



Circum-Indian ocean hydroclimate at the mid to late Holocene transition: The Double Drought hypothesis and consequences for the Harappan

Nick Scroton^{1,2,3}, Stephen J. Burns¹, David McGee², Laurie R. Godfrey⁴, Lovasoa Ranivoharimanana⁵, Peterson Faina⁵

¹Department of Geosciences, 611 North Pleasant Street, University of Massachusetts Amherst, MA 01030, USA

²Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

³School of Earth Sciences, University College Dublin, Bellfield, Dublin 4, Ireland

⁴Department of Anthropology, 240 Hicks Way, University of Massachusetts, Amherst, MA 01003, USA

⁵Mention Bassins sédimentaires, Evolution, Conservation (BEC) – BP 906 – Faculté des Sciences, Université d’Antananarivo – 101 Antananarivo, Madagascar

Correspondence to: Nick Scroton (nick.scroton@ucd.ie)

Abstract

The decline of the Mature Harappan period of the Harappan civilization in and around the Indus Valley between 4.3 and 3.9 kyr BP, its transition to the Late Harappan and subsequent abandonment by 3.0 kyr BP are frequently attributed to a reduction in summer monsoon rainfall associated with the 4.2 kyr event (4.26–3.97 kyr BP). Yet while the 4.2 kyr event is well documented in the Mediterranean and Middle East, its global footprint is undetermined, and its impact on monsoon rainfall largely unexplored. In this study we investigate the spatial and temporal variability of the tropical circum-Indian ocean hydroclimate in the mid to late Holocene. We conducted Monte-Carlo principal component analysis, taking into account full age uncertainty, on ten high-resolution, precisely dated paleohydroclimate records from the circum-Indian Ocean basin, all growing continuously or almost continuously between 5 and 3 kyr BP. The results indicate the dominant mode of variability in the region was a drying between 3.967 kyr BP (± 0.095 kyr standard error) and 3.712 kyr BP (± 0.092 kyr standard error) with dry conditions lasting for at least 300 years in some records, but a permanent change in others. We interpret PC1 and the drying event as a proxy of summer monsoon variability. A more abrupt event from 4.2 to 3.9 kyr BP is seen locally in individual records, but is often not of unusual magnitude, lacks regional coherence and is of minor importance to the principal component analysis. This result does not fit the prevailing narrative of a summer monsoon drought at the 4.2 kyr event contributing to the decline of Harappan civilisation. Instead we present the “Double Drought Hypothesis”. A comparison of existing Indian subcontinent paleoclimate records, modern climatology, the spatial and temporal evolution of Harappan archaeological sites, and upstream climatic variability in the Indian Ocean and Mediterranean and Middle East indicates two consecutive droughts were contributing factors in the decline of the Harappan. The first drought was an abrupt 300-year long winter rainfall drought between 4.26 and 3.97 kyr BP, associated with the 4.2 kyr event, propagated from the Mediterranean and Middle East. This led to Harappan site abandonment in the Indus valley and the end of Mature Harappan period. The second drought was a more gradual but longer lasting reduction in summer monsoon rainfall beginning 3.97 kyr BP leading to the further site abandonment



35 at sites in Gujarat, a transition towards a more rural society, and the end of the Late Harappan. The consequences for the new
 mid to late Holocene Global Boundary Stratotype Section and Point in a stalagmite from Meghalaya are explored.

1 Introduction

The Holocene (the last 11,700 years) is being increasingly recognized as a period of significant climate variability (Fleitmann
 et al., 2003; Gupta et al., 2003; Mayewski et al., 2004). Understanding the patterns and processes of recent variability is
 40 important in understanding the modern climate system's response to perturbation. In the Northern Hemisphere mid-latitudes
 the 4.2 kyr event (4.26-3.97 kyr BP (Carolin et al., 2019)) is one of the largest climate anomalies of the Holocene (Bini et al.,
 2019; Booth et al., 2005; Kaniewski et al., 2018), representing either a relatively modest forced event such as a freshwater
 input to the North Atlantic (Wang et al., 2013), or a very large unforced event (Yan and Liu, 2019). As one of the largest
 perturbations during the Holocene, the 4.2 kyr event was recently designated as the chronostratigraphic boundary between the
 45 Northgrippian and Meghalayan subdivisions of the Holocene epoch (Walker et al., 2018).

Because of chronological uncertainties inherent in paleoclimate records, the areal extent of the 4.2 kyr BP event beyond the
 data-rich heartland of Mediterranean Europe (Bini et al., 2019) and Mesopotamia (Kaniewski et al., 2018) is unclear. In the
 tropics and monsoonal areas, climate anomalies with age uncertainties that overlap 4.26-3.97 kyr BP are often attributed to the
 50 4.2 kyr event (Marchant and Hooghiemstra, 2004; Staubwasser and Weiss, 2006). This includes dry conditions in tropical
 Africa (Marchant and Hooghiemstra, 2004), wet conditions in tropical South America (Marchant and Hooghiemstra, 2004),
 changes to ENSO (Toth and Aronson, 2019) and aridification in India (Dixit et al., 2014; Dixit et al., 2018). However, these
 changes are often significantly longer than the <300-year climatic excursion of the 4.2 kyr event and/or date to slightly later.
 The global extent of the 4.2 kyr event is uncertain.

55 The 4.2 kyr event also garners attention because of its synchronicity to major societal transformations (Höflmayer, 2017; Wang
 et al., 2016), providing test cases for exploring the role of climate in societal change (Butzer and Endfield, 2012; deMenocal,
 2001; Weiss and Bradley, 2001). For example, the end of the Akkadian civilization in northern Mesopotamia at 4.2 kyr BP
 (Weiss et al., 1993; Weiss, 1997) can be related to contemporaneous drying through the presence and provenance of a well-
 60 dated 300-year increase in regional dustiness (Carolin et al., 2019; Cullen et al., 2000).

Similar to climatic and environmental changes, societal changes in civilizations outside of Mediterranean Europe and
 Mesopotamia with age error uncertainties that overlap the 4.26-3.97 kyr BP are also often attributed to the 4.2 kyr event.
 Significant attention has been focused on the societal changes and deurbanization at the end of the Mature Harappan period in
 65 and around the Indus valley around 3.9 kyr BP (Dixit et al., 2014; Petrie et al., 2017). The Mature Harappan describes an



approximately 700-year long period from 4500-3800 yr BP. During this time a dense distribution of over 700 settlements, including four or five cities in Gujarat and along the Indus and Ghaggar-Hakra rivers, underwent a standardization of material culture and urban planning ((Petrie et al., 2017) and references within). The decline of Harappan civilization sees a deurbanization and migration of sites towards the headwaters of the Ghaggar-Hakra, hypothesized to reflect habitat tracking (Gangal et al., 2010). Given errors on radiocarbon ages, the timing of the decline is uncertain, beginning as early as 4300 yr BP (Sengupta et al., 2020), likely well underway by 3900 yr BP (Giosan et al., 2012). The Harappan civilization continued in a more limited form well beyond the 4.2kyr event, known as the Late Harappan. However, by 3000 yr BP, all major urban sites had been abandoned, and the Harappan had become a more fragmented rural society, based in southern Gujarat and the Ganga-Yamuna interfluvium.

An association of the end of the Mature Harappan period and the 4.2 kyr event has been widely made in the literature (Berkelhammer et al., 2012; Dixit et al., 2014; Dixit et al., 2018; Giosan et al., 2012; Kathayat et al., 2017; Staubwasser et al., 2003). The assumed mechanism is usually a decline in summer monsoonal rainfall. However, the idea has been resisted by some in the archaeological community for several reasons: 1) There is evidence for long-term drying over the course of the Holocene, suggesting that the Mature Harappan developed in response to water stress rather than pluvial conditions (Gupta et al., 2003; Madella and Fuller, 2006). 2) There is evidence for drying, adaptation and continuation within the Mature Harappan (Pokharia et al., 2017). There are also two key climate problems with this interpretation. 1) evidence for drying in the subcontinent does not typically support an abrupt 300-year long drought with subsequent return to wet conditions, as might be expected if the 4.2 kyr event were the cause (Madella and Fuller, 2006; Wright et al., 2008). Second, the most likely climate mechanism of change to the Indian Summer Monsoon, a shift in ENSO state and increased El Niño frequency, occurs 300 years too late (MacDonald, 2011). While the causes of societal decline and transitions are undoubtedly multifaceted and complex, the role of climate in the end of the Mature Harappan requires further study.

To investigate key questions concerning 1) the areal extent of the 4.2 kyr event, and 2) how climate impacted the Harappan civilization, high resolution paleoclimate records are needed. With age errors often less than 1% (Cheng et al., 2013), speleothems provide high resolution, precisely dated records of past hydroclimate changes capable of providing insight into sub-centennial scale Holocene climate variability (Bar-Matthews and Ayalon, 2011; Fleitmann et al., 2003). Recent publication of new speleothem records in the last three years from west and east India (Kathayat et al., 2017; Kathayat et al., 2018), Sumatra (Wurtzel et al., 2018), Rodrigues Island (Li et al., 2018), and Madagascar (Wang et al., 2019)(Scroxton et al., 2019), along with a high resolution sediment core from the Arabian Sea (Giesche et al., 2019), have dramatically increased the number of high-resolution paleoclimate records of the circum-Indian Ocean basin hydroclimate. The available records now cover much of the circum-Indian Ocean basin, including the west, central and east Indian Ocean, both northern



and southern hemispheres, and equatorial latitudes. The new data now allow for the statistical analysis of changes in hydroclimate and assessment of regional versus local changes.

100

In this study we investigate the spatial patterns and reach of climate variability around the Indian Ocean (hereafter circum-Indian Ocean basin) during the mid to late Holocene. We take advantage of the abundance of new paleoclimate records to investigate regional coherency (or lack of) in circum-Indian Ocean basin hydroclimate by conducting Monte-Carlo principal component analysis (MC-PCA)(Deininger et al., 2017) on a suite of high resolution, precisely dated regional hydroclimate records (Figure 1, 2, Supplementary Table 1). The speleothem records used in the MC-PCA are mostly interpreted as proxies for summer monsoon rainfall changes through regional circulation changes, regional and local rainfall amount (Supplementary Discussion 1), and have near continual coverage from 5000 to 3000 yrs BP. In addition, we also analyze three paleoclimate records from two marine sediment cores with annual laminations and proxy records interpreted as responding to terrestrial hydroclimate variability. Together these records allow us to investigate the impacts of the 4.2 kyr event on tropical Indian Ocean basin monsoonal rainfall, within the context of the middle to late Holocene.

110

2 Methods

We conducted Monte-Carlo principal component analysis (MC-PCA) on high-resolution records from the circum-Indian Ocean basin using the technique and MATLAB code from (Deininger et al., 2017). In summary: For each record, 2000 age models are created by allowing ages to vary within 1 standard deviation assuming a Gaussian distribution and then linearly interpolating between the records (Supplementary Figure 1). This creates age models with different temporal resolutions based on the sample spacing. The age models are upscaled to 15 (PCA-1, PCA-2) or 20 (PCA-3) year-long bins using a Gaussian kernel applied to all data points within the bin. Climate records are normalized to mean 0 and standard deviation 1. Principal component analysis (PCA) is then conducted to the 2000 sets of upscaled normalized proxy records. Age uncertainties can result in bimodal distributions of principal component (PC) time series. A flipping procedure is used to reinvert the flipped PCs. The final PCA time series is calculated using the mean and standard deviation for each bin. The Kolmogorov-Smirnov (KS) test is used to ensure that only statistically meaningful (95% level) principal components are analyzed.

