most plausible reason for the deurbanization/decline of the Harappan Civilization is related to climate rather than other societal related causes. Probably a combined influence of the reduction of ISM rainfall and reduced discharge from the Himalayan glaciers due to colder condition and weak ISM caused decline and forceful migrations of the Harappan settlers. Many groups probably continued after 3.9 kyr BP but in reduced sizes (Mughal, 1997; Kenoyer, 1998; Possehl, 2002a). The post-Harappan urban phase witnessed establishment of smaller agricultural and pastoral communities especially in the Himalayan foothills and western part of the Ganges basin as indicated by abundant Neolithic and Chalcolithic settlements (Kenoyer, 1998; Possehl, 2002b; Korisettar et al., 2002; Panja, 2002; Singh, 2002; Kumar, 2009; Wright, 2009; Gangal et al., 2010).

The Vedic Civilization probably ended around 2.4 kyr BP and was marked by linguistic, cultural, and political changes, as well as eastward migrations (Witzel, 1987; Kulke and Rothermund, 2004). However, it is not well established how Vedic Civilization collapsed. According to Paliwal (2011), the Vedic Civilization collapsed due to climate changes and neotectonic activities that caused wide-spread salinization of soils and formation of saline lakes in the green fertile regions of the Vedic settlements. The weak ISM during the Roman Warm Period around 2 kyr BP (e.g., Laskar A. H. et al., 2013b) could be one of the causes of the decline of the Vedic Civilization. There is some speculation that the great war of Mahabharata caused the collapse of Vedic Civilization around 2 kyr BP, though evidence to support this is unreliable.

## DISCUSSION

Some available prominent proxy records from terrestrial and oceanic archives in and around the Indian subcontinent that are sensitive to changes in the ISM strengths along with solar changes are discussed here. The major changes of the ISM observed in the proxy records and that coincided with the global climate events and collapse of civilizations are highlighted. Solar insolation data at 65° N, tropical temperature anomaly between 30° S and 30° N, and some continental proxy records from regions affected by ISM are shown in **Figure 2** (see **Figure 1** for locations of proxy records). The rainfall variation, derived using $\delta^{13}$C in soil organic matter from a site from North Sikkim of Himalayan region, influenced by ISM strength is shown in **Figure 2C** (Ali et al., 2018). The annual rainfall is reconstructed based on an inverse relation between $\delta^{13}$C values of the plants and rainfall (Kohn, 2010). In the Ganga plain, it is observed that the $\delta^{13}$C values in modern $C_3$ vegetation increase by ~0.4‰ for a decrease in annual rainfall of 100 mm (Basu et al., 2015). For the last 10 kyr, it is clear that the ISM rainfall was high during the early Holocene (10.0–8.5 kyr) and decreased after 8.5 kyr BP. The annual rainfall was relatively low during the mid Holocene and again increased in the late Holocene from 3 kyr BP onward. The lowest rainfall observed during 4.8–3.9 kyr BP (~25% lower compared to the average of the last 1 kyr) probably coincides with the global 4.2 kyr event. The significantly lower rainfall probably caused the collapse/migration of the Harappan settlers. Also the strong decrease in annual rainfall after 8.5 kyr BP probably coincides with the global 8.2 kyr event. **Figure 3D** shows the stalagmite $\delta^{18}$O variation from Sahiya cave, Uttarakhand, North India for the last 5.7 kyr (Kathayat et al., 2017). Speleothem $\delta^{18}$O is sensitive to the changes in the ISM derived rainfall in the region (Yadava et al., 2004; Sinha et al., 2015; Band et al., 2018). A sharp increase in the $\delta^{18}$O values after ~4 kyr BP is probably related to the decrease in the rainfall in response to the 4.2 kyr event. A slight difference in timing could be due to spatial variation of the influences of the ISM and differences in chronological precision. A decrease in rainfall around 4.2 kyr BP is also evident from the stalagmite $\delta^{18}$O values from Mawmluh cave, Meghalaya, NE India (**Figure 2E**) (Berkelhammer et al., 2012). This indicates that the 4.2 kyr event was wide spread in the ISM-dominated regions. However, around the 8.2 kyr event, the $\delta^{18}$O values indicate an increase in the ISM strength from the same cave unlike many other parts of the subcontinent. This region, having the highest rainfall in the world (Cherrapunji and Mawsynram are located here), due to its orography, has a different rainfall pattern than the ISM alone and probably from ISM rainfall pattern in the past as well. Influences of various climate events on ISM strength during late Holocene are shown in **Figure 2F** with high resolution stalagmite $\delta^{18}$O values from Andaman Islands (Laskar A. H. et al., 2013b). All the major climate anomalies are reflected in the speleothem $\delta^{18}$O values. These include decrease in ISM rainfall during Roman Warm Period (2.1–1.8 kyr BP) and transition from Medieval Warm Climate to the Little Ice Age (0.8–0.4 kyr BP) and increase during Medieval Warm Climate (1.2–0.8 kyr BP). The decreased rainfall around 4.2 kyr BP and a sharp increase after that is also evident in the $\delta^{18}$O values in gastropod aragonite in paleo-lake sediments from Kotla Dahar, North India (**Figure 2G**) (Dixit et al., 2014a). Also the weakening in the ISM around ~8.2 kyr is visible in the biogenic carbonate $\delta^{18}$O data from another north Indian Paleolake Riwasa (Haryana, India) (Dixit et al., 2014b). Within the Holocene, two prolonged dry periods during 4.3–4.0 kyr BP and 2.0–0.6 kyr BP were observed with multiple proxy records including $\delta^{13}$C in carbonates and organic matter in the sediments from Lonar Lake, located in the core monsoon zone of central India (**Figure 2H**) (Prasad et al., 2014). The prolonged drought event during 4.3–4.0 kyr BP coincides with the 4.2 kyr event. Another prolonged dry period was observed between 2 and 0.6 kyr BP in the Lonar lake records. Along with other proxy records, a decrease in the $\delta^{13}$C values in organic matter and carbonate was observed around the drought periods (**Figures 2H,I**) and was attributed to changes in phytoplankton metabolism from $CO_2$ to $HCO_3^-$ under reduced $CO_2$ conditions. This caused enrichment in $^{13}$C in organic matter and preferential degassing of $^{12}$C from the supersaturated carbonates in lake water. The

