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Potential influence of the Pacific Ocean on the Indian summer monsoon and Harappan decline

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ABSTRACT

Harappan agriculture and urban water usage were likely sensitive to variations in Indian Summer Monsoon (ISM) rainfall. The strength of the ISM displays negative correlations with sea surface temperatures (SST's) in the eastern and central equatorial Pacific Ocean and with El Niño events and is positively correlated with temperatures in the western equatorial Pacific. The development, decline and disappearance of Harappan civilization between ~9000 and 3000 cal BP occurred against an environmental backdrop of decreasing northern hemisphere insolation, decreasing western equatorial Pacific SST's and increasing frequency and amplitude of ENSO events. Macro-regional paleohydrological records sensitive to the strength of the Indian Monsoon generally show increasing aridity and variability over this period consistent with the changes in insolation and the Pacific Ocean. Evidence also exists for a pronounced increase in aridity in the late Holocene and a particularly steep drought at ~4200 cal BP. However, the initiation of transition to the deurbanized Late Harappan Phase may have commenced some 300 years prior to that event and the persistence of the Late Harappan Phase until 3000 cal BP suggests a more complex story than societal collapse and disappearance induced by one discrete environmental event. The continued long-term trend towards greater aridity and interannual variability during the Late Harappan Phase would have continued to present water resource challenges beyond the 4200 cal BP event and could have been a contributing factor to Harappan decline and ultimate disappearance.

1. Introduction

Over the eight decades following the announcement its discovery by Sir John Marshall, the Bronze Age Harappan Civilization of the greater Indus Valley has remained one of the outstanding enigmas in archaeology. What is known from the numerous excavations since the time of Marshall is that during the Mature Harappan Phase the civilization extended along the axis of the Indus Valley from foothills at the base of the Himalaya to the Arabian Sea (Fig. 1), was agrarian – using wheat, barley, cattle and other domesticates, included a number of large cities and numerous smaller villages, displayed social stratification, had craft-based industry and arguably possessed a written language based upon a logo-syllabic script (Bryant, 2000; Mahadevan, 2002; Possehl, 2002; Farmer et al., 2004; Ratnagar, 2006; McIntosh, 2007). The Harappan writing unfortunately remains undeciphered and the language of the Bronze Age Indus Valley remains one of the great mysteries. From the presence of Harappan artifacts in Mesopotamia and Oman, it is clear that Harappan trade linkages not only extended up and down the Indus Valley, but reached much farther, touching the Bronze Age Akkadian empire of Mesopotamia (Possehl, 2002; Ray, 2003; Ratnagar, 2006; McIntosh, 2007). To the Akkadians, the Harrapans were likely known as the Maluhha, and if this is correct then the trade-goods regularly arriving in Mesopotamia from the Indus Valley included carnelian, pearls, lapis-lazuli, wood, plants and other items (Ray, 2003). One of the most impressive remains of the Harappan sea-faring and trading infrastructure is the ruins of a port at Lothal which lies in Gujarat near the southeastern edge of the Harappan civilization (Figs. 1 and 2) (Rao, 2000; Khadkikar et al., 2004). The precise angular layout of much of Lothal, its sophisticated water systems and the scale of what is interpreted as possibly its docking basin remains impressive today – almost 4000 years after the decline and eventual abandonment of the port.

The causes of the abandonment of Lothal, along with the decline and abandonment of all the great Harappan cities such as those at Harappa and Mohenjo-Daro in Pakistan and Dholovira in India in the late 3rd and early 2nd millennium BC remains perhaps the greatest mystery pertaining to the Harappa. Not only did the urban civilization disappear, but so did the writing and most of the unique manifestations of the material culture (Lahiri, 2000; Possehl, 2002; Ratnagar, 2000, 2006; Madella and Fuller, 2006; McIntosh, 2007).

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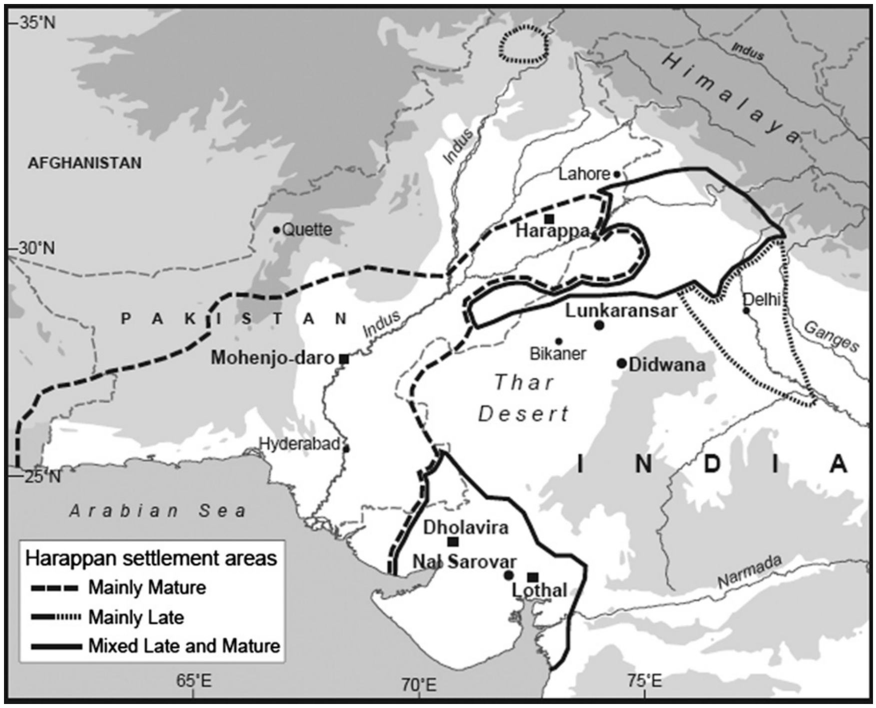

Fig. 1. Former Harappan settlement areas (temporal patterns extracted from mapped site data from Madella and Fuller, 2006) and locations mentioned in text.