115

120

125

PCA requires continuous, regularly spaced data. Two of the records: the KNI composite record from Australia (Denniston et al., 2013) and the AK1 record from Madagascar (Scropton et al., counterpart submission) contain short hiatuses. The hiatus in the Madagascar record is replicable across two different speleothems ((Wang et al., 2019) Scropton et al., counterpart submission) from two different caves and likely represents dry conditions rather than a drip specific or cave specific changes in ventilation. Similarly, the KNI record from Australia is composed of multiple stalagmites. The gaps between stalagmites can be treated as hiatuses in the composite record as the age models contain gaps. However, the age uncertainties are such that



the records could be considered continuous within error. We chose to treat the gaps as hiatuses. We filled in the hiatuses with
 130 dummy $\delta^{18}\text{O}$ values corresponding to dry conditions using $\delta^{18}\text{O}$ values 1.5 standard deviations above the mean $\delta^{18}\text{O}$ for each
 record between 5 and 3 kyr BP (Supplementary Figure 1). 1.5 standard deviations ensured that the dummy values were more
 positive than the stable isotopes values before and after the hiatuses (i.e. dry conditions) but did not assume that hiatuses
 represented the most positive values on the record (driest conditions). This is because speleothems drying out is likely a
 function of the length of drought as it is the severity, and as $\delta^{18}\text{O}$ is not necessarily a direct measure of rainfall amount it would
 135 be incorrect to assume a lack of growth represented the most positive $\delta^{18}\text{O}$ values for a continuous period of time. To test
 whether the dummy data had a significant effect on the MC-PCA, we conducted the analysis both with (PCA-2) and without
 (PCA-1) the Australian and Malagasy speleothem records. We found little difference between the two, suggesting the dummy
 data has little to no effect on the shape or timing of the variance explained by the first two principal components (Figure 3).

140 For the purposes of the MC-PCA code we also assumed that the two offshore Indus records (Giesche et al., 2019) had
 independent age models. As the two records are from the same core this is not true. This assumption introduces a small error
 to the MC-PCA, slightly under-estimating the similarity between the two records and over-estimating the confidence interval
 bounds in the principal component time series.

145 To detect the changepoints in PC1 we used RAMPFIT (Mudelsee, 2000; Mudelsee, 2013), a Fortran program that estimates
 change-points using a weighted least squares regression for the proxy value, a brute force search for the time value, and a
 moving block bootstrap to estimate uncertainty. We constrained the search to find one changepoint between 3.1 and 3.8 kyr
 BP and one changepoint between 3.8 and 4.5 kyr BP.

3 Results

150 To assess the commonality that might be present in circum-Indian Ocean basin hydroclimate records, we conducted three
 different Monte-Carlo principal component analyses with sets of ten high resolution hydroclimate records from around the
 Indian Ocean basin from 5000–3000 years ((Chen et al., 2016; Denniston et al., 2013; Deplazes et al., 2013; Fleitmann et al.,
 2007; Giesche et al., 2019; Kathayat et al., 2017; Li et al., 2018; Wurtzel et al., 2018), Scroxton et al., counterpart paper)
 (Figure 4, 5). The first PCA (PCA-1) was run on the five continuous speleothem $\delta^{18}\text{O}$ records from Oman, Rodrigues, W.
 155 India, Sumatra and Borneo at 15 year resolution. The second PCA (PCA-2) includes the five previous speleothem $\delta^{18}\text{O}$ records,
 plus two speleothem records from Madagascar and Australia which have short hiatuses filled with dummy $\delta^{18}\text{O}$ data. The third
 PCA (PCA-3) includes all seven speleothem $\delta^{18}\text{O}$ records, plus three laminated marine sediment core records from the Arabian
 Sea, with proxies interpreted as responding to terrestrial hydroclimate change (Table S2, Supplementary Discussion S2). PCA-
 3 was run at 20-year resolution to accommodate the lower sampling resolution of the marine sediment cores.



160

All three analyses produce similar results. The first principal component (PC1) is dominated by a gradual shift to dry conditions beginning at 3967 yr BP (± 95 yr standard error). The gradual drying indicated by PC1 is a feature of many of the original records and not the result of a regionally asynchronous abrupt transition (Figure 3). Drying associated with PC1 lasts until 3712 yr BP (± 92 yr standard error).

165

The majority of records have negative loadings on the PC1 score (Figure 4). The drying was therefore widespread across most of the Indian Ocean basin. A positive loading (wetting trend) is observed in the Borneo speleothem record. This opposite response of the Indo-Pacific Warm Pool to the more homogenous response in the circum-Indian Ocean basin suggests that zonal climatic processes may dominate over meridional processes in this low frequency variability (Denniston et al., 2013; Dutt et al., 2018; Prasad et al., 2014; Toth and Aronson, 2019).

170

The second principal component is a fluctuating wet and dry signal (Figure 3). For positively loading records (e.g. NW India): wetter conditions occur between 5.0-4.9, 4.5 to 3.7 and 3.2 to 3.1 kyr BP and dryer conditions 4.9 to 4.5 and 3.7 to 3.2 kyr BP (Figure 4). A zonal dipole is possibly also observed in the PC2 of PCA-1 and PCA-2, but this time with the Sumatra record plotting with the Borneo record with negative loadings, most records with small loadings and the western India speleothem record with positive loading.

175

For PCA-3 with the additional sediment cores, PC2 has a different shape than in the other analyses. An additional dry period is detected in PC2 between 4.2 and 3.9 kyr BP. This additional feature changes the PC2 loadings, such that only the sediment core records from the Arabian Sea (and Australia) load positively. This result is suggestive of a possible local signal of the 4.2 kyr event.

180

4 Discussion

The absence of a significant, widespread 4.2 kyr event in tropical Indian Ocean hydroclimate has consequences for the timing and causes of the deurbanization of the Harappan civilization in the Indus valley. The Harappan civilization began around 5.2 kyr BP (Possehl, 2002), reaching its peak between 4.8 and 3.8 kyr BP, during the Mature Harappan period. Cultural decline, including poor pottery craftsmanship and reduced reservoir maintenance or abandoned water reservoirs, began as early as 4.3 kyr BP (Sengupta et al., 2020) leading into the Late Mature Harappan period with societal reorganization, site abandonment and migration underway before 3.9 kyr BP (Possehl, 2002; Sengupta et al., 2020; Vahia and Yadav, 2011). During the Late Harappan period (3.9-3.0 kyr BP), technological decline, settlement size reductions and abandonment continued (Possehl, 1993; Possehl, 1997; Possehl, 2002; Sengupta et al., 2020). By 3.0 kyr BP, Post-Urban Harappan society had become rural

190



with few cultural similarities to the Harappan. Post-Urban Harappan settlements were concentrated around the Ganga-Yamuna interfluvium and southern Gujarat, which have higher summer rainfall than the Indus Plain (Gangal et al., 2010; Petrie et al., 2017). Here, we review the available archaeological, climatological and paleoclimatological evidence and propose a new hypothesis to explain the decline and abandonment of the Harappan civilization.

195 4.1 Spatial and temporal variability in Harappan site abandonment

There is geographic variation to the timing of abandonment (Figure 5, 6b). At the more northerly sites in the Ghaggar-Hakra and Indus plain, Kot Diji and Rakhighari show no dates beyond 4.25 kyr BP. Kalibangan has radiocarbon dates as late as 4.0 kyr BP but the region is largely devoid of radiocarbon dates beyond this period. Further south, sites in Gujarat consistently extend beyond 4.0 kyr BP at Prabhas Patan, Rojdi, Nageswar, Vagad, Lothal, Khirsara, Kanmer, Ratanpura and Surkotada. Of
200 note is the climatological difference between the late abandonment sites in Gujarat and the early abandonment sites in the Indus and Ghaggar-Hakra valleys (Figure. 5, 6d). The two river basins lie in the transition zone between winter dominated rainfall to the north-west and summer dominated rainfall to the south-east. Winter rainfall is largely derived from western disturbances originating in the eastern Mediterranean (Dimri et al., 2015), while summer rainfall is largely sourced from the Arabian Sea via the Indian Summer Monsoon. Therefore, more northerly sites derive a significant proportion of annual rainfall
205 from winter rainfall, while southern rainfall is almost entirely from the monsoon.

4.2 Paleoclimate records on the Indian subcontinent

Paleoclimate evidence for drying on the subcontinent between 5 and 3 kyr BP falls into three, non-mutually-exclusive temporal patterns. The first climatic change is a long-term unidirectional drying over the entire 5 to 3 kyr period. For example: a gradual change in temperature and rainfall between 4.8 and 3.0 kyr BP is observed at PT Tso Lake (Mehrotra et al., 2018).

210 The second climatic change matches the timing and style of the 4.2 kyr event in the Mediterranean, i.e. a short 300-year dry period with return to wet conditions. Paleoclimate records showing this pattern include high resolution records such as the foraminiferal *Globigerinoides ruber* $\delta^{18}\text{O}$ record (Giesche et al., 2019; Staubwasser et al., 2003) from the Indus fan, and the KM-A speleothem record from Mawmluh Cave (Berkelhammer et al., 2012). Lower resolution records include lithology,
215 pollen, biomarkers and trace elements from Lonar Lake which suggest a dry period from 4.6 to 3.9 kyr BP, peaking at 4.2 to 4.0 kyr BP, with wet conditions continuing until 3.7 kyr BP (Prasad et al., 2014).

The third climatic change is a 4.0 to 3.5 kyr BP gradual drying. It is typically associated with wet conditions between 4.5 and 4.0 kyr BP and sometimes a partial recovery from 3.5 to 3.0 kyr BP. This third pattern is observed in the Sahiya Cave
220 speleothem $\delta^{18}\text{O}$ record (Kathayat et al., 2017), the *Neogloboquadrina dutertrei* $\delta^{18}\text{O}$ record from the Indus fan (Giesche et



al., 2019), and the speleothem $\delta^{18}\text{O}$ records of stalagmites ML.1 and ML.2 from Mawmluh cave (Kathayat et al., 2018). For a full discussion of the Mawmluh cave records see section 4.5.

Expressions of the third pattern in lower resolution or short paleoclimate records include abrupt drying at paleolake Kotla
 225 Dahar at 4.1 kyr BP as recorded in ostracod $\delta^{18}\text{O}$, with no recovery (Dixit et al., 2014). Wet conditions at Surinsar Lake
 occurred between 4.4 and 4.0 kyr BP (Trivedi and Chauhan, 2009). While likely also influenced by westerlies, the Puruogangri
 ice cap is interpreted as a tropical record (Thompson et al., 2006). Ice cap $\delta^{18}\text{O}$ shows a decrease starting at 4.0 kyr BP with
 partial recovery at 3.4 kyr BP. The Didwana salt lake became ephemeral around 4.0 kyr BP (Singh et al., 1990). Gradual drying
 is recorded in peat bog pollen from Garhwal between 4.0 and 3.5 (Phadtare, 2000), and in speleothem $\delta^{18}\text{O}$ from Sainji Cave
 230 between 4.0 and 3.5 kyr BP (Kotlia et al., 2015). The paleolake Karsandi record shows wet conditions from 5.1 to 4.5 kyr BP,
 followed by drying (Dixit et al., 2018). The length of drying is unknown due to an undated massive gypsum layer, but there is
 partial recovery prior to 3.2 kyr BP. A stalagmite from Dharamjali Cave in the Himalaya shows a gradual drying trend between
 3.7 and 3.2 kyr BP (Kotlia et al., 2018). Similar changes are also observed in peninsular India, with a period of wet conditions
 followed by dry conditions between 4.5 and 3.3 kyr BP observed in the lake pollen record from Shantisagara Lake (Sandeep
 235 et al., 2017).