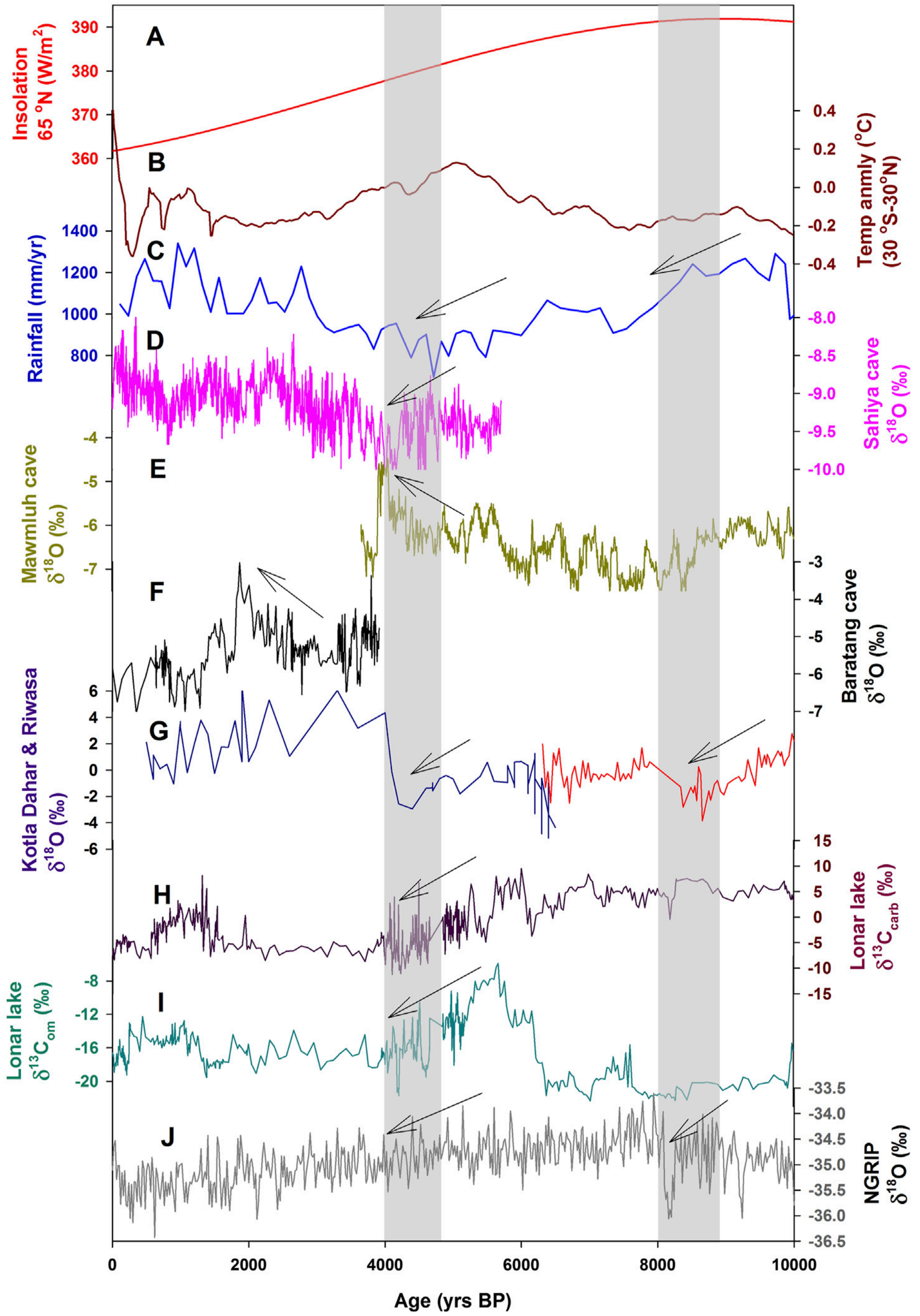

**FIGURE 2 | (A)** Solar insolation at 65°N (Laskar et al., 2006). **(B)** Temperature anomaly in the tropics (30°S–30°N) (Marcott et al., 2013). **(C)** Mean annual rainfall in the Himalayan region (Ali et al., 2018). **(D)** Sahiya cave oxygen isotope record (Kathayat et al., 2017). **(E)** Mawmluh cave speleothem δ$^{18}$O values from Meghalaya, NE India (Berkelhammer et al., 2012). **(F)** Speleothem δ$^{18}$O values from Baratang, Andaman Islands (Laskar A. H. et al., 2013b). **(G)** Lake sediment biogenic carbonate and gastropod aragonite δ$^{18}$O values from Riwasa and Kotla Dahar respectively (Dixit et al., 2014a,b). **(H,I)** Lonar lake δ$^{13}$C in carbonate and organic matter (Prasad et al., 2014). **(J)** North Greenland Ice Core δ$^{18}$O record for the last 10 kyr (Wolff et al., 2010). The shaded regions indicate the two global climate events around 8.2 and 4.2 kyr. The events are associated with significant changes in the ISM strengths and rise and fall of Indian ancient civilizations particularly around the 4.2 kyr event.

δ$^{18}$O data of North Greenland ice core (Wolff et al., 2010) are also plotted for comparison (**Figure 2J**) to assist in understanding the teleconnection with different proxy records from the ISM regions.