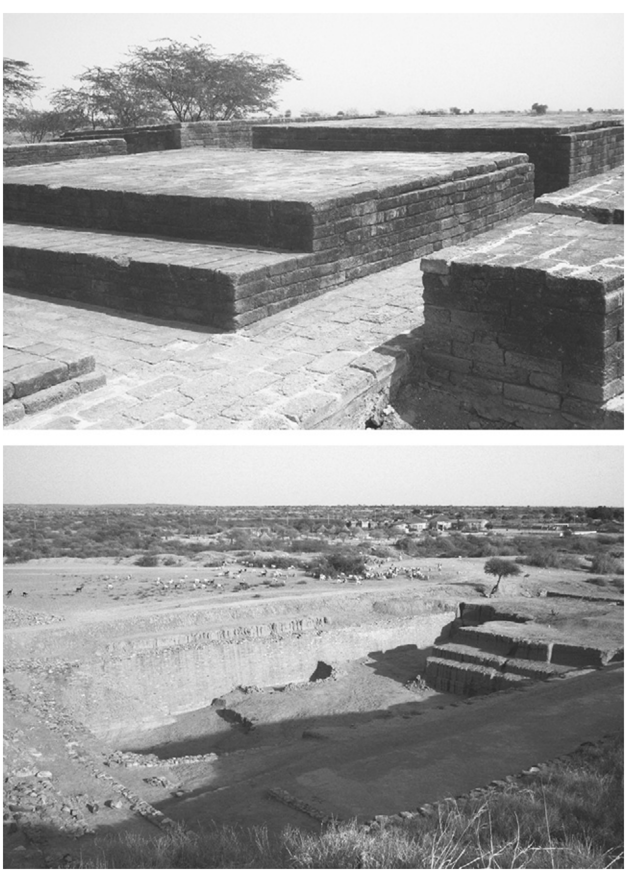

Fig. 2. Excavated ruins of Lothal (upper panel) and excavated reservoir at Dholovira (lower panel) (© G.M. MacDonald used by permission).

Indeed, so thorough was the disappearance of the Harappa that the presence of an urbanized Bronze Age society in the Indus Valley was unsuspected until the time of Marshall. There are differing subdivisions applied to the Indus archaeological record, but following the chronology of Possehl (2002) early phases in the development of agriculture and village life in the region are recognized between ~9000 and 5200 cal BP (calendar years before AD 1950); followed by the Early Harappan Phase between ~5200 and 4500 cal BP; a Mature Harappan Phase between 4500 and 3900 cal BP represented by the most abundant evidence of large urban complexes (Fig. 2), standardized seals, standardized trade weights, some standardized aspects of city planning, and trade linkages with Mesopotamia and Arabia; and a Late Harappan Phase between ~3900 and 3000 cal BP, marked by de-urbanization and eventual disappearance of distinctive Harappan artifacts. This final stage was transitional and appears to have included increased movement to village life in some regions and occasional small-scale reoccupation of some former Harappan city sites. There is also a geographic pattern of abandonment of the Indus Valley with declining occupation in the west in favor of the northern hill region, northwestern India including the westernmost Yamuna–Ganges rivers region, and Gujarat in the southwest (Fig. 1). Lothal (Fig. 2) lies in this final southeastern redoubt.

Over the past 80 years, many causes have been proposed for the decline and disappearance of the Harappan civilization. These range from Aryan invasion, to hydrological calamities related to floods, changing river courses and sea-levels, social instabilities and trade decline (Lahiri, 2000; Ratnagar, 2000, 2006; Possehl, 2002; McIntosh, 2007). From the perspectives of paleolimnology and paleoclimatology, perhaps the most intriguing debates revolve around the hypothesis that the disappearance of urbanized Harappan civilization was the result of prolonged and severe drought. An exposition of the drought theory based upon paleoecological data from lake sediments arose from the work of Singh et al. (1974, 1990) at Lake Didwana in the Thar Desert of western India (Fig. 1). In their pioneering work, Singh and his colleagues posited on the basis of palynological evidence that the florescence of the Mature Harappan civilization occurred under the favorable influence of increased precipitation and water availability during the 3rd millennium BC and the decline was brought about by subsequent increases in aridity. In a recent influential paper, Weiss and Bradley (2001) speculated that the Harappan decline may have been linked to a larger-scale climatic event at 4200 cal BP that may have produced cooling, drought and societal collapse throughout the Bronze Age world including the Akkadian empire, Old Kingdom of Egypt, the Early Bronze Age civilizations of Greece and Crete and the Harappans. The collapse of the Yangtze Civilization in China at about this time has also been attributed to the 4200 cal BP climatic event (Yasuda et al., 2004; Yasuda, 2008). However, analysis of the lacustrine sedimentological records and paleolimnoligical history of Lake Lunkaransar by Enzel et al. (1999 – Fig. 1) concluded that drying there commenced some 1000 years prior to the Harappan decline, and furthermore the peak of the Mature Harappan stage actually corresponded to an arid period typified by phenomena such as sand dune destabilization. To quote Enzel et al., "*The major Harrapan-Indus civilization began and flourished in this region 1000 years after desiccation of the lake during arid climate and was not synchronous with the lacustral phase*." (Enzel et al., 1999 p 125). There have been numerous studies using fossil pollen, charcoal, wood, paleolimnological, pedological data and geomorphology to examine Harappan-environment relations. As recently reviewed by Schuldenrein (2002), Madella and Fuller (2006), and Wright et al. (2008), the terrestrial data often provide unclear or conflicting evidence when the timing of climatic changes are compared to the history of the Harappan civilization. Alternative approaches for providing evidence of linkages between climate and Harappan history include the use of marine sediment records from the Arabian Sea and climate model simulations. Using stable isotope records from foraminifera taken from a core near the Indus Delta Staubwasser et al. (2003) produced a paleodischarge record for the Indus River and suggested that the Harappan decline was driven by a sharp drought at 4200 cal BP followed by the establishment of centennial-scale (200–800 year) drought cycles. Wright et al. (2008) used the 'Macrophysical Climate Model' to reconstruct the Holocene flow of the Beas River, which is a tributary of the Indus and has a concentration of Harappan sites. They concluded that flow in the river increased around 5800 cal BP and fell abruptly at 4100 BP, thus "*correlates nicely with the brief flourishing of Harappa*" (Wright et al., 2008, p. 37). However, with the exception of drying at around 4200–4100 cal BP, the general pattern of the Beas paleohydrology as reconstructed by Wright et al. (2008) does not match well the overall flow of the Indus as reconstructed by Staubwasser et al. (2003). Although this may be due to differences in source areas and climatologies for the Beas and other Indus tributaries, it must be remembered that Harappan decline took place across the entire Indus Valley region and likely reflects causes that had a wide, rather than local geographic scope. In their fulsome and thoughtful review of the evidence, Madella and Fuller (2006 p 1283) conclude that the current body of evidence supports the view that "*No climatic event can be blamed for a precipitous end of this civilisation, although strategic local shifts in agriculture that may have begun in response to prolonged droughts at ca 2200BC may have contributed to the de-urbanisation process and the restructuring of human communities over the following 200–300 yr.*".