The three groups are not mutually exclusive. The Lake Rara Mn/Ti record shows a weak monsoon starting early at 4.7 and a
 partial recovery at 3.5 kyr BP (Nakamura et al., 2016). Similarly, the Lake Agung Co carbonate $\delta^{18}\text{O}$ shows a gradual drying
 trend, but with termination of deposition at 3.9 kyr BP (Morrill et al., 2006). Meanwhile the Al/Ca record of Tso Moriri shows
 240 wetter conditions from 5.32 to 4.35 kyr BP, followed by a dry excursion that lasts until 3.4 kyr BP (Dutt et al., 2018). The
 multiproxy Tso Kar lake record shows a unidirectional drying transition starting around 4.8 kyr BP, with driest conditions
 around 4.2 kyr BP (Wünnemann et al., 2010).

All of these paleoclimate records are proxies for parts of the hydroclimate system. However, they cannot all be recording
 245 regional variability in the summer monsoon. Instead different proxy systems might record local effects, have variable system
 memory, be affected by changing temperatures, evaporation rates and cloud cover differently, or show sensitivity to different
 seasons. To elucidate which pattern might correspond to which season or climatic control, we compare the three Indian
 subcontinent hydroclimate patterns with wider regional hydroclimate.

4.3 Regional climate drivers

250 The gradual drying seen in some Indian subcontinent paleoclimate records between 5 and 3 kyr BP is likely part of the gradual
 reduction in northern hemisphere tropical and subtropical rainfall over the course of the Holocene (Haug et al., 2001; Schneider
 et al., 2014). This underlying secular trend in Holocene climate is caused by decreasing summer insolation from changing



orbital precession. In the Indian Summer Monsoon domain this trend is clearly expressed in full Holocene length speleothem records from Oman (Fleitmann et al., 2003) and Mawmluh Cave (Berkelhammer et al., 2012). A gradual trend in forcing can
 255 lead to threshold changes in climate due to feedbacks in the climate system, e.g. the termination of the African Humid Period (Tierney and deMenocal, 2013). Therefore, unidirectional drying events on the Indian subcontinent throughout the Holocene may be due to threshold effects and local feedbacks on this secular trend.

The second climate signal in the Indian subcontinent is an abrupt drying between 4.2 and 3.9 kyr BP with a return to wet
 260 conditions afterwards. This signal matches the expression of the 4.2 kyr event in the Mediterranean and Middle East as a major drought (Figure 6c). Western disturbances bring winter rainfall from the Mediterranean across the Middle East to the Indus valley, controlling both winter rainfall, and spring river flow via winter snowfall in the Himalayas (Dimri et al., 2015). Carbon isotope values of rice grains, a summer crop, show increased drought only after 4.0 kyr BP in both Gujarat and Indus valley locations, indicative of no substantial change to summer rainfall between 4.2 and 3.9 kyr BP (Kaushal et al., 2019). The 4.2
 265 kyr event is likely to be a winter rainfall drought, with weakened western disturbances originating in the Mediterranean reduced winter rainfall in the Indus valley (Dimri et al., 2015; Syed et al., 2006). However, the exact climate driver is unclear. While a negative excursion of the North Atlantic Oscillation close to 4.2 kyr BP (Olsen et al., 2012) would cause a reduction in rainfall from western disturbances (Syed et al., 2006), the pattern of Mediterranean suggests a more complex set of drivers than a simple North Atlantic Oscillation excursion influencing winter rainfall (Bini et al., 2019; Kaniewski et al., 2018). Regardless
 270 of the climate driver, we interpret the 4.2-3.9 kyr BP drying in the Indus valley as a winter rainfall drought.

The third climate signal in the Indian subcontinent is a drying trend from 4.0 to 3.5 kyr BP. The signal matches the PC1 of our circum-Indian Ocean basin hydroclimate PCA (Figure 6a) and is the dominant hydroclimate variability in the tropical Indian Ocean at the time. Our PCA focuses only on the highest resolution, most precisely dated records available, and is therefore
 275 dominated by speleothem records. Speleothem records tend to record amount-weighted changes in precipitation $\delta^{18}\text{O}$. As a result, they are likely biased towards local summer monsoonal rainfall. The 4.0 to 3.5 kyr BP drying trend can therefore be interpreted as the dominant regional signal of monsoon rainfall. In the Indus valley, this would be the Indian Summer Monsoon. The potential summer bias in the PCA might also explain why a winter dominated 4.2 kyr event is not strongly expressed in any of the PCs in our analyses.

280 The interpretation of the 4.0 to 3.5 kyr BP drying trend as a tropical climate signal matches numerous other tropical hydroclimate records. The inferred mechanism is an abrupt change in ENSO behavior around 4.0 kyr BP with an increase in the frequency of El Niño events, and/or a narrowing of the tropical rainbelt (de Boer et al., 2014; Denniston et al., 2013; Gagan et al., 2004; Giosan et al., 2018; Li et al., 2018; MacDonald, 2011; Toth et al., 2012). In the modern climate system, El Niño



285 events are associated with reduced Indian summer monsoon precipitation (Mooley and Parthasarathy, 1983). Therefore, an increase in El Niño events may have caused a decrease in time-averaged precipitation in the Indus valley.

4.4 The Double Drought hypothesis

290 We propose the “Double Drought hypothesis” to explain the decline of the Mature Harappan and abandonment of the Late Harappan. The hypothesis combines geographic variation in the timing of abandonment (Figure 6b) and differences in local rainfall seasonality (Figure 5, 6d) with an understanding of ‘upstream’ hydroclimate changes in the Indian Ocean basin (Figure 6a) and Mediterranean (Figure 6c) which influence summer and winter rainfall respectively.

An abrupt decline in winter rainfall from 4.26 to 3.97 was immediately followed by a more gradual but larger and longer
295 lasting decline in summer rainfall. Drying occurred between 3.97 and 3.71 kyr BP, and lasted for several centuries, in some areas being a permanent change in rainfall. Together these two droughts caused climate stress to the Harappan civilization and their trading partners. The winter rainfall drought is associated with the end of the Mature Harappan and abandonment of more northerly settlements. The summer rainfall drought is associated with the gradual abandonment of all remaining major Harappan settlements during the Late Harappan and transition to more rural society. Adaptation to changing climate is clear
300 from the archaeological evidence. Therefore, the style, timing and location of societal response is determined by the complex interaction of societal, biogeophysical and geomorphological feedbacks and responses, rather than by climate alone.

Both droughts occur on an underlying secular trend of decreasing northern hemisphere tropical summer rainfall over the course of the Holocene, driven by decreasing insolation. The Harappan civilization grew, thrived and declined on this gradual trend,
305 and the archaeological evidence points to a mastery of water resources. However, this first-order trend suggests that a drought driven decline in the civilization was a matter of when not if.

Superimposed on this multi-millennial scale trend is higher-frequency centennial-scale variability which would have led to periods of relatively wet and dry conditions. The Mature Harappan period likely coincided with one of these wetter periods
310 (Dixit et al., 2018; Giosan et al., 2018; Singh, 1971; Wright et al., 2008). The decline of the Mature Harappan and abandonment of the Late Harappan therefore occurred during two consecutive multi-centennial scale droughts superimposed on first order millennial scale drying.

The winter rainfall drought between 4.26 and 3.97 kyr BP was likely caused by a reduction in western disturbances that bring
315 rainfall from the Mediterranean and Middle East (Figure 6c). Under modern climate the proportion of winter rainfall varies greatly across the area of Harappan occupation, from couple of percent in Gujarat, through to 20% at the Indus valley and



Ghaggar-Hakra sites, to greater than 90% on the western boundary of the Harappan civilization in western Pakistan (Figure 5, 6d)(MacDonald, 2011). During the Mature Harappan prior to the drought, enhanced winter rainfall may have played an even larger role in annual rainfall (Giosan et al., 2018). Therefore, a significant reduction in winter rainfall could still cause significant climate stress.

The societal response to the climate stress caused by winter rainfall drought was significant, as evidenced by reduced maintenance, poor pottery craftsmanship, abandoned water reservoirs (Sengupta et al., 2020) and the abandonment of settlements in areas with a higher proportion of winter rainfall such as the Indus valley (Figure 6b). Trading relationships with civilizations in the Middle East heavily reliant on winter rainfall would have also likely been hit (MacDonald, 2011).

However, the Harappan were able to adapt. The Harappan grew both winter and summer rainfall crops and during the Mature Harappan switched from barley and wheat to millet (Petrie et al., 2017; Petrie and Bates, 2017; Pokharia et al., 2017). At present, barley and wheat are winter crops and millet a summer crop (Petrie and Bates, 2017). The agricultural evidence therefore suggests a switch from winter to summer crops. There are some important caveats and nuance to such a simple interpretation though, namely 1) there is substantial geographic variation, 2) winter crops are reliant on residual soil moisture from the summer rains, 3) the Harappan may have engaged in multicropping or strategies not aligned with modern practices and 4) the timing of rainfall and inundation may not be simultaneous owing to snow melt (Petrie and Bates, 2017). Regardless, agriculture adaptation strategies and continued summer rainfall ensured that the change was not critical to the Harappan civilization, which continued, albeit in a reduced form, beyond 3.97 kyr BP and the climatic recovery from the winter drought.

At a similar time to the winter rainfall recovery at 3.97 kyr BP, a multi-centennial decline in summer monsoonal rainfall began that was both more severe and substantially longer than the 4.2 kyr event (Figure 3, 6a). This second drought was the response to a shift in the mean state of tropical zonal circulation, and possibly an increase in El Niño frequency. We argue that it was this second transition that played the final role in the Late Harappan deurbanization over the course of the following centuries. The transition to Post-Urban Harappan societies saw migration to two areas: the Ganga-Yamuna interfluvium and southern Gujarat, areas with higher summer rainfall amounts.

The decline in summer rainfall was relatively gradual, occurring over 250 years rather than the decades of the 4.2 kyr event, and lasting for hundreds of years more. Further, abandonment of Late Harappan sites was not coincident and we know that the Harappan were adaptable and indeed thrived in the face of hydrological variability. Therefore, the nature, location, and precise timing of societal change in response to the two consecutive droughts are likely due to complex biogeophysical (Cookson et al., 2019), geomorphological (Giosan et al., 2012) and/or social processes and feedbacks (Madella and Fuller, 2006; Petrie et al., 2017; Schug et al., 2013).



350

The Double Drought hypothesis is consistent with the timing, location, and long-lasting nature of societal change during the decline and abandonment of the Harappan civilization. While this hypothesis is consistent with many paleoclimate records from the Indian subcontinent, it is not always consistent with their prior interpretation. For example, our hypothesis is in direct contrast to that of Giesche et al. (2019) who used foraminifera $\delta^{18}\text{O}$ records (interpreted as Arabian Sea salinity changes) to hypothesize a temporary reduction in summer rainfall at 4.2 kyr BP, and a longer lasting reduction in winter rainfall at 3.9 kyr BP. To reconcile these ideas, paleohydroclimate proxies with less ambiguous seasonality than speleothems and foraminifera will be required.