**Figure 3** presents some prominent paleoclimate proxy records obtained from marine sediments from the Arabian sea and Bay of Bengal, i.e., the regions affected by ISM (see **Figure 1** for locations). Oxygen isotope ratios (δ$^{18}$O) in planktonic

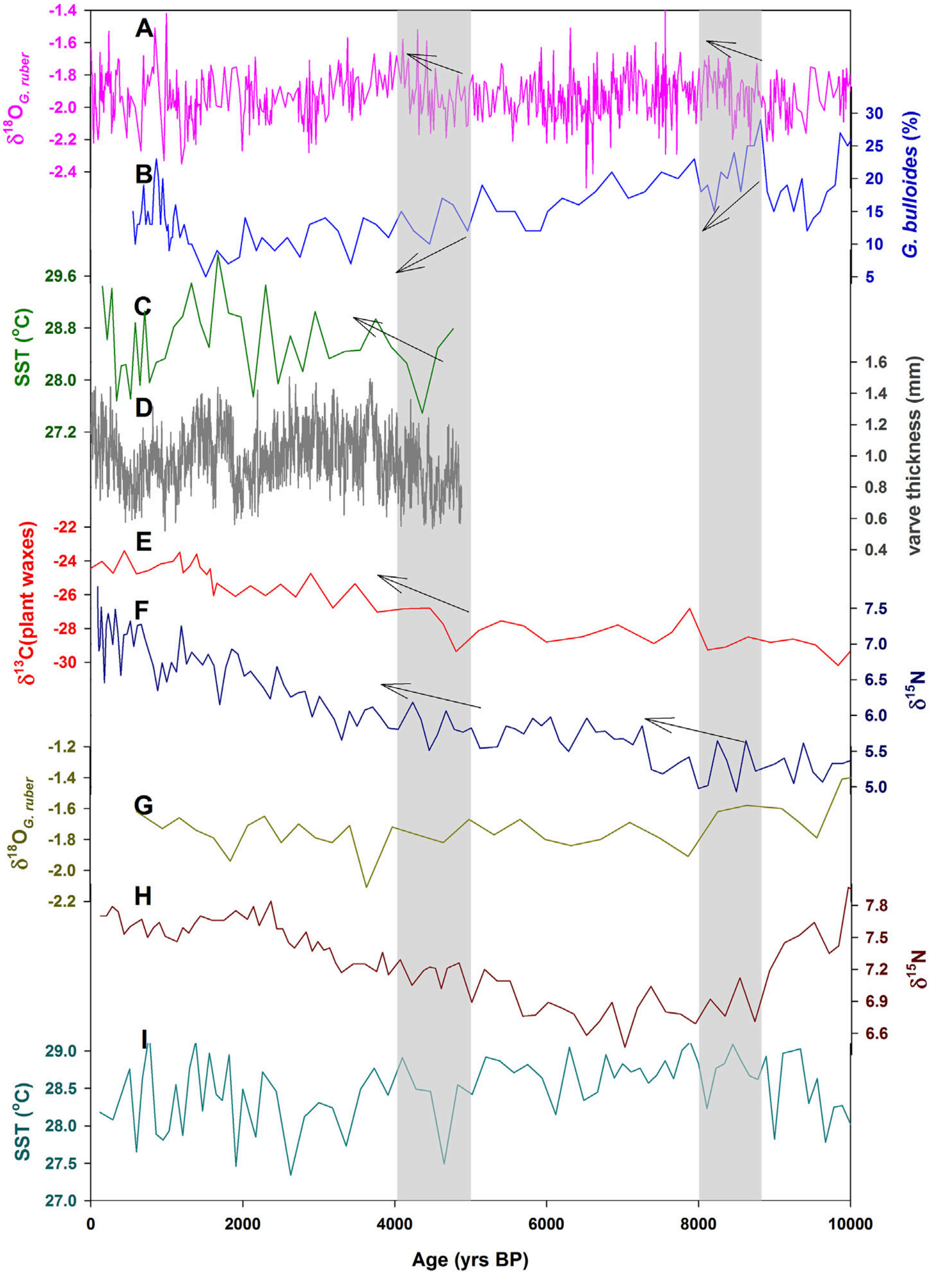

**FIGURE 3 |** Holocene marine proxy records from northern India ocean: **(A)** oxygen isotopic ratios in *G. ruber* from northern Arabian sea (Staubwasser et al., 2002). **(B)** Percentage abundance of *G. bulloides* from north-western Arabian sea (Gupta et al., 2003). **(C)** Sea surface temperature variation from Mg/Ca in the south-eastern Arabian sea (Tiwari et al., 2015). **(D)** Varve thickness from Northern Arabian Sea (von Rad et al., 1999). **(E)** Carbon isotope ratio in plant waxes from northern Bay of Bengal (Ponton et al., 2012). **(F)** Nitrogen isotope ratio in sediment as an indicator of denitrification and nitrous oxide emission in Arabian Sea (Pichevin et al., 2007). **(G)** Oxygen isotope ratio in *G. ruber* from Arabian Sea (Sirocko et al., 1993). **(H)** Nitrogen isotope ratio in sediment as an indicator of denitrification in Arabian Sea (Altabet et al., 2002). **(I)** Sea surface temperature reconstructed from Mg/Ca in foraminifera from south-eastern Arabian Sea (Saraswat et al., 2013). The shaded portions highlight the time periods during which the two major Holocene global climate events were reported by many researchers.

foraminifera *G. ruber* from the northern Arabian Sea sediment core 63 KA for the last 10 kyr are shown in **Figure 3A** (Staubwasser et al., 2002). At this location, the variations in the $\delta^{18}O$ value in planktonic foraminifera depend on the Indus River discharge, and the latter is largely governed by the ISM strength. During strong ISM episodes, high discharge of the Indus water with lower $\delta^{18}O$ value drags down the $\delta^{18}O$ values of the surface ocean water in the coastal region and hence the corresponding values in the planktonic foraminifera decrease. Clear increasing trends of $\delta^{18}O$ values in *G. ruber* around 8.2 and at 4.2 kyr BP indicate weakening of ISM strength around these climate events. **Figure 3B** shows the foraminifer *G. bulloides* concentration variation from a sediment core recovered from an oxygen minimum zone of the continental margin of Oman in the Arabian sea. The abundance variation of *G. bulloides* has been linked with the variation of