It may be argued that one element missing in most considerations of the climatic history of the greater Indus region and the Harappan civilization is the potential role that the Pacific Ocean played in climatic change and climatic variability. The recent discussions of climate and the Harappan civilization are generally silent about Pacific and how changes there may have influenced the strength or variability of the Indian Summer Monsoon (ISM) and resulting hydroclimatology of western India and Pakistan. In recent years there has been a growth in knowledge regarding the relationship of the Pacific Ocean to the strength of the ISM and the impacts this linkage on modern agriculture in India. There is also increased knowledge of the Holocene history of sea surface temperatures (SST's) and El Niño Southern Oscillation (ENSO) variability in the Pacific. This preliminary consideration briefly outlines the relationship of the ISM to precipitation and summer and winter crops in the Harappan region, and also comments the role that Pacific SST's appear to play in the strength of the ISM today as deduced from the instrumental climate record. It will then consider Holocene records of hydrology in the Harappan region and beyond, records of Pacific Ocean conditions and how these might link to Holocene changes in aridity and Harappan prehistory.

2. The Harappan settlement region and the importance of the Indian summer monsoon

Today the greater Indus Valley region and core of the former Harrapan settlement area (Fig. 1), lies in a zone of marked gradients in average annual precipitation and the importance of ISM precipitation (taken here as precipitation during June, July, August and September). The strike of the axes of these gradients runs roughly parallel to the Indus Valley itself. The average daily rates of precipitation (1979–2005) for the entire year and those for the ISM period highlight the geographic and seasonal contrasts in precipitation (Fig. 3). Average daily rates of precipitation at the southwestern boundary of Harappan settlement falls to less than 0.5 mm/day (<180 mm/yr) in parts of Baluchistan, Pakistan while at the eastern edges of former Harappan settlement in India it increases to values of over 3 mm/day (1000 mm/yr) (Fig. 3). The average daily rate of precipitation during the ISM period can be well over twice the annual daily average and ranges from less than 1 mm/day in the west to over 8 mm/day in the east. Based on 20th century climate normals (1961–1990), in the eastern zone of Harappan settlement near Delhi, India the Summer Monsoon contributes over 80% of total annual precipitation, but falls to about 10% beyond the western Harappan boundary in western Pakistan.

For wide areas of the Harappan world, wheat and barley appear to have been the mainstays of their agriculture (Weber, 2003) and moisture availability during the winter growing season for these crops must have been important for Harappan agriculture. Winter crops appear to have been of less importance in southern Harappan regions such as Saurashtra where summer millets and pulses may have been more common (Madella and Fuller, 2006). In addition to food crops, cotton was an important Harappan summer cultivar (Wright et al., 2008). Summer crops would obviously be sensitive to changes in summer monsoon strength. However, historical wheat cultivation in western India provides evidence of the importance of the summer rain to the winter grain crops also and this should be taken into account when considering potential Harappan dependence upon the ISM. In the late 1990s about 80% of crop fields in Himachal Pradesh were unirrigated, greater than 95% of the farmers cultivated with animal-drawn ploughs and uneven rainfall was identified as the main climatic cause of poor yields (Acharya et al., 1998). Fields were plowed and wheat (*Triticum aestivum* L.) was sown immediately in the post-monsoon period of late September or October. The crop then depends upon the remaining soil moisture from the summer monsoon until winter rains come in December. However, in many cases the soil moisture from the summer monsoon was below optimum and this produced poor wheat yields (Acharya et al., 1998). Adequate soil moisture availability in the first 30 days after planting is essential for the survival of wheat (Acharya et al., 1998). As it happens, October is the optimal time for rainfed wheat sowing throughout the arid-regions of India