Our Double Drought Hypothesis is consistent with broader climatic changes in ‘upstream’ areas of Indus valley rainfall; changes in winter mid-latitude westerlies are interpreted as influencing winter rainfall, while changes in tropical Indian Ocean hydroclimate are interpreted as influencing summer monsoonal rainfall.

4.5 Consequences for the mid to late Holocene GSSP

The Mawmluh Cave speleothem records which define the 4.2 kyr event (Berkelhammer et al., 2012; Walker et al., 2018) are too short to be included in our PCA analysis. However, the highest resolution replicated record from the cave, ML.1 (Kathayat et al., 2018), shows wetter than normal conditions at 4.1–4.0 kyr BP followed by longer term multi-centennial drying – consistent with PC1. The Global Boundary Stratotype Section and Point (GSSP) golden spike is located in stalagmite KM-A (Berkelhammer et al., 2012). Stalagmite KM-A contains two increases in $\delta^{18}\text{O}$ (drying events), one at 4.31 kyr BP and one at 4.05 kyr BP. While the timing of these changes might be consistent with drying anomalies for both a 4.26 and a 3.97 kyr BP drying event, there are notable issues with the stalagmite itself. The KM-A record replicates neither the other speleothem from Mawmluh Cave (Kathayat et al., 2018) nor any regional records (this study). While the ages of KM-A are very precise, there are only three ages between 5084 and 3654 yr BP and stalagmite growth is very slow. The shape of the stalagmite after 5 kyr BP is not convincing of unaltered equilibrium deposition. Even if the $\delta^{18}\text{O}$ record of KM-A does record both drying events, the golden spike location is defined as 4.20 kyr BP, part of a run of 40 consecutive $\delta^{18}\text{O}$ samples between the two droughts, with relatively minor variability ($<1\text{‰}$). The existence of the Northgrippian-Meghalayan GSSP golden spike in a low resolution, low dating frequency record, not replicable within its own locality, ambiguously defining a climate event (or two) that is not significant across its climatic domain, is problematic at a minimum (Helama and Oinonen, 2019). We recommend that an alternative GSSP golden spike for the mid- to late-Holocene transition be identified.



5 Conclusions

Monte-Carlo principal component analysis of ten high-resolution paleoclimate records from the region show tropical hydroclimate variability between 5 and 3 kyr BP in the circum-Indian ocean basin is dominated by a region-wide drying beginning at 3.97 kyr BP. The 4.2 kyr event had limited impact on tropical monsoon precipitation.

We combine the evidence from Harappan radiocarbon dates, analysis of paleoclimate records from across the Indian subcontinent, modern subcontinent climatology, and upstream paleoclimate records from the Mediterranean and circum-Indian Ocean basin to create the “Double Drought Hypothesis” to explain the decline and abandonment of the Harappan civilization. On a millennial scale secular drying trend, two back to back centennial scale droughts combined to cause significant and eventually critical climate stress to Harappan society. The first drought between 4.26 and 3.97 kyr BP, associated with the 4.2 kyr event, was caused by a reduction in winter rainfall. Site abandonment occurred in the Indus and Ghaggar-Hakra valleys, but in Gujarat, there was adaptation towards summer crops. The first drought resulted in the end of the Mature Harappan period. The second drought started at 3.97 kyr BP and saw 250 of drying followed by centuries of drought, if not a permanent shift in rainfall. This second drought was caused by a reduction in summer monsoon rainfall due to a global shift in the mean state of the tropics, possibly via an increase in El Niño event frequency. This second drought led to the abandonment of remaining Harappan sites, the end of the Late Harappan, and transition to a more rural society in southern Gujarat and the Ganga-Yamuna Interfluvium. The double droughts were a significant factor in the end of the Harappan civilization, causing significant climate stress to Harappan society. Other biogeophysical and geomorphological changes in response to changing rainfall patterns likely also contributed to societal stress. Ultimately, social responses to these pressures controlled the nature, timing and location of adaptation, abandonment and migration of Harappan society.

The findings presented here have implications for the attribution of the 4.2 kyr event as a global climatic event. While some individual records from the circum-Indian Ocean basin show locally significant climate excursions contemporaneous with the 4.2 kyr BP event, when viewed basin wide the event has little regional coherence nor is it of unusual severity at most sites. The 4.2 kyr event therefore had limited impact on tropical monsoonal rainfall around the circum-Indian Ocean basin. Previous studies may have falsely attributed low latitude, low frequency climate variability to the 4.2 kyr event when there are other significant changes in the tropical climate system at similar times. We propose that the 4.2 kyr event had a more limited geographical impact than is commonly assumed.

Data availability

Data are available from the authors (nick.scroxton@ucd.ie) and at the NOAA Paleoclimatology Database: <https://www.ncdc.noaa.gov/paleo/study/xxxxx>.



Author Contributions

410 NS conceived the study, ran data analysis, and was primarily responsible for writing the manuscript. SJB, DM and LRG provided guidance on project direction, discussion of findings and helped write and edit the manuscript. LR and PF contributed to the development and interpretation of the records from Madagascar.

Competing interests

The authors declare no competing interests.

415 Acknowledgements

NS, SJB and DM acknowledge support from NSF award AGS-1702891/1702691, LRG and SJB from NSF award BCS-1750598 and DM from NSF award EAR-1439559 and the MIT Ferry Fund. Fieldwork in northwest Madagascar was conducted under a collaborative accord for paleobiological research between the University of Antananarivo (Département de Paléontologie et d'Anthropologie Biologique) and the University of Massachusetts (Department of Anthropology);
420 collaborative work was further supported under a second accord for paleobiological and paleoclimatological research between the University of Antananarivo (Mention Bassins sédimentaires, Evolution, Conservation) and the University of Massachusetts Amherst (Departments of Anthropology and Geosciences). The research was sanctioned by the Madagascar Ministry of Mines, the Ministry of Education, and the Ministry of Arts and Culture.

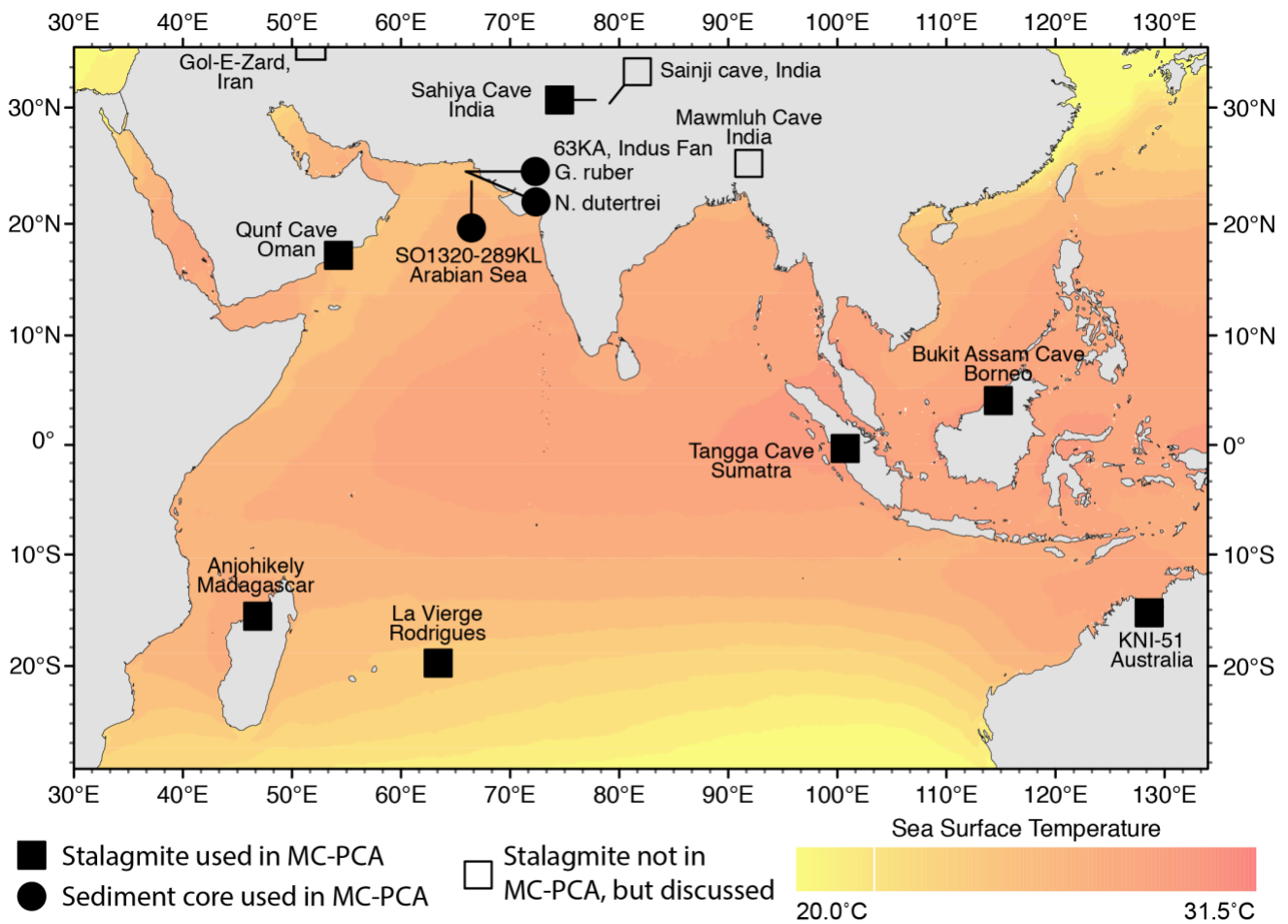
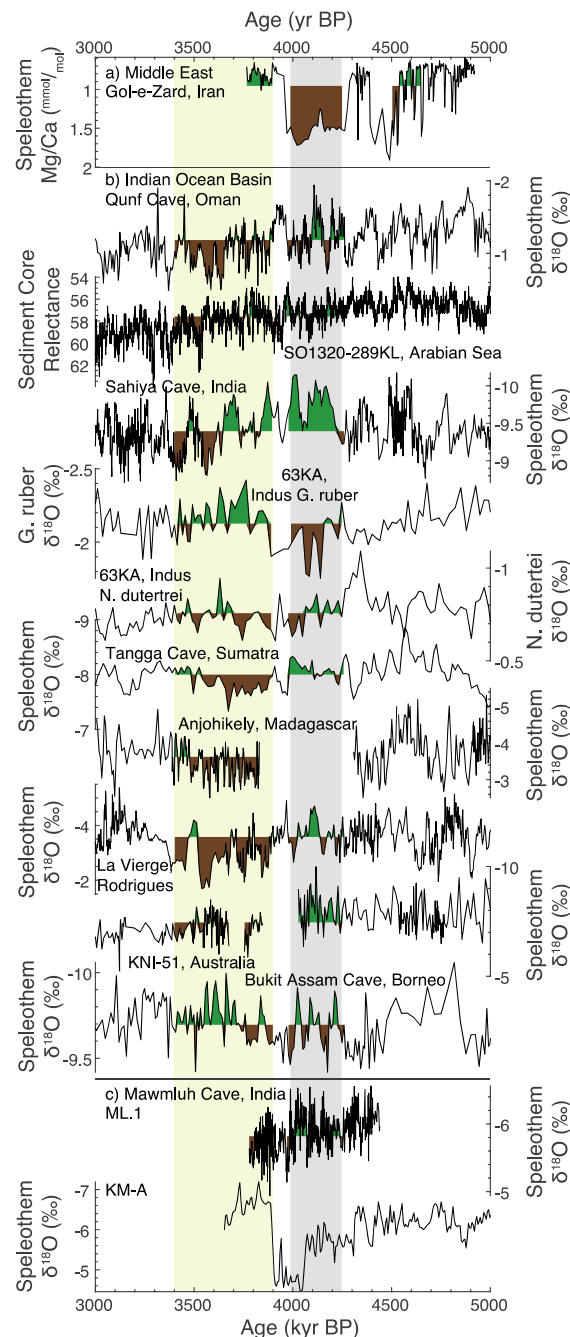


Figure 1: Location map. Squares denote locations of stalagmites; circles denote marine sediment cores. Closed symbols are used in the MC-PCA, open symbols are not. Color axis for oceans shows modern mean annual sea surface temperature 73,74. Land shown in gray. Map was created using ArcMap 10.7.1. ArcGIS and ArcMap are copyright Esri, www.esri.com.