ISM. Its abundance is associated with the wind-driven upwelling and strong sensitivity to wind speed and monsoonal atmospheric pressure gradient making it a suitable monsoon indicator (Gupta et al., 2003). Sharply decreasing trends in the concentration of *G. bulloides* around 8.2 kyr event indicate a weakening of the ISM. Similarly, around the 4.2 kyr event, decreasing trend in the *G. bulloides* indicates a weakening of the ISM strength. These are correlated with the North Atlantic Oscillations. Mid Holocene to the recent sea surface temperature (SST) reconstructed from Mg/Ca ratio in planktic foraminifera in the south-eastern Arabian sea is shown in **Figure 3C** (Tiwari et al., 2015). It is observed that the SST is significantly positively correlated with the sea surface salinity and negatively with monsoon intensity with value of coefficient of determination ($R^2$) of ~0.41 for 36 data points. Stronger monsoon causes reduced salinity and SST. Increasing SST trend after 4.3 kyr BP indicates significant reduction in ISM intensity which probably coincides with the 4.2 kyr event. ISM strength that started decreasing around 4.3 kyr was low until 1.3 kyr since when it increased significantly, as indicated by the SST values. **Figure 3D** shows the varve thickness record in a continuously laminated sediment core for the last 5 kyr from an oxygen minimum zone of the northern Arabian sea (von Rad et al., 1999). Their varve thickness is an indicator of the Indus River discharge and hence ISM strength. Relatively low varve thickness before 4 kyr BP indicates weak ISM around the 4.2 kyr event. Reduced varve thickness is also observed during the Roman Warm Period (~2 kyr BP) and Little Ice Age (0.5 kyr BP). **Figure 3E** shows the carbon isotopic composition ($\delta^{13}C$) in sedimentary leaf waxes in a core collected from offshore Godavari river estuary, north-western Bay of Bengal. $\delta^{13}C$ in leaf waxes is an indicator of the proportion of C3 and C4 vegetation in the Godavari River catchments (Ponton et al., 2012). A shift in the $\delta^{13}C$ values after 4.5 kyr BP indicates an increase in the proportion of C4 vegetation in the river catchments. C4 vegetation increases with increase in aridity. Therefore, the central Indian region experienced aridity after 4 kyr BP. **Figure 3F** shows nitrogen isotopic ratios ($\delta^{15}N$) from the oxygen minimum zone of the Northern Arabian sea reflecting the denitrification and plant