Climate at 4.2ka BP and deterioration of ancient civilisations

Chantelle Karina Fuller

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School of Earth and Environment

The University of Leeds

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Abstract

The deterioration of three ancient civilisations: The Egyptian Old Kingdom, The Harappans of the Indus River Valley and the Akkadian Empire of Mesopotamia, are thought to be linked to a climate event at 4.2ka BP in which rapid aridification occurred (Cookson et al., 2019). To evaluate this theory, proxy data was collated and climate data between 4.5-3.6ka was simulated through the HadCM3 model to gauge precipitation, evaporation, temperature, river output and monsoon strength. The archaeological record was referenced to give context and evaluate non-environmental causes of collapse. A discrete '4.2ka event' was not evident for any of the three regions. In Egypt, there was a general weakening of the East African Monsoon and a more rapid weakening ~4.5-3.5ka which led to low Nile river levels that remained due to the monsoon strength not recovering post 4ka. Consequently famine occurred, partly due to social/political issues and when the Pharaoh Pepi II died, the Egyptian Old Kingdom came to an end (Butzer, 2012). The Indian Summer Monsoon also decayed in strength between 6-3ka but more rapidly between both 4.75-4.5ka and 4.2-4.2ka. Regions of the Indus River Valley closer to the Thar desert thus experienced diminished precipitation below the threshold for drought resistant crops, which led to mass migration beginning ~4.4ka and advancing further ~4.2ka (Petrie, 2017; Petrie et al., 2017; Green and Petrie, 2018). Mesopotamia also experienced two main climate excursions ~4.4ka and 4.1ka but this appeared to be part of a larger scale climate shift between 6-3ka. The North Atlantic Oscillation was neither positive nor negative and therefore was not the driving force of climate change. However, as the civilisation urbanised massively ~4.6ka, settlements pushed further into drier regions which would then be more susceptible to drought (Lawrence et al., 2021).

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Abbreviations

Ka BP – Kiloannum before present

THC - Thermohaline Circulation

ITCZ – Intertropical Convergence Zone

EAM – East African Monsoon

AHP – African Humid Period

ENSO - El Niño Southern Oscillation

ISM – Indian Summer Monsoon

NAO – North Atlantic Oscillation

BC – Before Christ

HadCM3 – Hadley Centre Coupled Model 3

TRIFFID – Top-down Representation of Interactive Foliage and Flora Including Dynamics

MSLP – Mean sea level pressures

SST – Sea surface temperature

ENA - Early Neoglacial Anomalies

P-E – Precipitation minus evaporation

TOC – Total Organic Carbon

Masl. – Metres above sea level

1.0 Introduction and Research Aims

Climate around the time of 4.2ka BP (Kiloannum Before Present) is thought to have undergone a 200-300y shift to conditions of high aridity, cooler temperatures and strong winds (Walker et al., 2018). Researchers who propose this climate 'event', namely Weiss et al. (1993) as one of the first proponents, suggest it was one of the most dramatic during the Holocene and marked the entrance to the Late Holocene (Weiss et al., 1993; Walker et al., 2012; Hill et al., 2023). This may not have been a global occurrence but is said to have affected several major ancient civilisations at the time, namely the Egyptian Old Kingdom, the Harappan of the Indus River Valley and the Akkadian Empire of Mesopotamia (Cookson et al., 2019). There are proxy studies that both allude to this event or do not show evidence of it at all, however, on such a short time span of 2-3 centuries, this could be due to the resolution of the data (Weiss, 2016). Others argue this is just because the event simply did not happen or was a small fluctuation not worth its title (Jaffe and Hein, 2020).

What is proposed to have happened ~4.2ka? Some researchers suggest orbital forcing caused shifts in climate, specifically across western Asia and North Africa starting ~5.5ka until ~4ka (Bar-Matthews et al., 1997; Weiss et al., 1993; deMenocal et al., 2000; Gasse, 2000). It is theorised that this was the cold and dry phase of a natural climate cycle on a millennial scale influenced by changes in the Thermohaline Circulation (THC) in the Atlantic Ocean. This would trigger less annual rainfall in East Africa, the Indian Subcontinent and western Asia (Wang et al., 2004). The question is, were these changes indicative of a shift in climate regime over thousands of years, perhaps culminating at 4.2ka in aridification that became too extreme to endure? Was there a brief event of extremity that civilisations did not have time to mitigate? Or did natural climate variability cause drought over settlements that were already beginning to come apart? (Bar-Matthews et al., 1997; deMenocal et al., 2000; Gasse, 2000; Weiss et al., 1993 in Staubwasser et al., 2003).

There are very few papers in the literature that use climate modelling to look at 4.2ka, one being Renssen (2022) who used Sea-Surface Temperature (SST) inputs to model El Nino fluctuations and the impacts leading to aridification in North Africa, Even Yan and Liu (2019) used an originally 21ka simulation to then focus on 4.2ka in a single paper. In their transient model, they compared single and multiple forcings such as meltwater flux, ice sheets, greenhouse gases and orbital variation but put forward that the 4.2ka period was specifically a northern hemisphere event caused by internal variability (Yan and Liu, 2019). However, they suggested that the timing of this seemed incidental within the context of the long-term solar

orbital variation pattern and therefore warrants further investigation but that there could be a link to a supposed positive phase NAO (Yan and Liu, 2019).

Within the palaeoclimate proxy record, many studies claim to show evidence of a 4.2ka event, even when only presenting data from one/few sites, but very few papers elaborate on the significance statistically compared to the mean variability expected in the regions (Scroxton and McKay, 2024).They can also be subject to confirmation bias, especially when on a smaller scale as local climate variability could show dry periods at some point throughout a 500 period and thus be assumed to come under the 4.2ka event (Scroxton and McKay, 2024). Although, it should be noted that even if climate variability is not significant enough or spatially coherent to warrant the title of climate event, there could still be large impacts on civilisations due to robustness (or lack thereof) (Scroxton and McKay, 2024).

Similarly, with the archaeological discipline in respect to collapse, research is often one/few site(s) based, in a specific region looking at one specific civilisation or where one/more are compared, it is not in great detail (Butzer, 2012). Due to radiocarbon dating limitations and also coincidence, archaeological history can sometimes be wrongly associated with climate events where the dating falls within a ~500y period (Baillie, 1991).

Monsoonal shifts, drought and changes in river output are thought to have played a part in the downfall of the three civilisations looked at in this study, but more research and climate simulations on both a global and regional scale are needed to ascertain whether climate was a major factor of their collapse or part of a larger stressor (Hassan et al., 2017; Giesche et al., 2019). There is a lot of dispute over how long the event supposedly was and the influences/forcings that could have yielded the specific climate variation, and a lot of papers only look at site specific proxy data or atmospheric processes that are simulated for one specific region's climate (Yan and Liu, 2019). No papers in the literature address not only the three specific ancient civilisations but in an interdisciplinary method using proxy, climate modelling and archaeological data. Hence, to investigate this, the following objectives were evaluated:

1. Is there evidence of a climate event at 4.2ka when proxy data is collated from the regions of the three ancient civilisations?
2. How do the proxy data and inferences align with climate modelling simulations of 4.2ka?
3. Does the archaeological record give further evidence of climate change at 4.2ka or evidence of other factors of collapse?

2.0 Literature Review

2.1 Climate Systems

2.1.1 Egypt: East African Monsoon

The proposed context behind climate in Egypt at 4.2ka involves several environmental factors, including the Intertropical Convergence Zone (ITCZ), the East African Monsoon (EAM) and flows of both the White and Blue Nile river channels (Welc and Marks, 2014). Several millennia before, from ~9.5ka-6ka marked the African Humid Period (AHP) or Mid-Holocene Wet Phase, when the ITCZ was more northerly, slightly above the location at present (*Figure 1)* (Bubenzer and Riemer, 2007; Marshall et al., 2011). The theorised increased intensity of the EAM at this time led to heavy precipitation in the Ethiopian Highlands which increased the flow of the Blue Nile, which is the predominant influx to the Nile river (Marshall et al., 2011; Welc and Marks; 2014).