430 **Figure 2: Comparison of climatic shifts in the original records. a) Speleothem record of the 4.2 kyr event from the center of action**
in the Middle East. **b) Indian Ocean basin hydroclimate records from 5000-3000 yr BP used in Monte-Carlo principal component**
analysis. **c) speleothem records from Mawmluh Cave, India. Gray box indicates the timing of the 4.2 kyr event (4.26 to 3.97 kyr BP)**
as defined at Gol-E-Zard. **Yellow box indicates the dry shift from PC1: 3.9-3.4 kyr BP. Green and brown shading indicate values**
corresponding to wetter and drier conditions than mean values for the records between 5000 and 3000 yrs BP within the shaded
boxes.

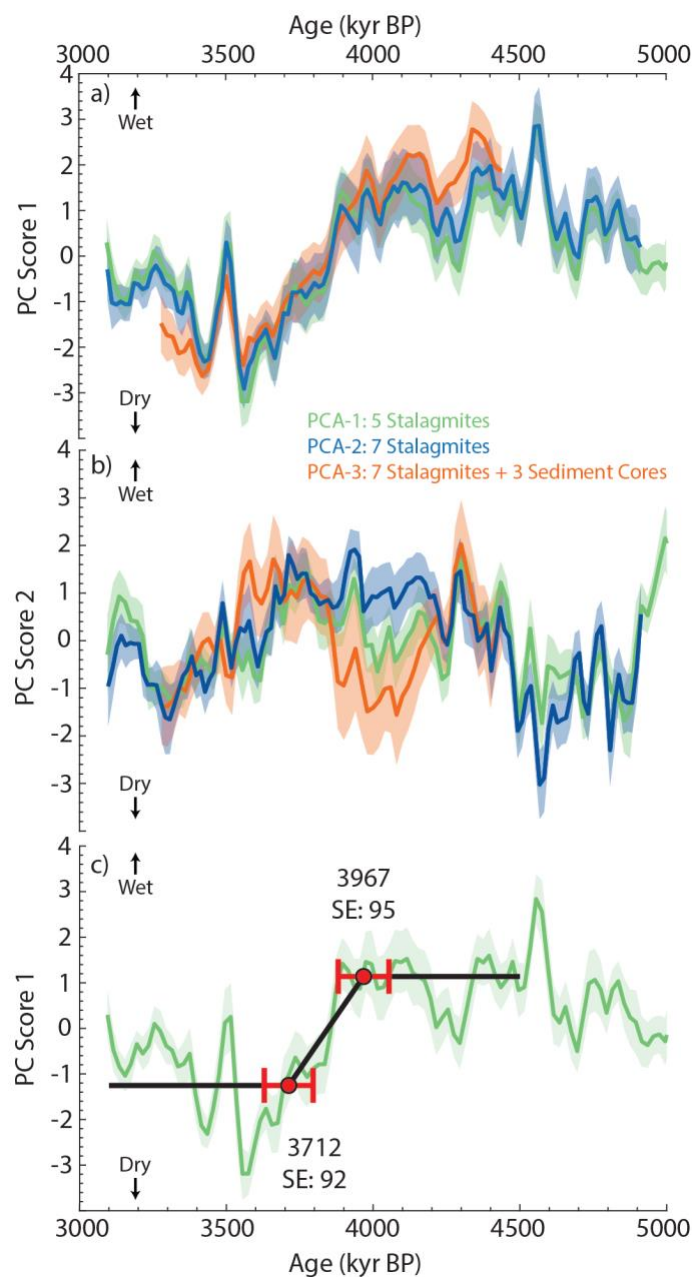


Figure 3: Monte-Carlo Principal component analysis of Indian Ocean hydroclimate records: a) Principal Component 1, b) Principal Component 2. Color lines indicate mean principal component from 2000 individual analyses on redrawn age models, with 1 standard deviation shading. c) RAMPFIT results of PCA-1, PC1 (black line with red error bars on ramp start and end points). Green: Five speleothem PCA, Blue: 7 speleothem PCA, Orange: 7 speleothem and 3 sediment core PCA.

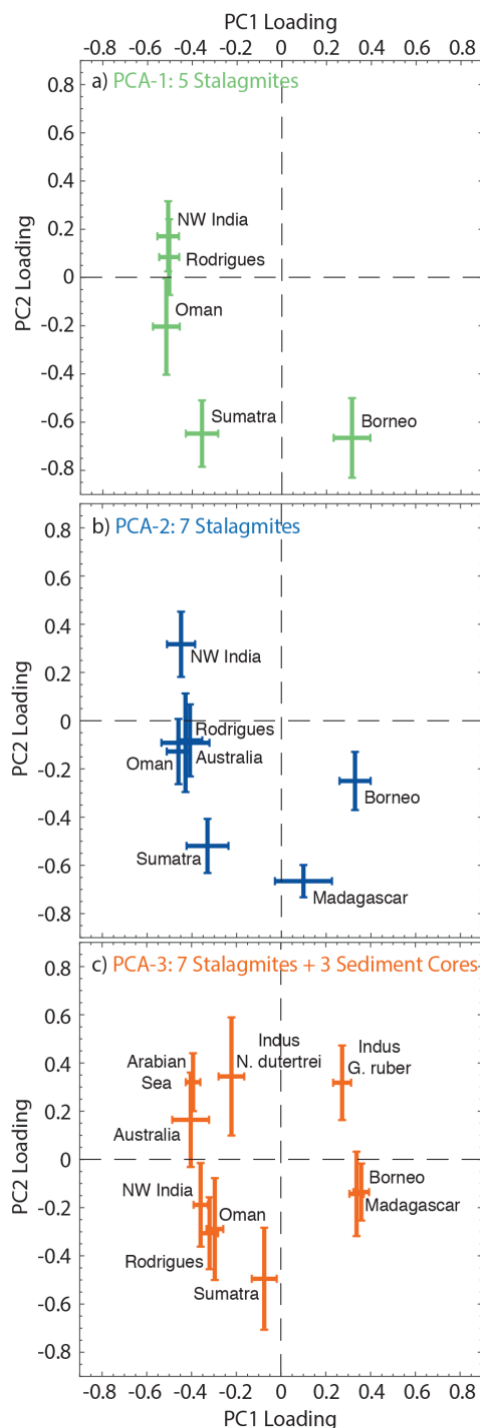


Figure 4: Loadings of individual hydroclimate records on the first two principal components for each MC-PCA analysis with 1 standard deviation error bars. a) PCA-1, b) PCA-2, c) PCA-3.

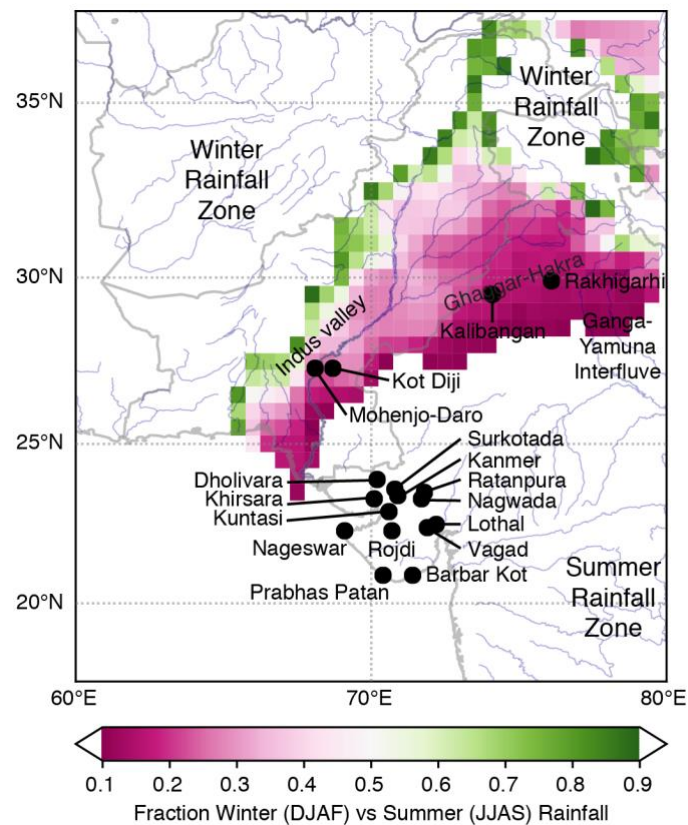


Figure 5: Location map of significant archaeological sites (black dots) with multiple radiocarbon dates. Color axis (pink to white to green) shows the fraction of rainfall falling during the winter (DJAF) season compared to the summer (JJAS season) between 1981 and 2010 using Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis Version 7 0.5°x0.5° Monthly Totals (Schneider et al., 2015). Areas with greater than 90% rainfall falling in summer compared to winter, or vice-versa are left white and labelled.