productivity in the region (Pichevin et al., 2007). Denitrification occurs under suboxic conditions and causes large nitrogen isotopic fractionation. Denitrification varies with local productivity and downward particle flux which in turn is linked to the strong summer time monsoon winds causing upwelling of the nutrient rich water in the northern Arabian sea. Therefore, under strong ISM conditions, denitrification increases, which leads to an increase in $\delta^{15}N$ values as more denitrification would enrich the remaining nitrate reservoir in $^{15}N$. An increasing trend of $\delta^{15}N$ after 8.1 and 4.4 kyr BP indicates weakening of ISM around these two climatic events. **Figure 3G** shows $\delta^{18}O$ values of *G. ruber* from a sediment core recovered from the upwelling region of the western Arabian sea (Sirocko et al., 1993). The change in the foraminiferal $\delta^{18}O$ is attributed to the change in ISM. A shift towards lower $\delta^{18}O$ values can be due to one or more of the following reasons: an increase in precipitation or decrease in evaporation, an increase in the proportion of Gulf outflow water with relatively lower $\delta^{18}O$ values, a change in the seasonal growth of the *G. ruber* species, or an increase in the SST (Sirocko et al., 1993). Relatively higher $\delta^{18}O$ values around 8.2 kyr probably indicated weaker ISM precipitation though the other factors mentioned above can also be partly responsible for the increased $\delta^{18}O$ values. However, the change around the 4.2 kyr event is not obvious in this sediment isotope record probably due to coarser time resolution. **Figure 3H** shows $\delta^{15}N$ values in a sediment core recovered from the Oman continental margin of the Arabian Sea reflecting the denitrification and productivity in the region. As mentioned before, denitrification in Arabian sea is controlled by ISM strength. For the period of last 10 kyr, weaker ISM was observed during 8.7–5.7 kyr BP indicated by low $\delta^{15}N$ values. The $\delta^{15}N$ values started increasing from 5.7 kyr BP indicating strengthening of ISM. **Figure 3G** shows centennial scale SST reconstructed from foraminiferal Mg/Ca ratio in a sediment core from south-eastern Arabian Sea. However, the sharp Holocene climatic events such as those observed around 8.2 and 4.2 kyr BP are not very clear in this sediment record probably because of its relatively coarser time resolution and core location.