Around 6-5ka marked the end of the AHP as the climate transitioned to more arid conditions. The ITCZ shifted southwards (*Figure 1*) and the monsoons over Ethiopia are suggested to have weakened (Welc and Marks, 2014). Due to this, the previously high flooding of the Nile became lower as the Blue Nile inflow reduced from the Highlands of Ethiopia. Sheet flooding still occurred in the North of Egypt theorised to be linked to the change in North Atlantic Oscillation (NAO), which may have had a connection to the southern shifting of the ITCZ (Welc and Marks, 2014). The climate model used by *Wang et al. (2004)* identified the possibility of a weakened THC at 4ka causing a rise in aridity in India, the Middle East and notably, East Africa. Many studies agree that climate from 5-4ka saw a shift towards higher levels of aridity, but whether there was a climate ‘event’ in Egypt at 4.2ka is still disputed (Welc and Marks et al., 2014).

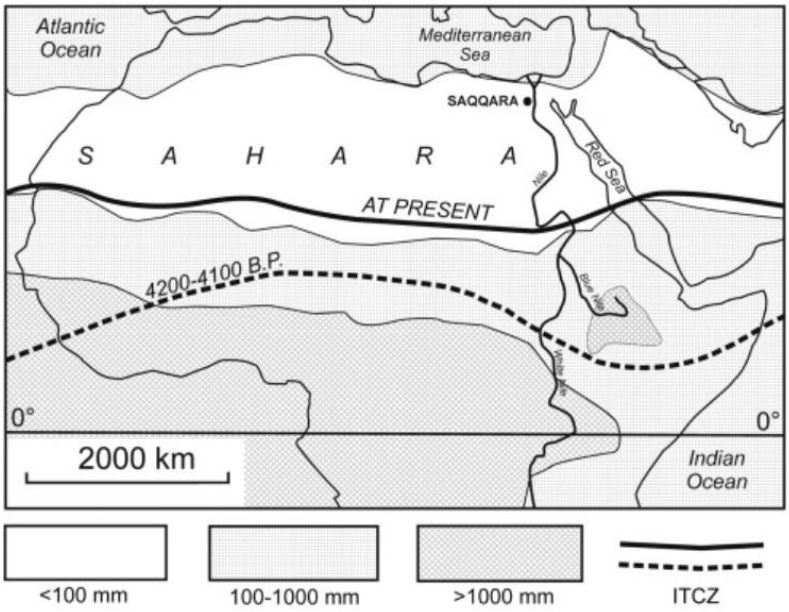


Figure 1: Showing migration of the Intertropical Convergence Zone (ITCZ) From Welc and Marks, 2014.

2.1.2 Indus River Valley: Indian Summer Monsoon

The proposed chronology of climate processes that drove climate ~4.2ka in the Indus River Valley starts with the Indian Ocean Dipole that was predicted to be in a negative phase at 4.3ka, leading to stronger El Niño Southern Oscillation (ENSO) events (Ashok and Guan, 2004; Abram, 2009; Toth et al., 2012). The intensity of ENSO at the time is thought to have caused ITCZ to shift more southerly, leading to the Indian Summer Monsoon (ISM) being delayed and also to occur over a shorter period (Dutt et al., 2018; Sinha et al., 2011; Berkelhammer et al., 2012). The ISM being weaker, would have meant less summer overbank flooding and Indus River discharge, which would have negatively affected agriculture that relied on the monsoon rains as up to 30% of all precipitation at the time came from the ISM (Giosan et al., 2012a; Giosan et al., 2018; Dutt et al., 2018). The winter monsoon has more debate around it and whether it was stronger or weaker in this time period (Giosan et al., 2018; Giesche et al., 2019). Giosan et al. (2018) put forward that the winter monsoon was strong between 4.5-3ka and although it brings drier airmasses, western disturbances bring winter rains (Dimri et al., 2015).

2.1.3 Mesopotamia: North Atlantic Oscillation & Westerlies

The civilisations that have made their homes across the Mesopotamian region throughout time have relied on the Tigris-Euphrates river system for their livelihoods; transport, irrigation, drinking water and food sources (Clarke et al. 2016). The more northern regions supported rain-fed agriculture whereas the more southerly regions used irrigation to enable cropping (Clarke et al., 2016). Unlike the Indus River Valley and Egypt, Mesopotamia was not a monsoonal region but instead the climate was thought to be influenced by the NAO, therefore, most of the annual precipitation was brought from the Westerlies (Lionello, Malanotte-Rizzoli, and Boscolo 2013). Studies put forward that around the time of 4.2ka, there could have been up to a 50% drop in rainfall that came from the Mediterranean Westerlies, and this would have predominantly affected Anatolia and Mesopotamia (Weiss et al., 2016). Persoiu et al. (2019) undertook a study on the Siberian High and put together a comprehensive theory on atmospheric circulation around the time of 4.2ka that could have led to the reduction of precipitation brought by the Westerlies. If the insolation gradient in the Northern Hemisphere high latitudes in summer and winter was high, this could have caused a weakened polar vortex and created a meandering jet (Persoiu et al., 2019). This would have produced an early winter in the north-east of Siberia, allowing an expansion of an enhanced Siberian High and also increased sea ice across the North Atlantic which would have weakened the subpolar gyre (Persoiu et al., 2019). The result would be a slowed THC with lower pressure in the ocean around Iceland which could have affected the NAO (Persoiu et al., 2019). Persoiu et al. (2019) argue for a negative phase NAO which was then blocked by the Siberian High while studies such as Jalali et al. (2019) agree that between 4.4-3.8ka, the subpolar gyre was weak but insist that this would have led to increased winter North Atlantic anticyclone blocking, influencing the NAO to be in positive phase and hence cause drier and colder climate across the Near East.

2.2 Ancient Civilisations

2.2.1 Egyptian Old Kingdom

Egypt around the time of 4.2ka was a land built upon irrigation farming, where pharaonic power controlled surpluses and assumed the role of a god over the people (Butzer, 1984; Bard, 1993). Being a kingdom within a desert, when Nile floods failed, migration of populations was not as simple as for in the Indus or Mesopotamia (Butzer, 2012). Compared to the other two civilisations in this study, the end of the Egyptian Old Kingdom is more complicated to

understand, and the evidence is more ambiguous (Höflmayer et al., 2017). As seen in *Figure 2*, the Egyptian Old Kingdom is said to have dissolved around the 9th dynasty, which would have been ~2180-2130BC (4.18-4.13ka) until its reformation in the 11th dynasty ~2040BC (4.04ka) (Butzer, 2012; Elkashef, 2023). The last significant ruler at the time was Pepi II, who some Egyptologists estimate ruled for between 90-100 years, but others suggest this is more likely between 30-60 years (Bard, 1993; Butzer, 2012). In the First Intermediate Period, 31 kings are listed after the time of Pepi II and overlap with one another so thus evidence the shift to decentralised power structures across Egypt as elites in the provinces scrabbled for power (Bard, 1993; Butzer, 2012). After Pepi II, there cease to be large pyramids and the pottery style, once uniform across the Old Kingdom is seen to develop into at least two distinct styles (O'Connor, 1974). Therefore, there was a gap without pharaonic power between dynasties 9-10 where the Old Egyptian Kingdom is said to have deteriorated, but this would eventually lead to the rebirthing of Egypt in what became known as the First Intermediate Period (Seidlmayer, 2003; Butzer, 2012).

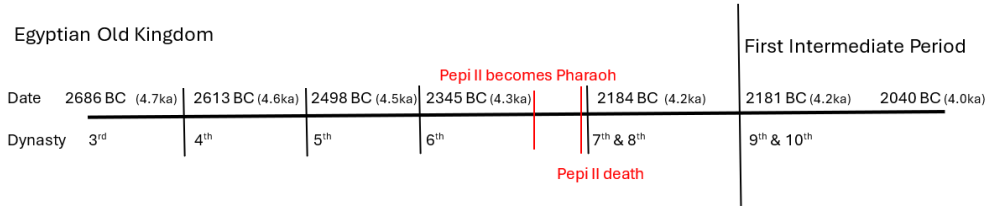


Figure 2: Timeline of dynasties of the Egyptian Old Kingdom (Butzer, 2012; Jiménez-Serrano, 2023).