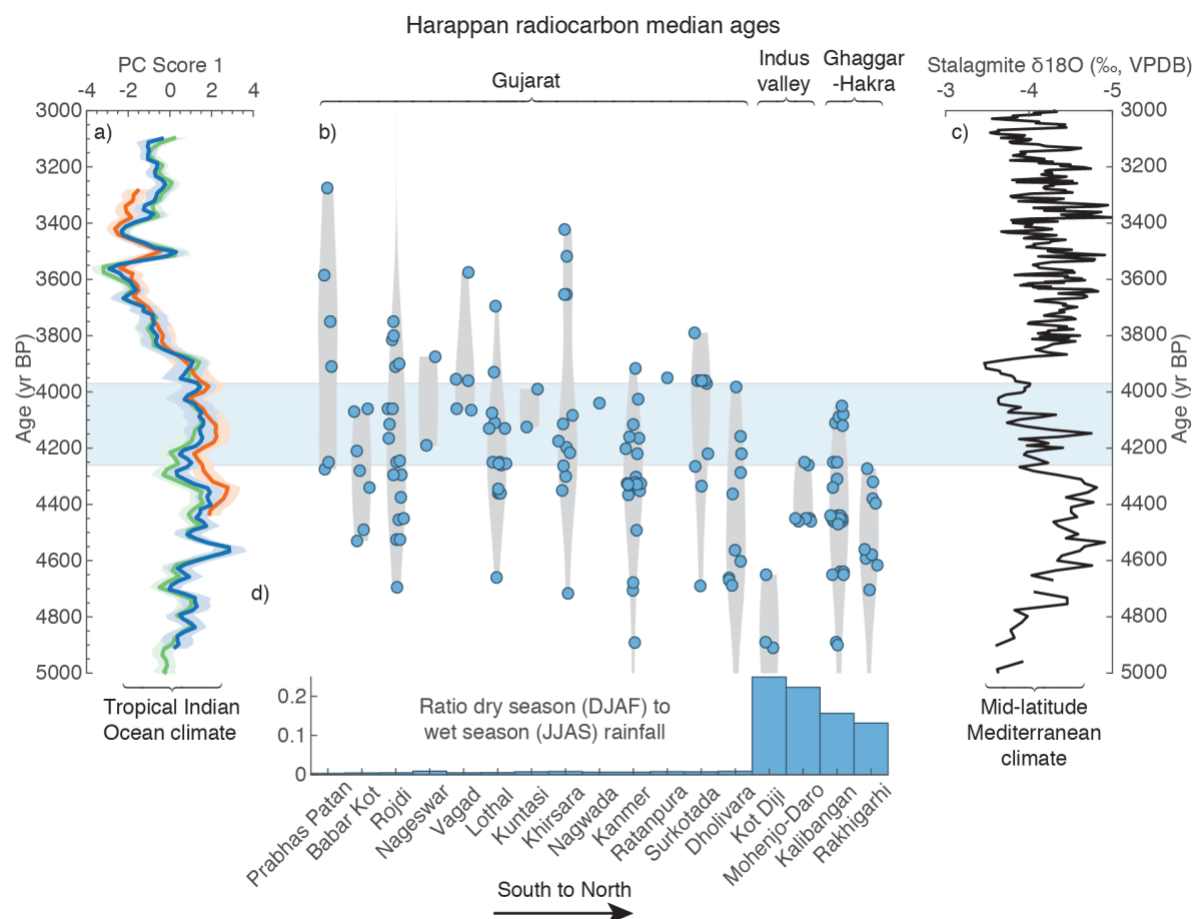


Figure 6: Climatic changes and the Harappan civilization between 5 and 3 kyr BP. a) results from the Monte-Carlo principal component analysis of Indian Ocean hydroclimate records. PC1 from the 5 speleothem PCA (green), 7 speleothem PCA (blue) and 7 speleothems plus 3 sediment core PCA (orange) with 1 standard deviation shading. b) Violin plot of median ages of radiocarbon dates at major Harappan archaeological sites (blue dots) with kernel density estimate (grey shading). Plot adapted from Sengupta et al. (2020) with radiocarbon data from: Kalibangan, Kot Diji, Mohenjodaro (Brunswig, 1975), Prabhas Patan, Babar Kot, Nagwada, Surkotada, Ratanpura, Kuntasi, Nagwada, Vagad, Lothal, Nageswar (Herman, 1996), Rojdi (Brunswig, 1975; Herman, 1996), Kanmer (Pokharia et al., 2011), Rakhigarhi (Nath et al., 2014; Vahia et al., 2016), Khirsara (Pokharia et al., 2017), Dholivara (Sengupta et al., 2020). c) Stalagmite RL4 from Renella cave, Italy ((Zanchetta et al., 2016), (Isola et al., 2019), using a 2018 updated chronology available in the SISAL database (Atsawawaranunt et al., 2018). d) Ratio of mean rainfall (1981-2010, GPCC V7 global gridded dataset at $0.5^\circ \times 0.5^\circ$ resolution (Schneider et al., 2015)) falling in winter (DJAF) vs summer (JJAS) at each archaeological site. Blue horizontal box indicates the timing of the 4.2 kyr event as determined in Carolin et al., 2019 (4.26–3.97 kyr BP).



References

- 465 Atsawawaranunt, K., Comas-Bru, L., Amirnezhad Mozhdehi, S., Deininger, M., Harrison, S. P., Baker, A., Boyd, M., Kaushal, N., Ahmad, S. M., Ait Brahimi, Y., Arienzo, M., Bajo, P., Braun, K., Burstyn, Y., Chawchai, S., Duan, W., Hatvani, I. G., Hu, J., Kern, Z., Labuhn, I., Lachniet, M. S., Lechleiter, F. A., Lorrey, A., Pérez-Mejías, C., Pickering, R., and Scroxton, N.: The SISAL database: a global resource to document oxygen and carbon isotope records from speleothems, *Earth System Science Data* <https://doi.org/10.5194/essd-10-1687-2018>, 2018.
- 470 Bar-Matthews, M. and Ayalon, A.: Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes, *The Holocene* 21, 163–171, <https://doi.org/10.1177/0959683610384165>, 2011.
- Berkelhammer, M., Sinha, A., Stott, L., Cheng, H., Pausata, F. S. R., and Yoshimura, K.: An Abrupt Shift in the Indian Monsoon 4000 Years Ago, edited by: Giosan, L., Fuller, D. Q., Nicoll, K., Flad, R. K., and Clift, P. D., *American Geophysical Union (AGU)*, Washington, D. C., 75–88, <https://doi.org/10.1029/2012GM001207>, 2012.
- 475 Bini, M., Zanchetta, G., Perşoiu, A., Cartier, R., Catala, A., Cacho, I., Dean, J. R., Di Rita, F., Drysdale, R. N., Finné, M., Isola, I., Jalali, B., Lirer, F., Magri, D., Masi, A., Marks, L., Mercuri, A. M., Peyron, O., Sadori, L., Sicre, M.-A., Welc, F., Zielhofer, C., and Brisset, E.: The 4.2 ka BP Event in the Mediterranean region: an overview, *Climate of the Past* 15, 555–577, <https://doi.org/10.5194/cp-15-555-2019>, 2019.
- 480 Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E., Bettis III, E. A., Kreigs, J., and Wright, D. K.: A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages, *The Holocene* 15, 321–328, 2005.
- Brunswig, R. H.: Radiocarbon dating and the Indus civilization: calibration and chronology, *East and West* 25, 111–145, 1975.
- Butzer, K. W. and Endfield, G. H.: Critical perspectives on historical collapse, *Proceedings of the National Academy of Sciences* 109, 3628–3631, <https://doi.org/10.1073/pnas.1114772109>, 2012.
- 485 Carolin, S. A., Cobb, K. M., Adkins, J. F., Clark, B., Conroy, J. L., Lejau, S., Malang, J., and Tuen, A. A.: Varied Response of Western Pacific Hydrology to Climate Forcings over the Last Glacial Period, *Science* 340, 1564–1566, <https://doi.org/10.1126/science.1233797>, 2013.
- 490 Carolin, S. A., Walker, R. T., Day, C. C., Ersek, V., Sloan, R. A., Dee, M. W., Talebian, M., and Henderson, G. M.: Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change, *Proceedings of the National Academy of Sciences* 116, 67–72, <https://doi.org/10.1073/pnas.1808103115>, 2019.
- Chen, S., Hoffmann, S. S., Lund, D. C., Cobb, K. M., Emile-Geay, J., and Adkins, J. F.: A high-resolution speleothem record of western equatorial Pacific rainfall: Implications for Holocene ENSO evolution, *Earth and Planetary Science Letters* 442, 61–71, <https://doi.org/10.1016/j.epsl.2016.02.050>, 2016.
- 495 Cheng, H., Lawrence Edwards, R., Edwards, R. L., Shen, C.-C., Polyak, V. J., Asmerom, Y., Woodhead, J., Hellstrom, J. C., Hellstrom, J., Wang, Y., Kong, X., Spötl, C., Wang, X., and Calvin Alexander Jr., E.: Improvements in ²³⁰Th dating, ²³⁰Th and ²³⁴U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry, *Earth and Planetary Science Letters* 371–372, 82–91, <https://doi.org/10.1016/j.epsl.2013.04.006>, 2013.
- 500 Cookson, E., Hill, D. J., and Lawrence, D.: Impacts of long term climate change during the collapse of the Akkadian Empire, *Journal of Archaeological Science* 106, 1–9, <https://doi.org/10.1016/j.jas.2019.03.009>, 2019.
- Cullen, H. M., deMenocal, P. B., Hemming, S., Hemming, G., Brown, F. H., Guilderson, T., and Sirocko, F.: Climate change and the collapse of the Akkadian empire: Evidence from the deep sea, *Geology* 28, 379–382, [https://doi.org/10.1130/0091-7613\(2000\)28<379:CCATCO>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<379:CCATCO>2.0.CO;2), 2000.
- 505 de Boer, E. J., Tjallingii, R., Vélez, M. I., Rijdsdijk, K. F., Vlug, A., Reichert, G.-J., Prendergast, A. L., de Louw, P. G. B., Florens, F. B. V., Baider, C., and Hooghiemstra, H.: Climate variability in the SW Indian Ocean from an 8000-yr long multi-proxy record in the Mauritanian lowlands shows a middle to late Holocene shift from negative IOD-state to ENSO-state, *Quaternary Science Reviews* 86, 175–189, <https://doi.org/10.1016/j.quascirev.2013.12.026>, 2014.
- Deininger, M., McDermott, F., Mudelsee, M., Werner, M., Frank, N., and Mangini, A.: Coherency of late Holocene European speleothem $\delta^{18}\text{O}$ records linked to North Atlantic Ocean circulation, *Climate Dynamics* 49, 595–618, <https://doi.org/10.1007/s00382-016-3360-8>, 2017.
- 510