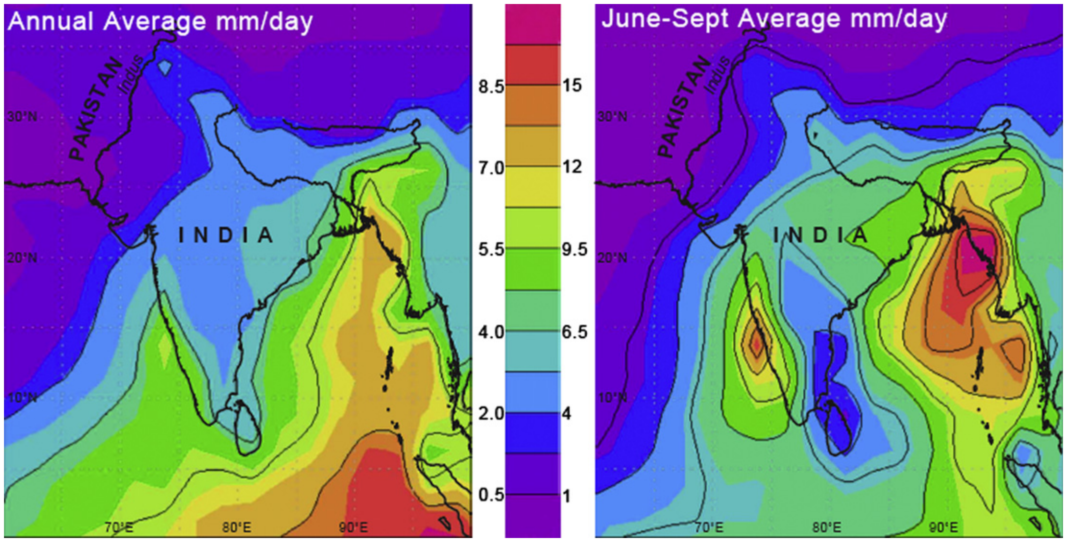

Fig. 3. Average annual daily precipitation rate and average daily precipitation rate during the monsoon season (JJAS) for India and Pakistan (CMAP data from NOAA/OAR/ESRL PSD, http://www.cdc.noaa.gov/).

(Tandon, 1993) making the ISM of critical importance to both summer crops and winter grain crop survival in the area of former Harappan settlement – a situation that was likely at least roughly similar during Harappan times.

Aside from agricultural uses, water must have been an important limited resource for Harappan cities. A hallmark of Harappan urban architecture is extensive systems for the movement and storage of water, not only to deal with wastewater, but also to capture and store run-off. A particularly striking example is the stone water channels and large reservoirs found at Dholovira (Fig. 2). Once can reasonably speculate that this infrastructure would be particularly useful in capturing and storing the higher daily rates of precipitation (Fig. 3) and episodic downpours typical of summer monsoonal precipitation. This water would then be available for consumption and other uses during the drier portions of the year.

3. The relationship of the Indian summer monsoon to the Pacific Ocean today

Conditions consisting of warmer than normal SST's in the eastern equatorial Pacific, relative cooling of the western equatorial Pacific and the resulting positive states (El Niño) of the ENSO index, have been shown to be one of the most important external forces acting upon ISM rainfall variability (Ihara et al., 2007). El Niño events typically result in increased subsidence of air over India and decreased summer monsoon precipitation (Kumar et al., 2006). Specifically, the thermocline depth in the Indonesian throughflow region between the Pacific and Indian Ocean can decrease during El Niño events, and this produces eastward migration of Pacific Walker circulation and increases subsidence over the Indian Ocean region (Fischer et al., 2005). This relationship over the 20th century is clearly apparent when the correlations between Pacific Ocean SST's and the Central Indian Monsoon Index are mapped. Some of the strongest negative correlations are found in the central and eastern Tropical Pacific while positive correlations are found in the western Pacific, particularly off Australia and near the Indonesian throughflow regions (Fig. 4). Wind patterns associated with strong summer monsoonal conditions produce enhanced upwelling and cooler SSTs in the western Arabian Sea and there is a negative correlation between SSTs there and the strength of the monsoon (Fig. 4).

A relationship between ENSO and changes in the tropical Indian Ocean SSTs and ISM strength appears to be a persistent feature of the Mid to Late Holocene, but one prone to variability due to other factors that affect SST's in the Indian Ocean (Abram et al., 2007). It has become clear recently that the strength of an El Niño event does not always predict the magnitude of ISM precipitation deficit and this may cause critical errors in drought forecasting (Ashok et al., 2001; Kumar et al., 2006; Ihara et al., 2008). For example, in 2002 India suffered one of the more severe of recorded droughts, but this event was associated with a relatively weak El Niño (Rajeevan et al., 2004; Ihara et al., 2008). Variations of SST's in the Indian Ocean may affect the strength of subsidence and aridity over India during El Niño events (Ashok et al., 2001; Ihara et al., 2008). In addition, specifics regarding the geography of central and eastern Pacific SST warming can also impact ENSO – ISM relations, with strongest droughts being associated with pronounced warming in the central equatorial Pacific (Kumar et al., 2006). Despite these other influences, as Ihara et al. (2007) demonstrate and Fig. 4 illustrates, taken over long periods a generally consistent relationship exists between Pacific SSTs and the strength of the ISM. Most importantly for issues of the impact of climate upon agriculture, summer grain yields and winter wheat yields in the states of western India (the zone of former Harappan occupation) typically show significant negative correlations with El Niño conditions as represented in June, July and August SST's in the Pacific Ocean (Kumar et al., 2004).