2.2.2 Harappan Civilisation

In the Indus River Valley, the Early Harappan Civilisation is said to have appeared at ~3200 BC (5.2ka) and has partly remained a mystery due to the Harappan script still not having been deciphered (Kenoyer, 1997; Giosan et al., 2012a; Green and Petrie, 2018). The civilisation sat between the Indus and Ghaggar-Hakra river basins in the West and Ganges to the East, with a bigger territory than Mesopotamia and Egypt combined (Giosan et al., 2012b; Middleton, 2017). The society is theorised to have been egalitarian, or rather without a class of elites ruling (Green, 2020). By the Mature Phase, starting ~4.6-4.5ka, several cities developed, including Harappa itself, with an economy based in crafting (Giosan et al., 2012b; Sarker et al., 2016). Trade flourished across Asia with other regions such as Mesopotamia and Arabia until

2000 BC (4ka) where physical evidence of this ceased (Robbins Schug et al., 2013; Sarker et al., 2016). In Mesopotamia, writings cite that trade continued after 2000 BC with Magan and Dilmun, but not Indus (Robbins Schug et al., 2013). The Late Mature period 2200-1900 BC (4.2-3.9ka) was a time of transition as the previously thriving civilisation with trade, large urban areas and distinct pottery style shifted (Mughal, 1990; Robbins Schug et al., 2013). Around 2000 BC (4ka), detailed pottery with depictions of goddesses, steatite squares and script, made way for a simpler new style called Jhukar – mostly found in the lower Indus Valley (Mughal, 1990).

This cultural shift out of the Mature Harappan phase and into the Late Harappan phase then occurred ~1900 BC (3.9ka) but was asynchronous across the plain (Mughal, 1990; Sarker et al., 2016). Before this point, the Harappans had dealt with changes in climate, migration patterns and population but perhaps the circumstances at this time were much larger, rendering the civilisation unable to thrive any longer after 600-800 years of expansion (Robbins Schug et al., 2013; Middleton, 2017). Some of what were once large cities became much smaller or were even abandoned, population declined and also shifted to the North-East and towards the western Ganges basin and Yamuna river system beneath the Himalayas (Madella and Fuller, 2006; Kumar, 2009; Wright, 2010; Giosan et al., 2012a; Petrie et al., 2017). Between 1900-1000 BC (3.9-3ka), city living shifted to smaller settlements like villages as the civilisation went through deurbanization, with a much smaller population remaining in the core (Giosan et al., 2012b; Robbins Schug et al., 2013; Sarker et al., 2016). It is around this time that the Harappan script is alleged to disappear from the archaeological record, perhaps due to reduced connectivity between settlements across the sub-continent (Giosan et al., 2012b; Sarker et al., 2016). Although Harappan cities ceased to exist or grew smaller, the civilisation was not annihilated but instead shifted to a more rural disconnected way of living, and in doing this, the people were able to survive (Mughal, 1990; Sarker et al., 2016). There is still the question of why the people of the Indus River Valley shifted so dramatically in lifestyle after the society had hundreds of years of growth and prosperity. Researchers hypothesise trends of violence, poverty, natural disasters, overpopulation and hydrological change, but perhaps it was not one single issue but instead a culmination that became too great for the civilisation to handle (Mughal, 1990; Sarker et al., 2016).

2.2.3 Akkadian Empire

Mesopotamia, the ancient region between the Tigris and Euphrates river valleys was an expanse over the plains of what we now call modern day Iraq, South-East Turkey, Syria and Kuwait (Ur, 2010). Culturally and environmentally, the region was split North and South, with northern Mesopotamia having rivers flowing from high relief in narrow channels which was harder to irrigate but precipitation levels allowed for crop varieties that did not require high annual rainfall (Wilkinson 2003; Ur, 2010). Whereas, southern Mesopotamia's flatter parts of river were slower, dropping silt and allowing the Euphrates to flow higher which aided irrigation in urban centres like Akkad (Wilkinson, 2003). Ancient civilisation in this region, particularly in northern Mesopotamia is thought to have emerged ~4400 BC (6.4ka) and lasted until ~2000 BC (4ka), but where deterioration is investigated at this end point ~4.2-4ka, perhaps was no different to the cycles of growth and retraction that the region had seen before (Ur, 2010).

Pre-3000 BC (5ka), southern Mesopotamia had been expanding and urbanising but over the next 400y, the civilisation retreated to more rural living and urban populations such as Uruk, collapsed (Ur, 2010). Researchers such as Lawrence et al. (2021) hypothesise population growth from 4000 until 2700 BC (6.0-4.7ka). In northern Mesopotamia, parts of Tell Brak were depopulated as settlements shifted to smaller villages away from urban cores (Wilkinson, 2000). This is evidenced in the pottery of the time, which switched from a general style to unique regional ceramics, indicating reduced connectivity across Mesopotamia (Ur, 2010). The burials at the time did not suggest a centralised power or state nor niche artisan works, but there was still a sense of hierarchy socially (Akkermans and Schartz, 2003).

2600 BC (4.6ka) brought about a new cycle of complexity as some villages expanded to become new urban centres (Akkermans and Schwartz, 2003; Stein, 2004; Wilkinson, 1994). At this time, large labour forces were mobilised to produce new palaces, temples and city walls surrounding them and cuneiform tablets start to appear in the records (Archi and Biga, 2003; Ismail et al., 1996; Ur, 2010). Social complexity increased with new institutions as well as the re-introduction of the artisan class producing new ceramics, metalwork and other crafts and this snowballed into the rapid rise in production of crops as populations boomed (Ur, 2010). In the North, settlements such as Hamoukar, Tell Mozan and Tell Leilan that started from ~15ha grew to between 90 and 120ha within 100y (Pfalzner et al., 2004; Ur, 2002; Weiss and Courty, 1993). Rural settlements, however, saw populations decline during this period as populations in urban

centres rose to a peak between 2400 – 2200 BC (4.4-4.2ka) and the civilisation entered the Akkadian phase (Lawrence et al., 2021).

This state of rapid urbanisation did not persist, as similarly to the previous cycle of de-urbanisation, 400y after its initiation, came plateau and then decline (Ur, 2010). In the drier South, this is thought to have been ~2300 BC (4.3ka) and for the wetter North, ~2200 BC (4.2ka) (Lawrence et al., 2021). In urban settlements of northern Mesopotamia, abandonment in perpetuity is suggested to have occurred over one phase of pottery style and in other cities that did eventually re-populate, this is theorised to have happened long after the Akkadian phase (*Figure 3*) (Ur, 2010). Researchers debate whether this 'collapse' of the Akkadian Empire of Mesopotamia occurred rapidly over 100y (Lawrence et al., 2021), even more rapidly at the hands of a climate event such as volcanism (Weiss et al., 1993), was asynchronous across the plains, or if a 'collapse' even happened at all (Akkermans and Schwartz, 2003; Marro and Kuzucuoglu, 2007).

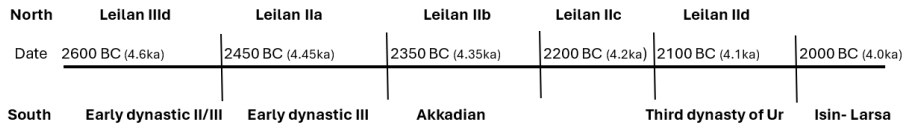


Figure 3: Timeline of civilisations and periods of Mesopotamia (Weiss in Hoflmayer et al., 2017).