- deMenocal, P. B.: Cultural Responses to Climate Change During the Late Holocene, *Science* 292, 667–673, <https://doi.org/10.1126/science.1059287>, 2001.
- 515 Denniston, R. F., Wyrwoll, K.-H., Polyak, V. J., Brown, J. R., Asmerom, Y., Wanamaker Jr., A. D., LaPointe, Z., Ellerbroek, R., Barthelmes, M., Cleary, D., Cugley, J., Woods, D., and Humphreys, W. F.: A Stalagmite record of Holocene Indonesian–Australian summer monsoon variability from the Australian tropics, *Quaternary Science Reviews* 78, 155–168, <https://doi.org/10.1016/j.quascirev.2013.08.004>, 2013.
- 520 Deplazes, G., Lückge, A., Peterson, L. C., Timmermann, A., Hamann, Y., Hughen, K. A., Röhl, U., Laj, C., Cane, M. A., Sigman, D. M., and Haug, G. H.: Links between tropical rainfall and North Atlantic climate during the last glacial period, *Nature Geoscience* 6, 213–217, <https://doi.org/10.1038/ngeo1712>, 2013.
- Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., and Sikka, D. R.: Western disturbances: a review, *Reviews of Geophysics* 53, 225–246, 2015.
- Dixit, Y., Hodell, D. A., and Petrie, C. A.: Abrupt weakening of the summer monsoon in northwest India 4100 yr ago, *Geology* 42, 339–342, <https://doi.org/10.1130/G35236.1>, 2014.
- 525 Dixit, Y., Hodell, D. A., Giesche, A., Tandon, S. K., Gázquez, F., Saini, H. S., Skinner, L. C., Mujtaba, S. A. I., Pawar, V., Singh, R. N., and Petrie, C. A.: Intensified summer monsoon and the urbanization of Indus Civilization in northwest India, *Scientific Reports* 8, 4225, <https://doi.org/10.1038/s41598-018-22504-5>, 2018.
- Dutt, S., Gupta, A. K., Wünnemann, B., and Yan, D.: A long arid interlude in the Indian summer monsoon during ~4,350 to 3,450 cal. yr BP contemporaneous to displacement of the Indus valley civilization, *Quaternary International* 482, 83–92, <https://doi.org/10.1016/j.quaint.2018.04.005>, 2018.
- 530 Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary, A. A., Buettner, A., Hippler, D., and Matter, A.: Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra), *Quaternary Science Reviews* 26, 170–188, <https://doi.org/10.1016/j.quascirev.2006.04.012>, 2007.
- 535 Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter, A.: Holocene Forcing of the Indian Monsoon Recorded in a Stalagmite from Southern Oman, *Science* 300, 1737–1739, <https://doi.org/10.1126/science.1083130>, 2003.
- Gagan, M. K., HENDY, E. J., Haberle, S. G., and Hantoro, W. S.: Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño–Southern oscillation, *Quaternary International* 118–119, 127–143, [https://doi.org/10.1016/s1040-6182\(03\)00134-4](https://doi.org/10.1016/s1040-6182(03)00134-4), 2004.
- 540 Gangal, K., Vahia, M. N., and Adhikari, R.: Spatio-temporal analysis of the Indus urbanization, *Current Science* 98, 846–852, <https://doi.org/10.2307/24109857>, 2010.
- Giesche, A., Staubwasser, M., Petrie, C., and Hodell, D.: Indian winter and summer monsoon strength over the 4.2 ka BP event in foraminifer isotope records from the Indus River delta in the Arabian Sea, *Climate of the Past* 15, 73–90, <https://doi.org/10.5194/cp-15-73-2019>, 2019.
- 545 Giosan, L., Clift, P. D., Macklin, M. G., Fuller, D. Q., Constantinescu, S., Durcan, J. A., Stevens, T., Duller, G. A. T., Tabrez, A. R., Gangal, K., Adhikari, R., Alizai, A., Filip, F., VanLaningham, S., and Syvitski, J. P. M.: Fluvial landscapes of the Harappan civilization, *Proceedings of the National Academy of Sciences* 109, E1688–E1694, <https://doi.org/10.1073/pnas.1112743109>, 2012.
- 550 Giosan, L., Orsi, W. D., Coolen, M., Wuchter, C., Dunlea, A. G., Thirumalai, K., Munoz, S. E., Clift, P. D., Donnelly, J. P., Galy, V., and Fuller, D. Q.: Neoglacial climate anomalies and the Harappan metamorphosis, *Climate of the Past* 14, 1669–1686, <https://doi.org/10.5194/cp-14-1669-2018>, 2018.
- Griffiths, M. L., Drysdale, R. N., Gagan, M. K., Zhao, J.-x., Ayliffe, L. K., Hellstrom, J. C., Hantoro, W. S., Frisia, S., Feng, Y., Cartwright, I., Pierre, E. S., St Pierre, E., Fischer, M. J., and Suwargadi, B. W.: Increasing Australian–Indonesian monsoon rainfall linked to early Holocene sea-level rise, *Nature Geoscience* 2, 636–639, <https://doi.org/10.1038/NGEO605>, 2009.
- 555 Gupta, A. K., Anderson, D. M., and Overpeck, J. T.: Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature* 421, 354–357, <https://doi.org/10.1038/nature01340>, 2003.
- Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C., and Röhl, U.: Southward Migration of the Intertropical Convergence Zone Through the Holocene, *Science* 293, 1304–1308, <https://doi.org/10.1126/science.1059725>, 2001.



- 560 Helama, S. and Oinonen, M.: Exact dating of the Meghalayan lower boundary based on high-latitude tree-ring isotope
 chronology, *Quaternary Science Reviews* 214, 178–184, <https://doi.org/10.1016/j.quascirev.2019.04.013>, 2019.
- Herman, C. F.: “Harappan” Gujara : the Archaeology-Chronology Connection., *Paléorient* 22, 77–112,
<https://doi.org/10.3406/paleo.1996.4637>, 1996.
- Höflmayer, F.: The Late Third Millennium B.C. in the Ancient Near East and Eastern Mediterranean: A Time of Collapse and
 565 Transformation, edited by: Höflmayer, F., *Oriental Institute Seminars*, 1–30, 2017.
- Hu, J., Emile-Geay, J., Tabor, C., Nussbaumer, J., and Partin, J.: Deciphering Oxygen Isotope Records From Chinese
 Speleothems With an Isotope-Enabled Climate Model, *Paleoceanography and Paleoclimatology* 34, 2098–2112,
<https://doi.org/10.1029/2019pa003741>, 2019.
- Isola, I., Zanchetta, G., Drysdale, R. N., Regattieri, E., Bini, M., Bajo, P., Hellstrom, J. C., Banerchi, I., Lionello, P., Woodhead,
 570 J., and Greig, A.: The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apuan Alps,
 central Italy), *Climate of the Past* 15, 135–151, <https://doi.org/10.5194/cp-15-135-2019>, 2019.
- Kaniewski, D., Marriner, N., Cheddadi, R., Guiot, J., and Campo, E. V.: The 4.2 ka BP event in the Levant, *Climate of the
 Past* 14, 1529–1542, <https://doi.org/10.5194/cp-14-1529-2018>, 2018.
- Kathayat, G., Cheng, H., Sinha, A., Berkelhammer, M., Zhang, H., Duan, P., Li, H., Li, X., Ning, Y., and Edwards, R. L.:
 575 Evaluating the timing and structure of the 4.2 ka event in the Indian summer monsoon domain from an annually
 resolved speleothem record from Northeast India, *Climate of the Past* 14, 1869–1879, <https://doi.org/10.5194/cp-14-1869-2018>, 2018.
- Kathayat, G., Cheng, H., Sinha, A., Yi, L., Li, X., Zhang, H., Li, H., Ning, Y., and Edwards, R. L.: The Indian monsoon
 variability and civilization changes in the Indian subcontinent, *Science Advances* 3, e1701296,
 580 <https://doi.org/10.1126/sciadv.1701296>, 2017.
- Kaushal, R., Ghosh, P., and Pokharia, A. K.: Stable isotopic composition of rice grain organic matter marking an abrupt shift
 of hydroclimatic condition during the cultural transformation of Harappan civilization, *Quaternary International* 512,
 144–154, 2019.
- Kotlia, B. S., Singh, A. K., Joshi, L. M., and Dhaila, B. S.: Precipitation variability in the Indian Central Himalaya during last
 585 ca. 4,000 years inferred from a speleothem record: Impact of Indian Summer Monsoon (ISM) and Westerlies,
Quaternary International 371, 244–253, <https://doi.org/10.1016/j.quaint.2014.10.066>, 2015.
- Kotlia, B. S., Singh, A. K., Joshi, L. M., and Bisht, K.: Precipitation variability over Northwest Himalaya from ~4.0 to 1.9 ka
 BP with likely impact on civilization in the foreland areas, *Journal of Asian Earth Sciences* 162, 148–159,
<https://doi.org/10.1016/j.jseaes.2017.11.025>, 2018.
- 590 Li, H., Cheng, H., Sinha, A., Kathayat, G., Spötl, C., André, A. A., Meunier, A., Biswas, J., Duan, P., Ning, Y., and Edwards,
 R. L.: Hydro-climatic variability in the southwestern Indian Ocean between 6000 and 3000 years ago, *Climate of the
 Past* 14, 1881–1891, <https://doi.org/10.5194/cp-14-1881-2018>, 2018.
- MacDonald, G.: Potential influence of the Pacific Ocean on the Indian summer monsoon and Harappan decline, *Quaternary
 International* 229, 140–148, https://doi.org/10.1016/j.quaint.2009.11.012&hl=en&num=1&as_sdt=0,5, 2011.
- 595 Madella, M. and Fuller, D. Q.: Palaeoecology and the Harappan Civilisation of South Asia: a reconsideration, *Quaternary
 Science Reviews* 25, 1283–1301, <https://doi.org/10.1016/j.quascirev.2005.10.012>, 2006.
- Marchant, R. and Hooghiemstra, H.: Rapid environmental change in African and South American tropics around 4000 years
 before present: a review, *Earth-Science Reviews* 66, 217–260, <https://doi.org/10.1016/j.earscirev.2004.01.003>, 2004.
- Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van
 600 Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R., and Steig, E. J.:
 Holocene climate variability, *Quaternary Research* 62, 243–255, <https://doi.org/10.1016/j.yqres.2004.07.001>, 2004.
- Mehrotra, N., Shah, S. K., Basavaiah, N., Laskar, A. H., and Yadava, M. G.: Resonance of the ‘4.2ka event’ and terminations
 of global civilizations during the Holocene, in the palaeoclimate records around PT Tso Lake, Eastern Himalaya,
Quaternary International 507, 206–216, <https://doi.org/10.1016/j.quaint.2018.09.027>, 2018.
- 605 Moerman, J. W., Cobb, K. M., Partin, J. W., Meckler, A. N., Carolin, S. A., Adkins, J. F., Lejau, S., Malang, J., Clark, B., and
 Tuen, A. A.: Transformation of ENSO-related rainwater to dripwater $\delta^{18}\text{O}$ variability by vadose water mixing,
Geophysical Research Letters 41, 7907–7915, <https://doi.org/10.1002/2014gl061696>, 2014.
- Mooley, D. A. and Parthasarathy, B.: Indian summer monsoon and El Nino, pure and applied geophysics 121, 339–352, 1983.