4. Paleohydrology during Harappan times

The work of Singh and colleagues on climate and Harappan collapse (Singh et al., 1974, 1990) was based upon analysis of lake deposits from the Thar Desert of Rajasthan and some of the most striking paleorecords of changes in Indian hydrology over the Holocene comes from the Thar and adjacent areas (eg. Singh et al., 1974, 1990; Bryson and Swain, 1981; Swain et al., 1983; Wasson et al., 1984; Prasad et al., 1997; Enzel et al., 1999). However, the archaeological record does not suggest that there was significant Harappan occupation in most of the Thar Desert (Fig. 1) and Wright et al. (2008) state "*Other data are too distant to be representative of the Harappa area. They include sediments excavated from lake beds in*

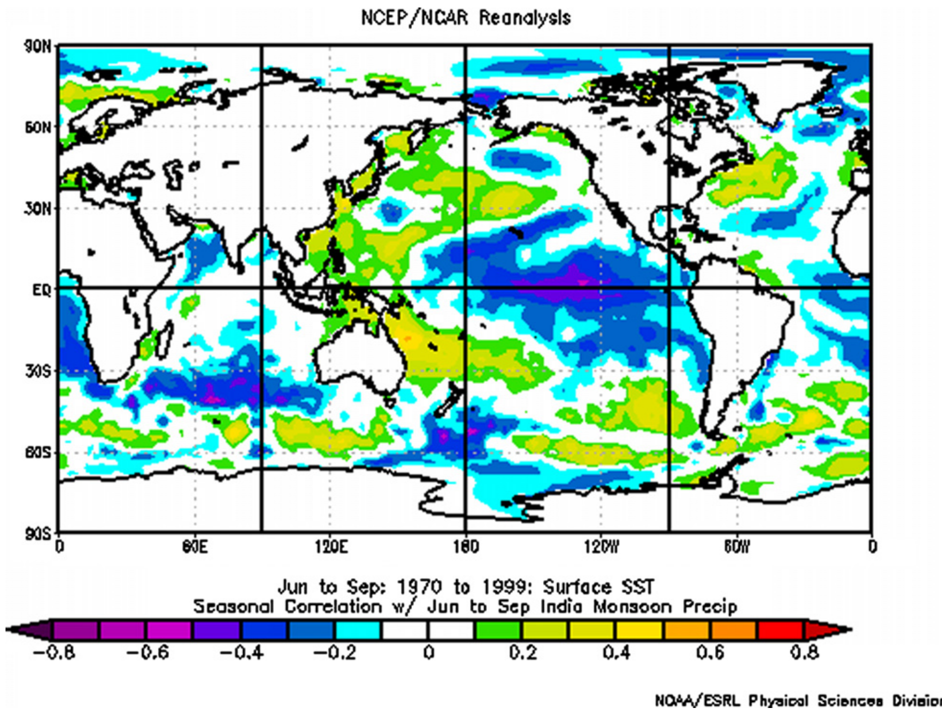

Fig. 4. Correlations between Central Indian Monsoon Index and JJAS SST's. (1970–1999) (data from NOAA/OAR/ESRL PSD, http://www.cdc.noaa.gov). Yellow and orange areas are zones where SST's display high positive correlations (>0.4) with the strength of the ISM and purple areas are zones where SST's display high negative correlations (<−0.4) with the strength of the ISM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Thar Desert (Enzel et al., 1999; Singh et al., 1974, 1990)…". This pronouncement deserves some scrutiny. The Thar Desert does lack evidence of significant Harappan occupation sites, but it is surrounded on three sides by major areas of Harrapan occupation (Fig. 1). The Thar region also sits along the same major precipitation and monsoonal gradients that typify the Harappan occupation area in the greater Indus Valley Region (Fig. 3). Significant positive correlations exist between mean annual precipitation as recorded in 20th century instrumental records (Global Historical Climatolgy Network-Monthly Data; 1900–1989 common period) from Bikaner in the Thar Desert, Lahore, Pakistan near the northern Harappan settlement area ($r = 0.434$ $p \leq 0.01$) and Hyderabad, Pakistan in the southern Harappan area ($r = 0.317$ $p \leq p$ 0.05). For comparative purposes the correlation between Lahore and Hyderabad within the Indus Valley proper is only $r = 0.266$ $p \leq 0.05$. Thus, on the basis of geographic position and modern climate linkages it can be argued that the Thar Desert paleohydrological records may have some potential to reflect larger-scale climatic trends that affect western India, adjacent Pakistan and the Harappan settlement area.

Paleohydrological reconstructions from the Thar Desert and adjacent northern Gujarat come from analysis of the sedimentology, mineralogy and geochemistry of lake sediments by Wasson et al. (1984) at the classic Lake Didwana site of Singh et al. (1974, 1990), the analysis of sediment facies and the presence/absence of gypsum by Enzel et al. (1999) at Lake Lunkaransar and the analysis of C/N rations, $\delta^{13}C$ and the presence/absence of shells at Lake Nal Sarovar by Prasad et al. (1997) (Fig. 1). In addition, pollen-based reconstructions of summer precipitation are available from Didwana and Lunkaransar (Bryson and Swain, 1981). Before discussing the profiles it should be noted though that detailed comparison is hampered by chronological uncertainties regarding the stratigraphies. Apart from the Lunkaransar sedimentological analysis, the temporal resolution of the core samples is relatively coarse. At both Didwana and Lunkaransar there are radiocarbon date inversions while at Nal Sarovar one 50 cm section of the of the sediment package was deposited in less than 300 years according to the available radiocarbon dates (Wasson et al., 1984; Prasad et al., 1997; Enzel et al., 1999). Chronological correlations using these records must remain very general in nature.