2.3 Collapse Theory

There is a lot of debate in the literature over the definition of collapse and also many synonyms that adjust the way we view it (Schwartz, 2006; Lawler, 2010; Middleton, 2012). 'Collapse' creates imagery of a catastrophic failure whereas 'decline' and 'fall' conjure up more gradual breakdown and 'transition' or 'transformation' paint a more positive, less violent picture of change (Middleton, 2012). Tainter (1988) put forward the idea that collapse happened quickly, with major decline of social and political structures that had once been complex. In the theory of diminishing returns, this was due to a civilisation reaching a threshold of growth that could no longer be maintained as the efforts and hazards became far larger than the returns (Tainter, 1988). Kemp in Centeno et al., (2023) argued the theory should not be based on complexity but rather extraction, with the catalyst of collapse being the extortion of both natural resources and inhabitants of a civilisation, leading to scarcity and deficits. Whereas Diamond and Smil (2005) said collapse must include one or more of the following factors: depletion of

environment (often but not limited to the effects of overpopulation), lack of trade, climate change, hostility and lack of cultural robustness (Maggio, 2017). There is the question of what does collapse look like? Researchers suggest decentralisation of state, abandonment of urban cores, decreased interconnectivity, disintegration of elite structures and either population decline or change in culture (Schwartz, 2006; Lawler, 2010; Middleton, 2012). The evidence of this would look like significant shifts to resource management/agricultural planning, migration away from urban centres and loss of construction, artisanal works and monuments (Middleton, 2012). One of the reasons that collapse is not simple to define is that in the context of ancient civilisations, it mostly impacted urban and elite populations and sometimes had positive impacts on those living rurally, away from the control of state (Haldon, Chase et al., 2020). Civilisations have always been cyclical; how do we differentiate change of dynasty or regime vs collapse? (Marcus, 1998; Middleton, 2012; Chapter 1 in Centeno et al., 2023). Of course, civilisations often experience periods of growth and retraction across time, as most systems in nature (humans included) are cyclical rather than linear (Chapter 1 in Centeno et al., 2023). Modern society emphasises growth and expansion and perhaps ancient civilisations also thought they could transcend the inevitable cycle of everything, but going against the natural rise and fall can make systems vulnerable (Chapter 1 in Centeno et al., 2023). While focused on expansionism and being optimistic of the civilisation's future, the system could be reaching a peak or threshold which then leads to rapid decline (Chapter 1 in Centeno et al., 2023). Most do agree collapse comes after a tipping point where the society breaks down whereas dynasties often come with shift in powers, where an elite class remains or shortly takes control (Chapter 1 in Centeno et al., 2023). Although it can seem abrupt, there are often several factors contributing to breakdown, with feedback loops or synchronous failures that eventually overburden the various connected systems that make up a civilisation (Butzer, 2012; Chapter 1 in Centeno et al., 2023).

2.3.1 Components of Collapse

Collapses can be put into three categories of cause: purely endogenous, purely exogenous or a mixture of the two (Chapter 1 in Centeno et al., 2023). Exogenous meaning external causation which can include the climate, invasion or natural disasters and endogenous meaning internal causation, based on governance and political/economic issues (Chapter 1 in Centeno et al., 2023). In the case of mixed, this is where an exogenous factor places strain on a system that is already experiencing endogenous problems (and vice versa), which could be the tipping point

to collapse (Chapter 1 in Centeno et al., 2023). Other factors involved in collapse include feedback loops which can be positive or negative – despite the name, positive feedback loops amplify existing issues and drive a system towards collapse to reach a new equilibrium (Miller and Page, 2007; Chapter 1 in Centeno et al., 2023). Negative feedback loops, however, negate incoming shocks which can be beneficial in the case of resisting against natural disasters but detrimental if a dictatorship needs to be overthrown (Walker and Salt, 2006; Chapter 1 in Centeno et al., 2023). An example of positive feedback loops could be certain environmental factors (internal – human influences like deforestation/soil degradation or external – lack of groundwater due to drought) which can seem small but become larger issues over time. When these factors interact with endogenous shocks like ineffective agricultural planning, farmer strikes or migration away from rural areas, the effect becomes exacerbated (Butzer, 2012).

Contagion can also be a catalyst of collapse, when different areas of a civilisation are thought of as nodes in a system and contagion is the passing of information or impacts across nodes. Due to the interconnectivity, shocks can permeate across nodes of a civilisation, whether it be anarchist ideas, disease or crop failures (and resulting economic impacts) (Chapter 1 in Centeno et al., 2023). This can even create a cascade, where one/several nodes reach a tipping point and contagion follows, causing collapse to the entire system with synchronous failures (Butzer, 2012; Chapter 1 in Centeno et al., 2023). This is particularly difficult to avoid as often systems are prepared for singular failures, whereas collapse is often multicausal and systems often lack surplus resources to handle simultaneous shocks (Butzer, 2012; Chapter 1 in Centeno et al., 2023).

2.3.2 Environmental Triggers

Often in the literature, collapse theory focuses on environmental causation (Diamond and Smil, 2005; Middleton, 2012; Butzer, 2012). In recent times, with human impact on climate (and the inverse) in the media, perhaps projection of this onto ancient times is more commonplace (Tainter in Centeno et al., 2023). Environmental theories focus on three main branches: Natural disasters, land degradation and climate change (Diamond and Smil, 2005; Middleton, 2012). This includes, abrupt natural events or climate shifts, general climate variation and human impact on the landscape (Tainter in Centeno et al., 2023). Environmental factors can act as triggers of civilisational breakdown but also, they can precondition systems for collapse from other factors (Butzer, 2012). Singular variations or events may seem non-threatening but over time can amplify and in combination with endogenous factors like civil war or inefficient

governance, reach a tipping point (Butzer, 2012). Factors can also be coupled and reinforcing, such as crop failure leading to enhanced pressure on farming the land which can increase degradation and cause further failures. Drought and floods can both lead to further land deterioration as well as affecting other factors such as pandemics or epidemics, leading to higher mortality rates (Butzer, 2012). In all 3 civilisations looked at in this study, researchers state climate change as a major factor of their supposed collapse but also other internal factors such as civil conflict are noted by several studies (Tainter in Centeno et al., 2023). There is the question of whether climate is focused on predominantly at the detriment of sociopolitical dynamics of civilisation (Middleton, 2012; Butzer, 2012).

2.3.3 Resilience in the face of collapse

When systems are built to handle shocks and mitigate issues, they can be robust and resilient in the face of potential collapse (Levin and Lubchenco, 2008; Walker and Cooper, 2011; Evans and Reid, 2013). This does not mean there is never failure in some nodes of a civilisation but there is adaptability that enables quick recovery, so why is resilience not built into every system? (Butzer, 2012). Robustness requires governance, capital and upkeep which is why there are often weaknesses in every system but unfortunately this enables the possibility of collapse, especially by internal means (Chapter 1 in Centeno et al., 2023). Growth and efficiency are often prioritised over surplus and reserves in production, requiring more and more reliance on the agriculturalists in rural areas and meaning failures can easily cascade across the nodes (Chapter 1 in Centeno et al., 2023). Butzer (2012) puts forward a conceptual model of historical collapse in which civilisations can experience triggers of collapse, but it is how they respond that seals their fate. On one side, initial breakdown and decadal instability can escalate to advanced breakdown and collapse (on a centennial scale) but there is also the possibility for stabilisation through adaptation and resilience which can lead to reconstruction and reconstitution (Butzer, 2012). Whether a civilisation goes down one branch or the other depends on built-in planning but also lack of rigidity in the face of hardship, resilience requires adaption and re-adaptation that societies must be prepared to undergo (Butzer, 2012).

Collapse is a complex subject and is subjective in the eyes of different researchers but in general is recognised by patterns of populations moving from urban centres, reaching a threshold of growth and social/economic downturn (Schwartz, 2006; Lawler, 2010; Middleton, 2012). Urban cores and elite groups are affected predominantly, and rural communities can sometimes see benefits of urban decline (Haldon, Chase et al., 2020). The forced linear growth

of modern and ancient civilisations can experience breakdown as nature is cyclical with periods of growth but also retraction (Chapter 1 in Centeno et al., 2023). There are usually multiple factors of civilisational decline, which can be external, internal or often a mixture of the two with coupled factors leading to amplification (Chapter 1 in Centeno et al., 2023). Interconnectivity is important for the rise of urbanisation, but nodes of a system can experience contagion of shocks, meaning the system takes several hits simultaneously that cannot be mitigated (Butzer, 2012; Chapter 1 in Centeno et al., 2023). Climate and the environment can be creeping factors that seem small but build up over time and allow endogenous events to have bigger impacts that can snowball into collapse (Butzer, 2012). Therefore, it is important to have an interdisciplinary view of collapse theory and not just focus on the environment, even in the case of abrupt and catastrophic natural disasters (Butzer, 2012; Middleton, 2012). At the first signs of breakdown, or even before, societies can choose the resilience pathway with cooperation, mitigation, flexibility and adaptation, to continue on and thrive in the face of adversity (Levin and Lubchenco, 2008; Walker and Cooper, 2011; Evans and Reid, 2013).