- Morrill, C., Overpeck, J. T., Cole, J. E., Liu, K.-b., Shen, C., and Tang, L.: Holocene variations in the Asian monsoon inferred from the geochemistry of lake sediments in central Tibet, *Quaternary Research* 65, 232–243, 2006.
- Mudelsee, M.: Ramp function regression: a tool for quantifying climate transitions, *Computers & Geosciences* 26, 293–307, [https://doi.org/10.1016/s0098-3004\(99\)00141-7](https://doi.org/10.1016/s0098-3004(99)00141-7), 2000.
- Mudelsee, M.: *Climate time series analysis*, Second Edition, Springer, Heidelberg, 2013.
- Nakamura, A., Yokoyama, Y., and Maemoku, H.: Weak monsoon event at 4.2 ka recorded in sediment from Lake Rara, Himalayas, *Quaternary International* 397, 349–359, <https://doi.org/10.1016/j.quaint.2015.05.053>, 2016.
- Nath, A., Garge, T., and Law, R.: Defining the economic space of Harappan Rakhigarhi: an interface of local subsistence mechanism and geologic provenience studies, *Prattatva* 44, 83–100, 2014.
- Olsen, J., Anderson, N. J., and Knudsen, M. F.: Variability of the North Atlantic Oscillation over the past 5,200 years, *Nature Geoscience* 5, 808–812, <https://doi.org/10.1038/ngeo1589>, 2012.
- Partin, J. W., Cobb, K. M., Adkins, J. F., Clark, B., and Fernandez, D. P.: Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum, *Nature* 449, 452–455, <https://doi.org/10.1038/nature06164>, 2007.
- Petrie, C. A. and Bates, J.: ‘Multi-cropping’, intercropping and adaptation to variable environments in Indus South Asia, *Journal of World Prehistory* 30, 81–130, 2017.
- Petrie, C. A., Singh, R. N., Bates, J., Dixit, Y., French, C. A. I., Hodell, D. A., Jones, P. J., Lancelotti, C., Lynam, F., Neogi, S., Pandey, A. K., Parikh, D., Pawar, V., Redhouse, D. I., and Singh, D. P.: Adaptation to Variable Environments, Resilience to Climate Change: Investigating Land, Water and Settlement in Indus Northwest India, *Current Anthropology* 58, 1–30, <https://doi.org/10.1086/690112>, 2017.
- Phadtare, N. R.: Sharp Decrease in Summer Monsoon Strength 4000–3500 cal yr B.P. in the Central Higher Himalaya of India Based on Pollen Evidence from Alpine Peat, *Quaternary Research* 53, 122–129, <https://doi.org/10.1006/qres.1999.2108>, 2000.
- Pokharia, A. K., Agnihotri, R., Sharma, S., Bajpai, S., Nath, J., Kumaran, R. N., and Negi, B. C.: Altered cropping pattern and cultural continuation with declined prosperity following abrupt and extreme arid event at~ 4,200 yrs BP: Evidence from an Indus archaeological site Khirsara, Gujarat, western India, *PloS one* 12, 2017.
- Pokharia, A. K., Kharakwal, J. S., Rawat, R. S., Osada, T., Nautiyal, C. M., and Srivastava, A.: Archaeobotany and archaeology at Kanmer, a Harappan site in Kachchh, Gujarat: evidence for adaptation in response to climatic variability, *Current Science* 100, 1833–1846, 2011.
- Possehl, G. L.: The date of Indus urbanization: a proposed chronology for the Pre-urban and Urban Harappan Phases, in: *South Asian Archaeology*, edited by: Gail, A. and Mevissen, G., Franz Steiner Verlag, Stuttgart, 231–249, 1993.
- Possehl, G. L.: Climate and the Eclipse of the Ancient Cities of the Indus, Springer, Berlin, Heidelberg, Berlin, Heidelberg, 193–243, https://doi.org/10.1007/978-3-642-60616-8_8, 1997.
- Possehl, G. L.: *The Indus Civilization: A Contemporary Perspective*, Rowman Altamira, 2002.
- Prasad, S., Anoop, A., Riedel, N., Sarkar, S., Menzel, P., Basavaiah, N., Krishnan, R., Fuller, D., Plessen, B., Gaye, B., Röhl, U., Wilkes, H., Sachse, D., Sawant, R., Wiesner, M. G., and Stebich, M.: Prolonged monsoon droughts and links to Indo-Pacific warm pool: A Holocene record from Lonar Lake, central India, *Earth and Planetary Science Letters* 391, 171–182, <https://doi.org/10.1016/j.epsl.2014.01.043>, 2014.
- Sandeep, K., Shankar, R., Warriar, A. K., Yadava, M. G., Ramesh, R., Jani, R. A., Weijian, Z., and Xuefeng, L.: A multi-proxy lake sediment record of Indian summer monsoon variability during the Holocene in southern India, *Palaeogeography, Palaeoclimatology, Palaeoecology* 476, 1–14, <https://doi.org/10.1016/j.palaeo.2017.03.021>, 2017.
- Schneider, T., Bischoff, T., and Haug, G. H.: Migrations and dynamics of the intertropical convergence zone, *Nature* 513, 45–53, <https://doi.org/10.1038/nature13636>, 2014.
- Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC full data reanalysis version 7.0 (at 0.5°, 1.0°, 2.5°): Monthly land-surface precipitation from rain-gauges built on GTS-based and historic data, https://doi.org/10.5676/DWD_GPCC/FD_M_V7_050, 2015.
- Schug, G. R., Blevins, K. E., Cox, B., Gray, K., and Mushrif-Tripathy, V.: Infection, disease, and biosocial processes at the end of the Indus Civilization, *PLoS One* 8, e84814, 2013.
- Scroton, N., Burns, S. J., McGee, D., Hardt, B., Godfrey, L. R., Ranivoharimanana, L., and Faina, P.: Hemispherically in-phase precipitation variability over the last 1700 years in a Madagascar speleothem record, *Quaternary Science Reviews* 164, 25–36, <https://doi.org/10.1016/j.quascirev.2017.03.017>, 2017.



- 660 Sengupta, T., Deshpande Mukherjee, A., Bhushan, R., Ram, F., Bera, M. K., Raj, H., Dabhi, A. J., Bisht, R. S., Rawat, Y. S.,
 Bhattacharya, S. K., Juyal, N., and Sarkar, A.: Did the Harappan settlement of Dholavira (India) collapse during the
 onset of Meghalayan stage drought, *Journal of Quaternary Science* 35, 382–395, <https://doi.org/10.1002/jqs.3178>,
 2020.
- Singh, G.: The Indus Valley culture: Seen in the context of post-glacial climatic and ecological studies in north-west India,
Archaeology & Physical Anthropology in Oceania 6, 177–189, 1971.
- 665 Singh, G., Wasson, R. J., and Agrawal, D. P.: Vegetational and seasonal climatic changes since the last full glacial in the Thar
 Desert, northwestern India, *Review of Palaeobotany and Palynology* 64, 351–358, 1990.
- Staubwasser, M., Sirocko, F., Grootes, P. M., and Segl, M.: Climate change at the 4.2 ka BP termination of the Indus valley
 civilization and Holocene south Asian monsoon variability, *Geophysical Research Letters* 30, 155,
<https://doi.org/10.1029/2002GL016822>, 2003.
- 670 Staubwasser, M. and Weiss, H.: Holocene Climate and Cultural Evolution in Late Prehistoric–Early Historic West Asia,
Quaternary Research 66, 372–387, <https://doi.org/10.1016/j.yqres.2006.09.001>, 2006.
- Syed, F. S., Giorgi, F., Pal, J. S., and King, M. P.: Effect of remote forcings on the winter precipitation of central southwest
 Asia part 1: observations, *Theoretical and Applied Climatology* 86, 147–160, 2006.
- Thompson, L. G., Tandong, Y., Davis, M. E., Mosley-Thompson, E., Mashiotta, T. A., Lin, P.-N., Mikhalev, V. N., and
 675 Zagorodnov, V. S.: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau,
Annals of Glaciology 43, 61–69, 2006.
- Tierney, J. E. and deMenocal, P. B.: Abrupt Shifts in Horn of Africa Hydroclimate Since the Last Glacial Maximum, *Science*
 342, 843–846, <https://doi.org/10.1126/science.1240411>, 2013.
- Toth, L. T. and Aronson, R. B.: The 4.2 ka event, ENSO, and coral reef development, *Climate of the Past* 15, 105–119,
 680 <https://doi.org/10.5194/cp-15-105-2019>, 2019.
- Toth, L. T., Aronson, R. B., Vollmer, S. V., Hobbs, J. W., Urrego, D. H., Cheng, H., Enochs, I. C., Combosch, D. J., Van
 Woesik, R., and Macintyre, I. G.: ENSO drove 2500-year collapse of eastern Pacific coral reefs, *Science* 337, 81–84,
 2012.
- Trivedi, A. and Chauhan, M. S.: Holocene vegetation and climate fluctuations in northwest Himalaya, based on pollen evidence
 685 from Surinsar Lake, Jammu region, India, *Journal of the Geological Society of India* 74, 402–412,
<https://doi.org/10.1007/s12594-009-0142-5>, 2009.
- Vahia, M. N., Kumar, P., Bhogale, A., Kothar, D. C., Chopra, Sundeep, Shinde, V., Jadhav, Nilesh, and Shastri, R.:
 Radiocarbon dating of charcoal samples from Rakhigarhi using AMS, *Current Science* 111, 27–28, 2016.
- Vahia, M. N. and Yadav, N.: Reconstructing the History of Harappan civilization, *Social Evolution & History* 10, e9506,
 690 <https://doi.org/10.1371/journal.pone.0009506>, 2011.
- Voarintsoa, N. R. G., Matero, I. S. O., Railsback, L. B., Gregoire, L. J., Tindall, J., Sime, L., Cheng, H., Edwards, R. L., Brook,
 G. A., Kathayat, G., Li, X., Michel Rakotondrazafy, A. F., and Madison Razanatseno, M. O.: Investigating the 8.2
 ka event in northwestern Madagascar: Insight from data–model comparisons, *Quaternary Science Reviews* 204, 172–
 186, <https://doi.org/10.1016/j.quascirev.2018.11.030>, 2019.
- 695 Walker, M., Head, M. H., Berkehamer, M., Björck, S., Cheng, H., Cwynar, L., Fisher, D., Gkinis, V., Long, A., Lowe, J.,
 Newnham, R., Rasmussen, S. O., and Weiss, H.: Formal ratification of the subdivision of the Holocene Series/Epoch
 (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new
 stages/subseries., *Episodes* 41, 213–223, <https://doi.org/10.18814/epiiugs/2018/018016>, 2018.
- Wang, J., Sun, L., Chen, L., Xu, L., Wang, Y., and Wang, X.: The abrupt climate change near 4,400 yr BP on the cultural
 700 transition in Yuchisi, China and its global linkage, *Scientific reports* 6, 27723, 2016.
- Wang, L., Brook, G. A., Burney, D. A., Voarintsoa, N. R. G., Liang, F., Cheng, H., and Edwards, R. L.: The African Humid
 Period, rapid climate change events, the timing of human colonization, and megafaunal extinctions in Madagascar
 during the Holocene: Evidence from a 2m Anjohibe Cave stalagmite, *Quaternary Science Reviews* 210, 136–153,
<https://doi.org/10.1016/j.quascirev.2019.02.004>, 2019.
- 705 Wang, S., Ge, Q., Wang, F., Wen, X., and Huang, J.: Abrupt climate changes of Holocene, *Chinese Geographical Science* 23,
 1–12, <https://doi.org/10.1007/s11769-013-0591-z>, 2013.
- Weiss, H.: Late third millennium abrupt climate change and social collapse in West Asia and Egypt, *Third millennium BC
 climate change and Old World*, edited by: Dalfes, H.N., Kukla, G., Weiss, H., Springer, 1997.



- 710 Weiss, H., Courty, M. A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., and Curnow, A.: The Genesis and Collapse
 of Third Millennium North Mesopotamian Civilization, *Science* 261, 995–1004,
<https://doi.org/10.1126/science.261.5124.995>, 1993.
- Weiss, H. and Bradley, R. S.: What Drives Societal Collapse?, *Science* 291, 609–610,
<https://doi.org/10.1126/science.1058775>, 2001.
- 715 Wright, R., Bryson, R., and Schuldenrein, J.: Water supply and history: Harappa and the Beas regional survey, *Antiquity* 82,
 37–48, <https://doi.org/10.1017/s0003598x00096423>, 2008.
- Wünnemann, B., Demske, D., Tarasov, P., Kotlia, B. S., Reinhardt, C., Bloemendal, J., Diekmann, B., Hartmann, K., Krois,
 J., and Riedel, F.: Hydrological evolution during the last 15 kyr in the Tso Kar lake basin (Ladakh, India), derived
 from geomorphological, sedimentological and palynological records, *Quaternary Science Reviews* 29, 1138–1155,
<https://doi.org/10.1016/j.quascirev.2010.02.017>, 2010.
- 720 Wurtzel, J. B., Abram, N. J., Lewis, S. C., Bajo, P., Hellstrom, J. C., Troitzsch, U., and Heslop, D.: Tropical Indo-Pacific
 hydroclimate response to North Atlantic forcing during the last deglaciation as recorded by a speleothem from
 Sumatra, Indonesia, *Earth and Planetary Science Letters* 492, 264–278, <https://doi.org/10.1016/j.epsl.2018.04.001>,
 2018.
- Yan, M. and Liu, J.: Physical processes of cooling and mega-drought during the 4.2 ka BP event: results from TraCE-21ka
 simulations, *Climate of the Past* 15, 265–277, <https://doi.org/10.5194/cp-15-265-2019>, 2019.
- 725 Zanchetta, G, Isola, I., Drysdale, R. N., Bini, M., Baneschi, I., and Hellstrom, J.: The So-Called “4.2 Event” in the Central
 Mediterranean and its Climatic Teleconnections, *Alpine and Mediterranean Quaternary* 29, 5–17, 2016.