The paleolimnological and paleoclimatic records available from the lakes in the Thar Desert and Gujarat show both similarities and differences when compared to each other (Fig. 5). In all cases there is evidence that late Holocene conditions, certainly after 4000–2000 cal BP, have been arid compared to the Early and Mature Harappan Phases (~5200 cal BP to 3900 cal BP). However, the timing of the decline in moisture and establishment of relatively arid late-Holocene conditions appears to differ from site to site. At Didwana and Lunkaransar reconstructed declines in lake levels appear to have commenced possibly between 6000 and 5000 cal years BP (Fig. 5). *Typha* (cattail) pollen in early and mid-Holocene sediments of Lake Didwana (Singh et al., 1990) provides evidence of relatively freshwater conditions until the disappearance of this pollen taxa at ~5000–4500 cal BP. In contrast, the reconstruction from Nal Sarovar (Prasad et al., 1997) suggests that the decline to late Holocene aridity from moist middle Holocene conditions commenced somewhat later, between about ~4000 and 3000 cal years BP. A pollen-based reconstruction of summer precipitation at Didwana (Fig. 5) suggests a general decline throughout the middle to late Holocene. Desiccation of the sites precluded paleoclimate analysis of portions of the late Holocene pollen records from both Didwana and Lunkaransar, but the available record from the latter site also suggests drier conditions in the late Holocene relative to the middle Holocene (Fig. 5). In summary, the Rajasthan and Gujarat paleohydrological records show consistent evidence of drying in the late Holocene relative to the mid-Holocene and the Early and Mature Harappan Phases. However, there is not strong consistent evidence of any particular extreme event or step-change

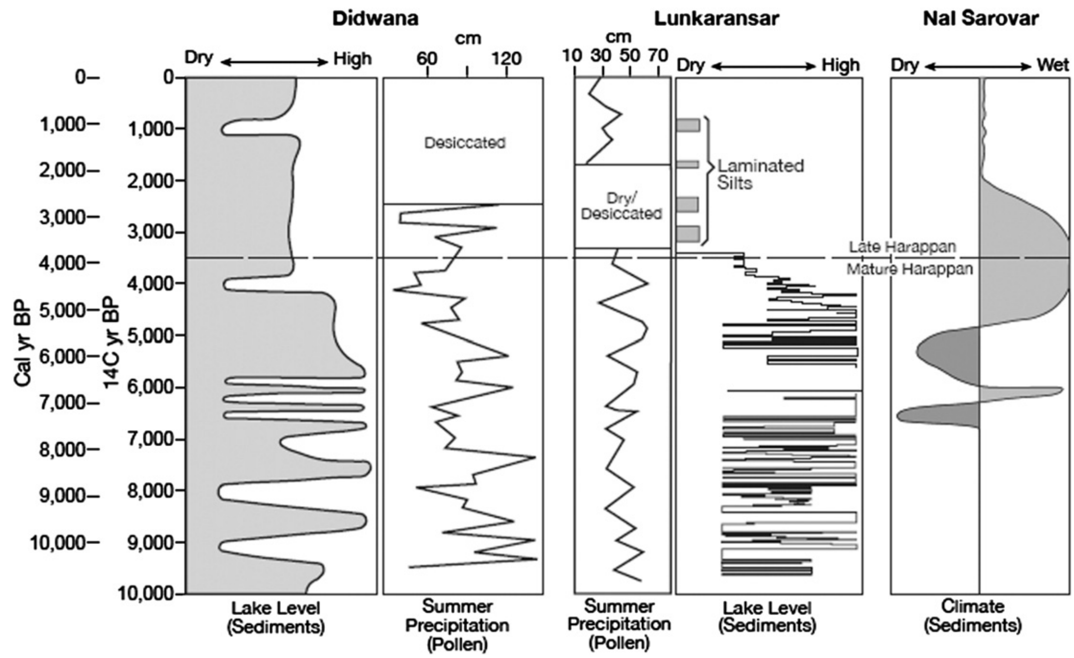

Fig. 5. Generalized lake level reconstruction from Lake Didwana (Wasson et al., 1984); fossil pollen-based estimates of precipitation from Lake Didwana and Lake Lunkaransar (Bryson and Swain, 1981); lake level reconstruction from Lake Lunkaransar (Enzel et al., 1999) and climatic reconstruction based on analysis of Lake Nal Sarovar (Prasad et al., 1997). ^{14}C chronological model and extracted environmental data excluding Lunkaransar sediment analysis from Prasad et al. (1997). cal BP chronology is approximate.

at the Mature Harappan – Late Harappan transition (~3900 cal BP). However, coarse temporal resolution for the sections and radiocarbon chronology uncertainties make definitive conclusions difficult from these data.

5. Pacific Ocean variability and regional records of paleohydrology

Paleoclimatic and paleohydrological records from several different sources can be used to provide a broader view of aridity changes in western India and Pakistan and provide a basis for comparison with paleoceanographic records from the Pacific Ocean. Seasonal changes in insolation due to variations in the Earth's orbit likely affected the strength of the ISM directly and also influenced Pacific Ocean SSTs. Taking the broad approach of considering orbital forcing, Pacific Ocean conditions and regional paleorecords offers a wider context for understanding the late Holocene aridity seen in the Thar Desert and Gujarat records and potential hydrological changes during the Harappan period (Fig. 6). Evidence of solar and Pacific Ocean forcing factors which would be expected to influence the ISM over the Holocene include calculated values for orbitally induced changes in summer insolation (JJA) at 30° N latitude (Berger and Loutre, 1991; Fleitmann et al., 2007), a stacked record of western tropical Pacific SSTs based on Mg/Ca palaeothermometry using the foraminifer *Globigerinoides ruber* from four cores (Stott et al., 2004) and a proxy record of El Niño events per-century based upon the sedimentological analysis of a core from Laguna Pallcacocha, Ecuador (Moy et al., 2002; Abram et al., 2007). Evidence of monsoon-influenced upwelling rates in the Arabian Sea has been derived from the relative abundance of the foraminifer *Globigerina bulloides* in a core taken off the coast of Yeman (Gupta et al., 2003), stalagmite records of δ^{18}O from Qunf Cave in southern Oman and Dongge Cave in western China that have been shown to be sensitive to the strength of the ISM (Dykoski et al., 2005; Wang et al., 2005; Fleitmann et al., 2003, 2007) and the δ^{18}O stratigraphy derived from the planktonic foraminifer *G. ruber* in a core from the Arabian Sea taken close to the Indus Delta that has been linked to discharge of the Indus (Staubwasser et al., 2003).