3.0 Methods

In order to understand how climate may have changed ~4.2ka, proxy data and studies were collected and evaluated from in and around the regions of the three civilisations in question. A climate simulation was produced using the Hadley Centre Coupled Model 3 (HadCM3) and ran from 5-3ka, with this study focussing on the period from 4.5-3.6ka. Using the locations of the proxy sites, climate modelling data was then assessed to see if theories about climate patterns from the proxy studies could be further proven/disproven in the model. The features of climate focused on were precipitation, evaporation, temperature and river output. Trends were analysed on a site-by-site basis, on the scale of the civilizations, and on a larger regional scale to analyse large-scale atmospheric/oceanic processes such as monsoons. Spatial maps of precipitation were created to see regional patterns and monsoon/oscillation indices were calculated for both the EAM, ISM and NAO. Finally, these results were compared to archaeological research to evaluate both potential reactions to climate change and also other human factors which may have contributed to or caused collapse.

3.1 Data

3.1.1 Proxy data collection

Secondary proxy data was collected from online journals and databases from locations close to the three civilisations or in regions with relevant influence over the climate/hydrology. For Egypt, these locations were mostly former branches of the Nile, along the Nile river valley or in Lakes of East Africa where the Nile sources flow. For Indus, proxies came from nearby oceans, palaeolakes in the Thar desert, caves and lakes close to the Himalayas. For Mesopotamia, proxies were from caves in the Levant, sites in Southern Anatolia, two sites close to the Tigris-Euphrates and lakes further East. Many different proxy types were used, with sediment cores being the most abundant from land, lakes and the ocean. Other studies used geology/sediments, pollen, diatoms, gastropods, planktonic foraminifera, isotopes such as oxygen, carbon and deuterium, charcoal, isotopic ratios and cave speleothems. Where direct data was available, it was plotted to analyse trends. Other data and theories associated with it were collated and compared both by locality and also groups of similar proxy type.

3.1.2 Climate modelling

Transient climate model simulations from 5-3ka were performed using the HadCM3 coupled ocean-atmosphere General Circulation Model of the UK Met Office Unified Model (Gordon et al., 2000; Pope et al., 2000). This version has an atmospheric resolution of 3.75° × 2.5° with 19 vertical levels, and a 20-level ocean with a resolution of 1.25° × 1.25°. The model was run with the MOSES2 land surface scheme incorporating interactive vegetation through the TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) model (Cox, 2001; Valdes et al., 2017). River output is calculated from a simple water balance model, where the excess water from each grid box is added to the appropriate ocean grid boxes.

HadCM3 may be lower resolution than many of the latest climate models and does not include some of the components that have been added in the latest generation of Earth System Models. However, this means that the model runs at significantly less computational cost and enables long transient simulations. The model produces a good historical simulation of climate, and it produces large-scale features of the climate and precipitation that compare favourably to observations (Stott et al., 2000; Valdes et al., 2017) and has one of the better representations of monsoon precipitation (Anand et al., 2018). This simulation was initialised from the end of a 250-year continuation of a spun up pre-industrial simulation under the greenhouse gas and

orbital forcing appropriate to 5ka (Cookson et al., 2019). This was then run for a further 2000 years under changing greenhouse gas forcing, from transient changes in carbon dioxide concentrations (Monnin et al., 2004), nitrogen dioxide (Flückiger et al., 2002) and methane (an average of Greenland (Blunier et al., 1995) and Antarctic (Flückiger et al., 2002) ice core measurements) and changes in orbital forcing (Laskar et al., 2004) that were implemented every 50 years (*Figure 4*). All other climate model boundary conditions were kept as present day, including volcanic forcing, meltwater flux and ice sheets as there were not significant changes in these features during the time period 5-3ka, especially when investigating a climate event on a 100-300y timescale.

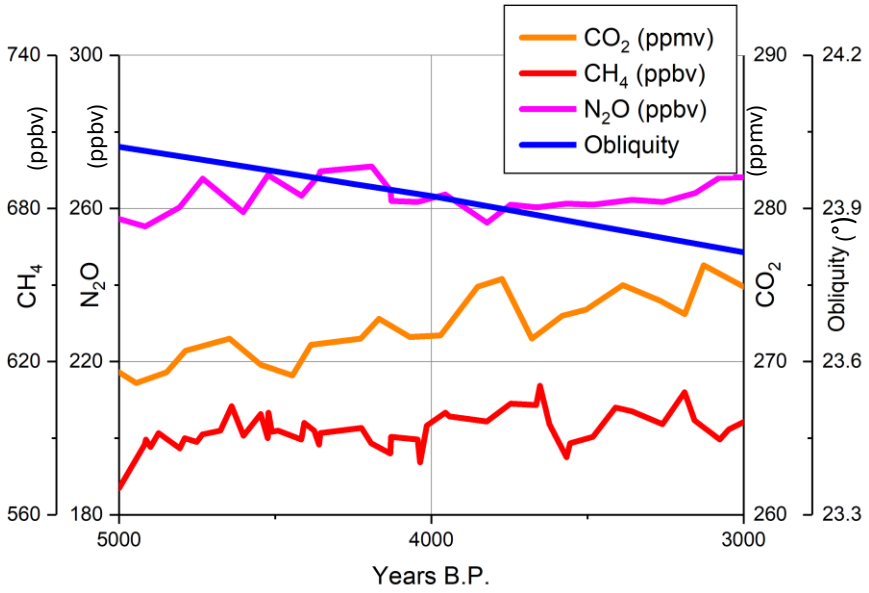


Figure 4: Climate forcings used in HadCM3 transient simulation. Atmospheric concentrations of carbon dioxide (Monnin et al., 2004), methane (Blunier et al., 1995; Flückiger et al., 2002) and nitrogen dioxide (Flückiger et al., 2002), with only the obliquity component of the full orbital solution shown (Laskar et al., 2004).

3.1.3 Archaeological research

The archaeological research of this thesis was secondary research from online journals and books. This included archaeological data and hypotheses and was used as a tool to gather a more interdisciplinary view of events ~4.2ka as climate/proxy studies and archaeological studies can often be separate with opposing views. Recent history of the civilisations (~1000y before 4.2ka) was evaluated to highlight potential previous cycles of retraction and growth or any past responses to climate changes. This research enabled a view into potential evidence of climate change at 4.2ka through any adaptations/mitigation of climate change or lack thereof

but also exploration of other potential factors of collapse that were social/political/economic, highlighted through the archaeological record.

3.2 Analysis

3.2.1 Climate data plots

In order to analyse the climate modelling data, python programming was used in Jupyter Notebook. The NetCDF data was read into the programme as well as the coordinates of proxy sites. The data was then interpolated, and plots were produced for total precipitation rate, precipitation minus evaporation, temperature at 1.5m and river output (for the River Nile, Tigris-Euphrates Basin and the Indus River), running from 4.5-3.6ka. Precipitation minus evaporation was used instead of just evaporation in order to gauge changes in aridity, as if precipitation was high at a time of higher evaporation, they may have cancelled each other out. 10y average running means were used to see clearer plots of the data through time and any patterns that may have emerged. Precipitation and precipitation minus evaporation were converted from $kg/m^2/s$ to mm/year and temperature from kelvin to degrees Celsius. The coordinates of proxy sites were used to generate plots for each site, except temperature plots which were only generated for key sites.

3.2.2 Spatial maps

For creation of the spatial maps, NetCDF files were read into Panoply to generate maps of 100y precipitation averages. This enabled visualisation of trends over large regions close to the civilisations and associated regions of climatic influence. Maps were generated for 100y averages between 4.3-4.2ka and 4.2-4.1ka. Then further visualisations were created of the difference between the two, highlighting how the 100y averages had changed and to see if a '4.2ka event' was evident. This removed the high levels of interannual variability and was a test of whether the 4.2ka event occurred on the centennial timescales hypothesised for this event. An f-test was used and plotted onto the figure for understanding of the significance of the centennial changes.