A number of global climate events influenced the Holocene ISM rainfall including the two major events around 8.2 and 4.2 kyr BP and are evident in most of the terrestrial and oceanic proxy climate records. The changes in the proxy records in the terrestrial archives are larger in magnitude due to direct influence from ISM rainfall, and the signals are dampened in the oceanic reservoir due to its large size and slow response. It is to be noted that the two climatic events are not obvious in all the climate proxy records obtained in different geographical locations and, as mentioned before, there are differences in the timing of the events indicating spatial variation of the influences of ISM. We also note that there are climatic events comparable to the 8.2 or 4.2 kyr BP in some of the proxy records but not highlighted as much as these two events. Probably those events were confined to regional scale and are not reflected at global scale. It is also important to address how these local climate events influenced the human settlements. This needs further focused studies with better constrained chronology, wider geographic distribution, and quantitative analysis. Some possibilities for quantitative studies are discussed below.

## OUTLOOK

There are two important aspects that need to be addressed to better understand the timing and causes of falls of ancient Indian civilizations. First, more archaeological data from the existing and new archaeological sites are required for understanding the timing of evolution of various civilizations and their terminations. There are many unexplored archaeological sites in the subcontinent and they can be used for this purpose though the majority are not easily accessible for political reasons. Second, more focused studies on quantitative estimates of the changes in climate parameters such as temperature and rainfall that favored/disfavored the ancient settlers with better chronological constraints are required. Most of the available studies used strengthening/weakening of the Indian Summer Monsoon qualitatively. It is important to obtain quantitative estimates of the extent of increase/decrease of the monsoon strengths at different ancient periods that are societally relevant. This would help to better manage future climate catastrophes. The role of change in air temperature might have influences on human settlements as well. It is important to see if prolonged drought periods were associated with any increase in regional air temperatures significantly. Tree ring is one of the best terrestrial paleoclimate records and can improve our understanding of the past monsoon and temperature variation. Unfortunately, the available dendroclimatology studies from India and surrounding regions do not cover the time periods of most of the ancient civilizations (Yadav, 2009; Yadav, 2013). With tree ring data covering the periods of interest, it is probably possible to better understand the monsoon variability at higher temporal resolutions.