There is a general cooling of western tropical Pacific SSTs over the mid through late Holocene that was driven by decreasing summer insolation in the northern hemisphere (Fig. 6). Declining summer insolation would have caused decreased summer warming of the Indian subcontinent, and lessened the strength and extent of the ISM directly (Marzin and Braconnot, 2009). At the same time the cooling of the western Pacific would have also contributed to increasing aridity. The current ENSO system with its pattern of El Niño related changes in tropical Pacific SST's began to develop at about 7000 cal BP and became persistently frequent after about 4000 cal BP (Fig. 6) (Moy et al., 2002; Gagan et al., 2004). A recent reconstruction of Indo-Pacific SST' and ENSO variability and amplitude based upon a variety of indices including foraminiferal Mg/Ca, alkenone, and coral Sr/Ca palaeothermometers suggests that both the frequency and amplitude of ENSO events increased in unison in a long-term trend (Gagan et al., 2004). The causes for the onset of the ENSO oscillations remains a question and is likely a complex response to changing insolation, seasonality of insolation and interactions of atmospheric and oceanic circulation (Koutavas et al., 2002; Gagan et al., 2004). Increased ENSO activity would have both increased overall average aridity and variability in the ISM influenced regions.

The declines in northern hemisphere summer insolation and western Pacific SSTs are mirrored by decreases in the strength of the ISM as evidenced in the Oman and China stalagmite records (Fig. 6). In addition, there is similar evidence of a long-term trend of decreased summer monsoon strength in the western Arabian Sea foraminifer record (Fig. 6). However, these trends towards decreased monsoon strength commenced well prior to the rise and fall of the Harappan civilization. At around 3500 cal BP there commences a period of increased ENSO activity and some evidence of a slight steepening of the progression to more arid conditions in the Oman and China stalagmite records. In contrast to the other records, the Indus discharge record does not display a long-term

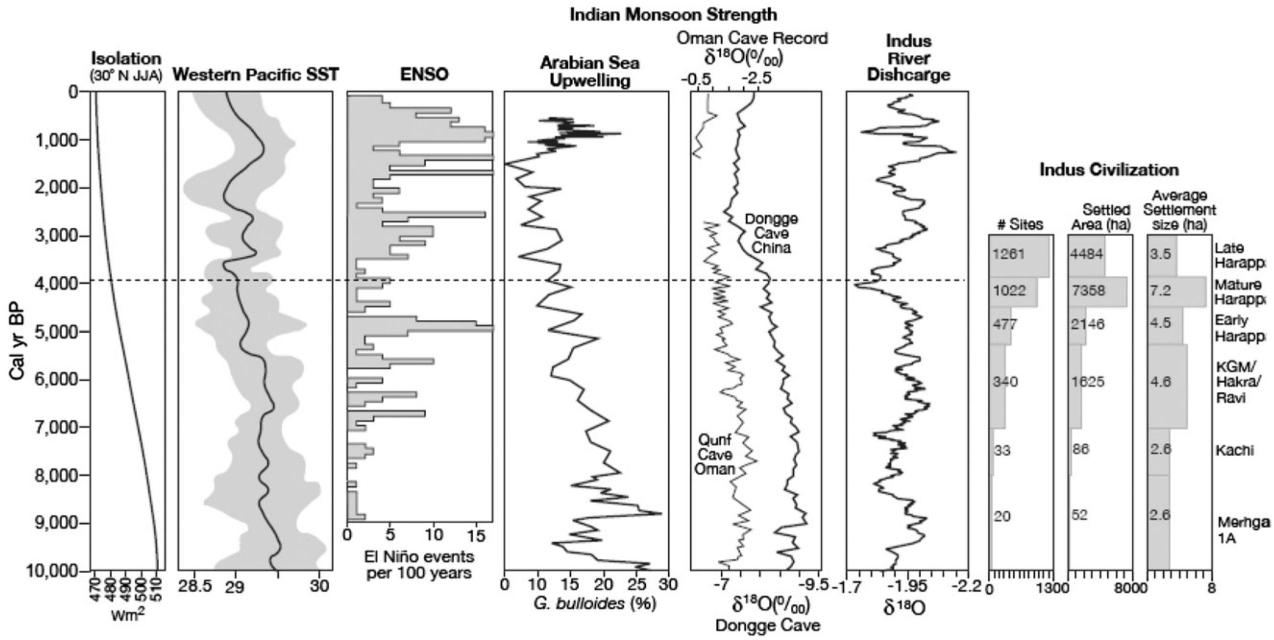

Fig. 6. Summer insolation (JJA) at 30° N (Berger and Loutre, 1991); Average stacked western tropical Pacific SST's estimates with uncertainty envelope (shaded) (Stott et al., 2004); smoothed ENSO events reconstructed from Laguna Pallcacocha, Ecuador (Moy et al., 2002; Abram et al., 2007); smoothed western Arabian Sea upwelling record related to monsoon strength (Gupta et al., 2003); smoothed cave records of Indian monsoon intensity from Oman and China (Fleitmann et al., 2003, 2007; Dykoski et al., 2005; Wang et al., 2005); smoothed paleodischarge of Indus River (Staubwasser et al., 2003); Harappan site counts and settlement area data (Madella and Fuller, 2006).