3.2.3 Monsoon & Oscillation indices

With many studies from the proxy research papers theorising change of the East African and Indian Summer Monsoons, a monsoon index was thought to be useful as a tool to analyse the proposed change in monsoon intensity. Firstly, orography and annual mean sea level pressures (MSLP) over East Africa and North of the Indus Valley were used to define locations for comparison against nearby MSLP in the Arabian sea. The maximum monthly land-sea MSLP contrast for each year in a 2000y simulation was then used to produce a normalised (mean of zero and standard deviation of one) annual monsoon index. Pearson's correlation coefficient was calculated between the monsoon index and a key proxy site location's precipitation (Lake Tana for EAM and Kotla Dahar for ISM). The precipitation data for both the monthly maximum and the total annual precipitation was simulated over 4000y between 6-2ka. The coefficient was calculated on annual, decadal and centennial scales, giving confidence in calculated centennial mean monsoon indices. Correlation of the index to surrounding grid boxes showed that the index was reflecting the wider monsoon region.

The process was similar for the North Atlantic Oscillation, using MSLP gradients in the North Atlantic Ocean which when the centennial mean was plotted, highlighted whether the NAO was in positive or negative phase.

4.0 Results

4.1 Proxy data

4.1.1 Egypt

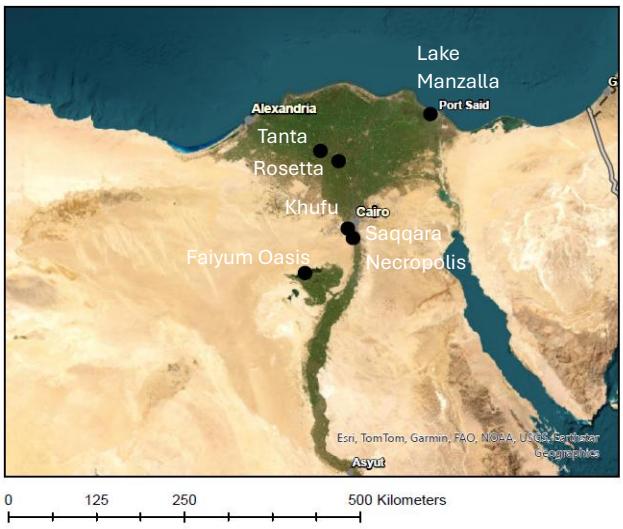


Figure 5: Map of sediment cores in Egypt. Data from Welcs and Marks, 2014; Sheisha et al., 2022; Stanley et al., 2003 and Marks et al., 2018.

Saqqara-Memphis, 30m

Sediment cores were evaluated at Saqqara-Memphis in a study by Hassan et al. (2017) and found thick alluvial sediments and evidence of vegetation dating to 5ka which indicated wet climate in this region in what would have been the AHP. This aligns with the dating of successful pyramid building from 4.6-4.2ka in the Saqqara area when Nile waters could be used to transfer materials by boat (Hassan et al., 2017). In the SAQA6 core, there are indications of dune invasion at 4.25ka from the Western Desert that would have extended from Saqqara to Abusir – highlighting a shift to less climatically favourable conditions (Hassan et al., 2017). From 4.2-4.0ka, the cores are marked by an erosional surface, indicating a dry period that Welc and Marks (2014) also investigated in their study nearby at Saqqara Necropolis.

Saqqara Necropolis, 30m

Similarly to Saqqara-Memphis, sediment cores at Saqqara Necropolis also demonstrated intense rainfall seasons with high run-off events leading up to 4.2ka as shown by thick layers of debris from sheet and mud flows (Welc and Marks, 2014). During this phase, there were no

erosional layers in the cores, demonstrating the intensity of hydrological events that could have occurred in a single season (Welc and Marks, 2014). This supports depicted images in tombs dated around the time at Saqqara and Abusir of vegetation and trees, allowing inference of a much wetter conditions than the desert climate that emerged post 4.2ka and remains in the modern day (Butzer, 1976). Between 4.1-4.0ka, there is a phase in the sediment cores of wind-blown thinly laminated sediment that consists of sand and limestone of various grain sizes which were deposited at differing wind speeds (Welc and Marks, 2014). Welc and Marks (2014) identified this geology as evidence of a quick shift to a more arid climate with strong winds and only occasional wintry rainfall (Trzcinski et al., 2010).

Khufu Branch, 20m

The Khufu branch is a now extinct part of the Nile which enabled movement of materials by boat through the Delta during the AHP (Sheisha et al., 2022). Sheisha et al. (2022) used pollen as a proxy and analysed the pollen of various plant families found in the cores. Plotting the data, this highlights that populations of plant families that thrived in wetter environments started decreasing after 5ka and then reached a minimum at 4.125ka (Figure 6). For tropical Nilotic taxa, these families had the most dramatic decline and reached a minimum earlier ~4.4ka, then stabilised until further dropping after 4.125ka. Helophytes were able to increase in population between 4.7-4.4ka but then decline until 4.125ka. Cyperaceae followed a similar decline like tropical Nilotic taxa but smaller until ~4.7ka and then a similar increase like helophytes but smaller until 4.125ka. Tropical Nilotic taxa were the only families to decline post 4.125ka, whereas the other two plant families increased in populations. Higher water levels are associated more with higher populations of Cyperaceae (Papyrus and sedge) and Helophytes (Sheisha et al., 2022).

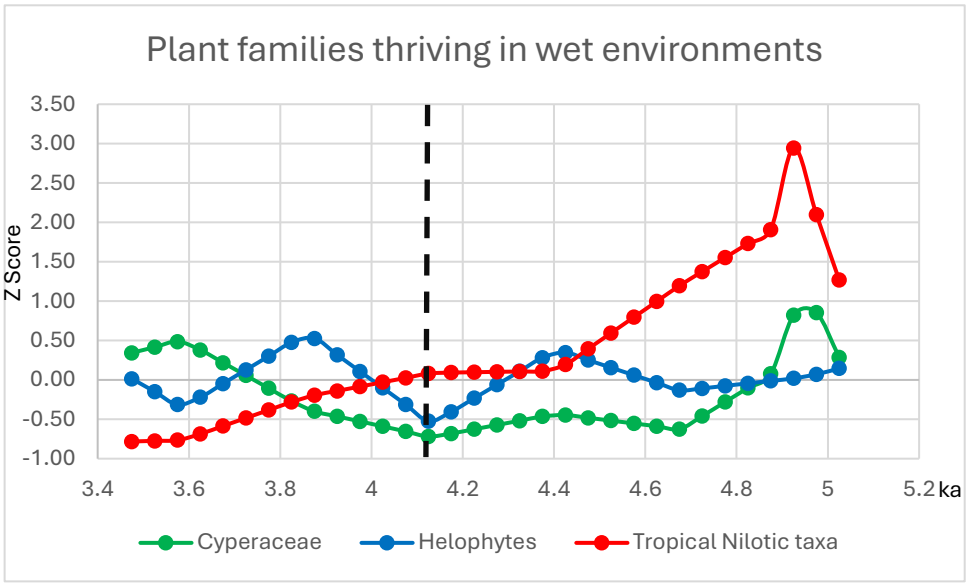


Figure 6: Graph showing z scores (standard deviations above the mean) of Cyperaceae, Helophytes and Tropical Nilotic taxa populations from 3.5-5ka from sediment cores at the Khufu branch. These populations thrived under wet conditions. Data from Sheisha et al., 2022.

Faiyum Oasis (Qarun), -45m

The water level of Faiyum Oasis depended on seasonal floods of the Nile which correlated with monsoonal precipitation over the Ethiopian highlands that feed into the Blue Nile and Atbara rivers (Hassan et al., 2011; Marks et al., 2018). The sediment core here in the study by Marks et al., (2018) indicated that in the depth dating between 4.4-3.0ka, there was an increase of Mg^{2+}, Ca^{2+} and SO_4^{2-} ions, indicating increased salinity in the lake from lack of Nile inflow and hence diatom values also appeared lowered. Sand sediments dated to 4.4-3.0ka indicate sheet flooding from rare rainfall events but partial desiccation of the lake (Welc and Marks, 2014). The diatom genus of *Stephanodiscus* increased in the assemblage, theorised due to high winds in the winter leading to enhanced mixing of the water column (Marks et al., 2018). As the diatom species *Aulacoseira* only blooms seasonally in winter, its presence demonstrated occasional winter inflows from the Nile and there were also clayey silts which would have provided influxes of nutrients (Marks et al., 2018). The sediment core had an absence of diatoms until 3.2ka, when there was evidence that the oasis became brackish and then shifted back to a freshwater lake between 3.0-1.5ka (Marks et al., 2018). Marks et al. (2018) theorise a longer arid phase lasting for over 1000y and ending at 3.2ka.