Many of the aforementioned proxy records are controlled by combined influences of rainfall, evaporation, and temperature (e.g., $\delta^{18}$O in speleothems, foraminifera, and lake sediment carbonates), and it is difficult to disentangle the signatures. For example, tropical speleothem $\delta^{18}$O values are interpreted based on amount effect in many studies (Yadava and Ramesh, 2005; Laskar A. H. et al., 2013b), but this effect is absent or feeble in many ISM dominated regions (Laskar et al., 2015; Lekshmy et al., 2014). Even in the regions influenced by the amount effect, the rainfall variation explains the $\delta^{18}$O variability partially making it difficult for a quantitative reconstruction of past rainfall. Therefore, it is important to look into new experimental and modelling techniques for quantitative reconstruction of paleomonsoon and temperature. Carbonate clumped isotope thermometry (e.g., Ghosh et al., 2006; Laskar et al., 2016) has the potential to independently constrain the temperature and can be combined with conventional oxygen isotope ratios to quantitatively estimate the rainfall variation in some paleoarchives. However, the thermometer has not been successfully applied to reconstruct temperatures from cave carbonates, but it has potentials in sediment carbonates (e.g., Quade et al., 2013; Beverly et al., 2021). With the advances of techniques, it is possible to constrain the absolute changes in temperature to a precision of 1–2°C (Thiagarajan et al., 2014; Tripati et al., 2014). Once temperature is constrained, the changes in the $\delta^{18}$O values probably would help to quantitatively estimate the changes in the rainfall. Another recently developed proxy is the triple oxygen isotopic composition which can also be applied in carbonate archives (Passey et al., 2014; Sha et al., 2020). It depends on the extent of kinetic isotopic fractionation during carbonate precipitation, which in turn depends on the ambient relative humidity. The new experimental measurements can be combined with model data to quantitatively reconstruct the past rainfall and temperature variation.

## SUMMARY

We have discussed the cultural shifts in the Indian subcontinent and reviewed some important marine and terrestrial climate data for the last 10 kyr from the ISM dominated regions to understand the role of monsoon on rise and collapse of the ancient Indian civilizations. The human settlement and agricultural activity in Indian subcontinent probably started around 9 kyr BP as evident from multiple archaeological findings. The two major climate events at 8.2 kyr and 4.2 kyr BP are evident in most of the climate proxies. Though the 8.2 kyr event influenced the ISM significantly, but its role on the civilization is not obvious mainly due to lack of early Holocene archaeological data in the Indian subcontinent. The collapse of the Harappan Civilization was probably due to the weakening of the Indian Summer Monsoon after 4.2 kyr BP as indicated by many climate proxies. We observed that most of the available paleoclimate records discussed the monsoon rainfall change qualitatively. It is extremely important to quantitatively obtain estimates of the various climate parameters including change in rainfall and temperature that probably caused the collapse of the civilizations. Some recently established paleoclimate proxies such as carbonate clumped isotope thermometry along with conventional oxygen isotope ratios in carbonate archives can probably disentangle the temperature and rainfall signature and help to estimate the rainfall variation quantitatively. Further combined analysis of multiple proxies in high resolution paleoclimate archives, precise dates of diverse archaeological samples, and more extensive paleoclimate model studies may help enhance our understanding of the rise, evolution, and collapse of early human civilizations and impacts of climate change on them.

## DATA AVAILABILITY STATEMENT

The data reviewed in the present study are available with the original publications and are cited at the appropriate places of the article; further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

AL formulated the study and wrote the manuscript in discussion with AB. AB reviewed the manuscript.

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