Holocene trend towards greater aridity (Fig. 6). The Indus record suggests relatively high discharges from about 6500 cal BP with a decline centered on the 4200 cal BP event (Fig. 6). The sharp decline in Indus River discharge inferred from this record corresponds generally with the Mature Harappan-Late Harappan transition. The general pattern of Indus discharge variability inferred from the Indus Delta core shows some similarity to the Didwana lake level reconstruction (Wasson et al., 1984) in so far as there is high variability prior to 7000 cal BP, relatively high and stable conditions between then and ~4500 cal BP, and then a rapid decline (Figs. 5 and 6). There is some evidence of increased variability in the western Pacific SST's, Arabian Ocean Monsoon and Indus discharge record following 5000 cal BP when the El Niño index first reaches values comparable to late Holocene peaks in El Niño frequency (Fig. 6). All of the ISM related indices (Fig. 6) display some evidence for increased in monsoon activity in the late Holocene. The reasons for this remain to be resolved.

6. Pacific Ocean variability and Harappan history

The evidence reviewed above suggests that changes in Pacific Ocean SST's could have played two roles in influencing the ISM related hydrology of western India and Pakistan during the Harappan period. First, throughout most of the Holocene there has been a gradual decline in summer insolation in the northern hemisphere and a general diminishment in western tropical SST's. The declining summer insolation and decreasing SST's in the western equatorial Pacific would have contributed to a diminishment in the strength of the ISM over this period. Around 7000 cal BP there is evidence for the development of frequent ENSO-type oscillations that would have contributed to decreasing summer monsoon strength and increasing interannual precipitation variability. Evidence for a similarly timed and relatively gradual secular decline in ISM strength comes from both monsoon related upwelling records from the western Arabian Sea and from stalagmite records from Oman and China that are sensitive to variations in the ISM (Fig. 6). There is also evidence of increased variability in the Arabian Sea upwelling record as the Holocene progressed and particularly after the frequency of ENSO events increased after ~5000 cal BP (Fig. 6). In terms of large-scale Holocene hydroclimatology the development and eventual decline of Harappan civilization can be considered to have occurred against a background of a long-term trend towards diminished summer precipitation and greater interannual monsoon variability. This view is consistent with the surmises of Madella and Fuller (2006 p 1283) that "*Harappan urbanism emerged on the face of a prolonged trend towards declining rainfall*".It is clear the changes in the Pacific Ocean likely contributed to both increasing summer aridity and increasing summer precipitation variability during this period.

The paleolimnological record from Didwana and the Indus River discharge reconstruction suggest that aside from a long-term secular trend of increasing aridity and variability in the strength of the ISM there may have been an episode of pronounced drought at around 4000 cal year BP (Figs. 5 and 6) that may well relate to the 4200 cal BP event that has been posited to have had widespread negative impact on Bronze Age societies both west and east of the Indus Valley (Weiss and Bradley, 2001; Staubwasser et al., 2003; Yasuda et al., 2004; Yasuda, 2008). However, if Harappan chronologies are correct the Mature Harappan – Late Harappan transition may have occurred several hundred years after the 4200 cal BP event. In any case, the decline and disappearance of the Harappan civilization during the Late Harappan Phase extended over almost 1000 years between ~3900 cal BP and 3000 cal BP and simply cannot be attributed solely to one discrete event. During this relatively long Late Harappan Phase the continued long-term decrease in summer insolation, cooling of the western equatorial Pacific and increase in ENSO variability suggest the Late Harappan Phase may have been typified by a continued trend of increasing summer water scarcity and precipitation variability. These continued trends would likely have continued to exacerbate water resource challenges. The abandonment of the relatively dry western Indus region, including the urban centers of Harappa, Mojeno-Daro, and Dholovira, and shift of the population centers eastward to Gujarat and the general region of the western Ganges Plain (Fig. 1) in the Late Harrapan Phase are consistent with a decrease in the strength and geographic penetration of the ISM and a concentration of Harappan populations to moister regions with perhaps less variable monsoon rainfall. The shift of Harappan settlement patterns away from large urban centers to smaller villages may have also been a response to resource limitations brought on by increasing aridity. The disappearance of most manifestations of Harappan material culture suggests though that these strategies may have been ultimately unsuccessful to maintain traceable cultural continuity.

Although it can be argued that increasing drought and aridity, some of which was likely produced by changes in the Pacific Ocean, may have contributed to the decline of the Harappans, it is also the case that aridity and drought, along with changing geographic patterns of water availability, may have well contributed to what the Harappan civilization was. The extensive and sophisticated water collection and storage infrastructure typical of Mature Harappan cities such as Dholavira (Fig. 2) are the remaining physical manifestations of a society addressing the challenges of general water scarcity and water supply variability through pioneering technological innovation. The geographic disposition of the population through its history and shifts in geographic location and settlement style in response to river channel abandonment or decreasing monsoon strength and increasing precipitation variability in the Late Harappan Phase are seemingly rational responses to progressive water challenges. What remains unclear is what internal or external factors were most important, or what specific social or environmental tipping-point was reached, that made it impossible for the Harappan civilization to persist, much less resume its earlier urbanized form in the long slide to extinction of the archaeologically visible culture in the 2nd millennium BC.

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