Rosetta and Tanta branches of the Nile (S-86 and S-87), 15m

Two sites of sediment cores on the western side of the Nile Delta (S-86 and S-87) were studied by Stanley et al. (2003). Although found to date at different points, both of these cores had phases with a thin red-brown silt layer of iron/manganese hydroxide which was created by chemical reaction when sediments are exposed to air (Stanley et al., 2003). The identifying streak remains in the sediment record even after further submersion so can highlight times when discharge was at a minimum (Stanley et al., 2003). For the S-86 core at Rosetta, this appeared at 4.25ka and for the S-87 core near Tanta, later at 4.05ka (Stanley et al., 1996).

Lake Manzalla, Nile Delta (S-21) (1m)

The changes of dominating inflow from the White or Blue Nile catchments can be measured by the Strontium isotope ratios which showed in the S-21 core that between 6.1-4.2ka there was a shift in prevalence from White Nile sediment to Blue Nile sediment (Stanley et al., 2003). The minimum 87Sr/86Sr ratio appears at 4.2ka, which would indicate low Nile discharge at this time. This usually correlates with higher reliance on the Blue Nile waters, coming from the Ethiopian Highlands which are influenced by the strength of the EAM (Stanley et al., 2003). Therefore, in order to explore this, proxies must be evaluated further South on the continent, in the monsoon-influenced region of East Africa.

4.1.2 East Africa

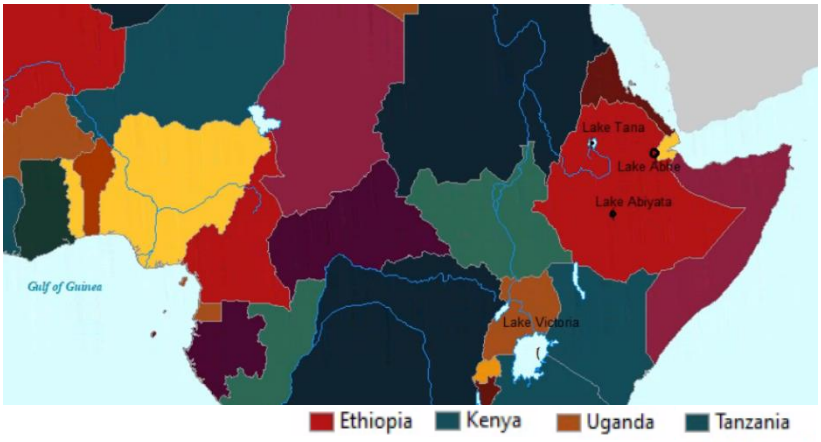


Figure 7: Map of Eastern Africa showing locations of lake sediment cores. Data from Marshall et al., 2017; Chalié and Gasse, 2002; Mologni et al., 2021; Stager et al., 2003a.

Lake Tana, Ethiopia – Blue Nile, 1780m

There is a gradual shifting to more arid conditions assumed from this site, starting from 6.8ka and terminating at 4.2ka (Marshall et al., 2011). The lowest value of sediment supply at this time highlights low moisture availability and the relatively high levels of antiferromagnetic minerals seen are theorised to have come from dry, oxidised soils (Marshall et al., 2011). The evidence of climate shifts in this region agrees with the theory of a more southerly ITCZ and weaker ISM but the study puts forward the case for a gradual aridification, rather than a climate event (Marshall et al., 2011). As a source for the main Nile river, the decreased lake level and thus decreased Blue Nile flow would have caused drought across the Nile delta and in particular the summer flood season that fed Egyptian agriculture (Welcs and Marks, 2014).

Lake Abiyata, Ethiopia, 1170m

Climate events of lake deterioration are recorded at 5.6ka and 3.0ka, but not around 4.2ka (Chalié and Gasse, 2002). In particular, between 5.4-3.8ka, the lake was shallow with increased salinisation and a high population of periphytic diatoms which decreased towards 3.8ka with more freshwater intrusion (Chalié and Gasse, 2002). The climatic history of this lake follows a similar pattern of other lakes in the area, like Lake Abhe (Chalié and Gasse, 2002; Mologni et al., 2021).

Lake Abhe, Ethiopia, 240m

This lake saw a gradual reduction in water level from 5.6-4.6ka where the sediment core then had evidence of a sharp decline marked by the absence of littoral sedimentation (Mologni et al., 2021). Lake Abhe then began to see higher levels from 2.8ka, reaching a peak at 1.5ka (Mologni et al., 2021).

Lake Victoria – White Nile, 1130m

The most Southerly lake of the sediment cores, Lake Victoria, borders across Uganda, Kenya and Tanzania (Kayombo and Jorgensen, 2006). The lake levels here reduced after 5.8ka, similar to other lakes of the region but there may have been a small increase around 4.0ka (Stager et al., 2003a). Unfortunately, there are gaps in the diatom proxy data between ~4.2-4.6ka, which is not explained by Stager et al. (2003a). This aside, the general trend of the data is increasing

diatom populations over time with inter-decadal variation. This variation is increased between 4.23-4.09ka (Figure 8).

Berke et al. (2012) also researched Lake Victoria by sediment core analysis but looking at the carbon 13 ($\delta^{13}C$) and deuterium (δD) levels in terrestrial leaf waxes which they used as a proxy for precipitation levels. TEX_{86} was also used as a proxy for palaeotemperature and the lowest temperature of the Holocene in the lake was estimated to be between 4.5-4.0ka after a slow decline from ~8ka, with then a further slow decrease of 0.5˚C after 4ka to present day (Berke et al., 2012). δD began to decline after 10ka and reached a low between 4-3.5ka and there were two anomalous periods in the $\delta^{13}C$ data. These were between 10-8ka and 4.7-2.6ka, where there was more variation in the former and a more obvious pattern of decline in the latter (Berke et al., 2012).

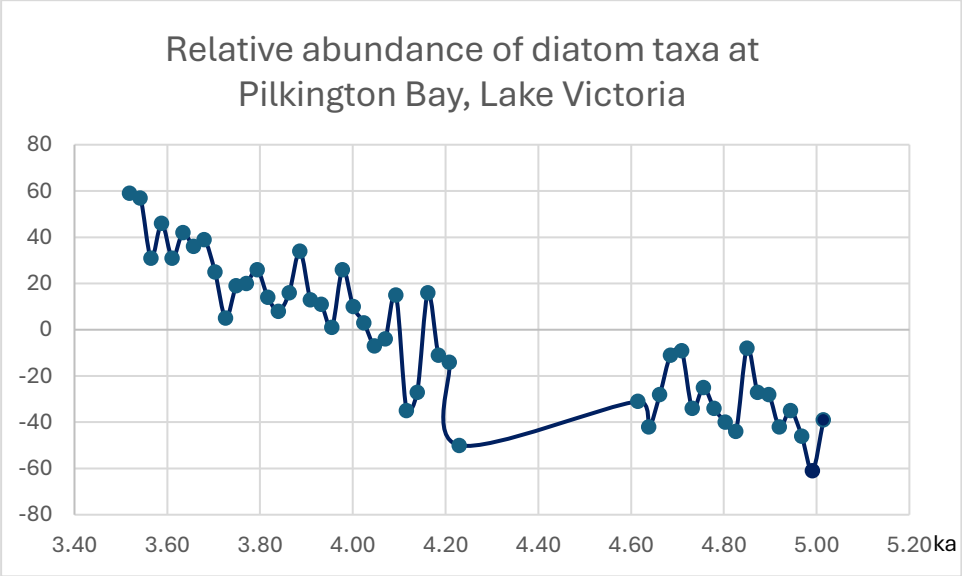


Figure 8: Relative abundance of shallow and deep-water diatom taxaat Pilkington Bay, Lake Victoria from 5.1-3.5ka. With missing data from 4.6-4.2ka. Data from Stager et al., 2003b.

Summary

To summarise, Lake Manzalla at the northerly point of the Nile Delta saw shifts from White Nile sediments to Blue from as early as 6.1ka until 4.2ka, when evidence suggests that the Nile had its lowest discharge (Stanley et al., 2003). The sediment cores at the Rosetta and Tanta branches of the Nile gave evidence of aridity and low Nile discharge between 4.25-4.05ka ((Stanley et al., 2003). The Saqqara region saw sand dunes expand across the area ~4.25ka and underwent a rapid shift from intensive flooding during the AHP, to a very windy and dry climate

up until ~4ka (Hassan et al., 2017; Welcs and Marks, 2014). The extinct Khufu branch of the Nile experienced vegetation changes from 5ka, and the lowest water levels are estimated to have been ~4.125ka (Sheisha et al., 2022). Faiyum oasis, the proxy site furthest south in Egypt, was desiccated/shallow and brackish between 4.4-3.0ka (Marks et al., 2018). Therefore, climatically in Egypt, although several sites gave proxy evidence of low Nile discharge and a marked change to drier conditions between 4.2-4.0ka, there seems to have been a longer more gradual shift leading up to this from as early as 6.1ka.

In monsoonal East Africa, the Ethiopian lakes in the region of the Blue Nile also saw a steady modification from wetter conditions to a drier environment as early as 6.8ka – specifically at Lake Tana (Marshall et al., 2011). For Lake Abiyata, this was a bit later at ~5.4ka but lasting until 3.8ka and for Lake Abhe, 4.6ka marked a more rapid reduction of water level (Chalié and Gasse, 2002; Mologni et al., 2021). Lake Victoria, the source of the White Nile reduced in water level ~5.8ka, with lowest temperatures suggested to have been between 4.5-4.0ka but declining since 8ka (Stager et al., 2003a; Berke et al., 2012). Precipitation here is estimated to have started to decline by 10ka, reaching a low between 4.0-2.6ka (Berke et al., 2012).

Taking these proxy timelines into account, it seems that Lake Victoria was the first region to experience changes in climate, starting between 10-8ka which perhaps indicates a pattern running South to North (Berke et al., 2012) Consequently, the proxy sites at the Ethiopian lakes experienced declining precipitation from 6.8ka and then by 6.1ka, this was evident in the change of sediments found at Lake Manzalla in Northern Egypt (Marshall et al., 2011; Stanley et al., 2003). Therefore, it can be presumed that when the White Nile inflow declined, the Nile relied more heavily on the Blue Nile inflow, but this would also lessen as time went on. When the Nile Delta itself then became more arid with less precipitation, the Nile outflow was stunted not only by conditions in Egypt itself but from the monsoonal regions further South. This led to dune invasion as the desert expanded, taking over some branches of the Nile that would never recover. This timeline is not indicative of a distinct rapid event but instead a longer shift to a more arid climate over millennia.

4.1.3 Indus River Valley

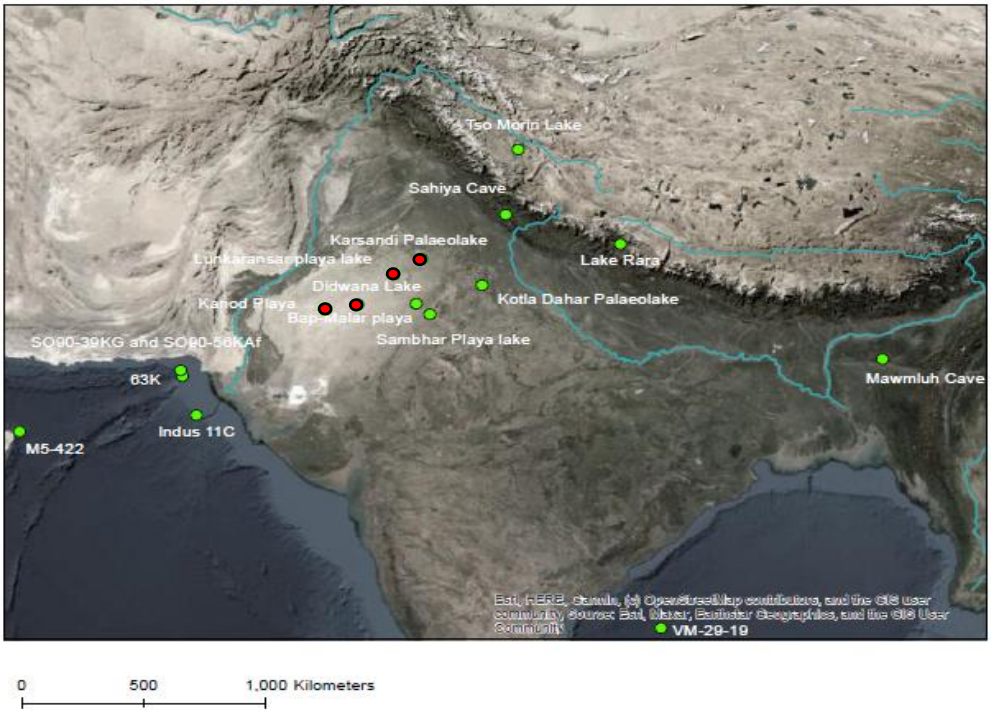


Figure 9: Map of locations of proxy sites in the region of the Indus River Valley. Sites in the Thar Desert are marked in red and experienced earlier aridification. Data from Dutt et al., 2018; Nakamura et al., 2016; Dixit et al., 2014; Dixit et al., 2018; Enzel et al., 1999; Singh et al., 1990; Deotare et al., 2004; Sinha et al., 2006; Doose-Rolinski, 2001; Staubwasser et al., 2003; Giosan et al., 2018; Cullen et al., 2000; Rashid et al., 2011; Kathayat et al., 2017; Walker et al., 2018.

4.1.3.1 Lake sediment cores

<u>Tso Moriri Lake, 4500m</u>

The sediment core here, dating to 4.5ka, is mostly separated into two phases around the time of interest, pre and post 4.35ka (Dutt et al., 2018). Before 4.35ka, the sediments were mostly sands with low lacustrine clay and silt deposits. Sand deposition from high intensity flow then decreased massively until 2.1ka. Lacustrine clay deposits, however, were seen to increase steadily until 2.45ka which would indicate movement towards very low intensity of river flow and hence discharge (Dutt et al., 2018). Silt deposition rose between 4.35ka and 3.45ka but then reduced until 2.45ka which shows initially low energy flow which then increased after 3.45ka (Dutt et al., 2018).

Very low ratios of Aluminium / Calcium (Al/Ca) and Rubidium / Strontium (Rb/Sr) were present in the deposits between 4.50-4.35ka which indicated climate that is warm and wet until the ratios increased after 4.35ka and did not reduce again until 3.45ka (Dutt et al., 2018). The abrupt rise of Al/Ca and Rb/Sr ratios at 4.35ka suggest a change in climate that was colder and

more arid (Dutt et al., 2018). This record therefore shows a dry period lasting 900 years starting from 4.35ka, rather than an abrupt event that the 4.2ka period is often described as (Dutt et al., 2018). This manifested as low precipitation and glacial melt and therefore the Indus river had lower discharge during this time (Dutt et al., 2018).

Lake Rara, 2970m

This location, close to the Himalayas, is important due to the influence of the Himalayas on the ISM (Nakamura et al., 2016). This study used Manganese/Titanium (Mn/Ti) And Manganese/Iron (Mn/Fe) ratios to infer monsoon strength as Mn isotopes relate to redox and seasonal mixing in the lake (Nakamura et al., 2016). Total Organic Carbon (TOC) was also used to infer precipitation changes in the lake as fluxes of terrestrial input vary depending on rainfall and aridity (Xiao et al., 2006; Nakamura et al., 2016)

In *Figure 10* the ratio of Mn/Ti rapidly drops, reaching a minimum at ~4ka. Looking at this closer, levels start to decrease ~4.75ka and begin to rise again after ~3.75ka (*Figure 11).* Monsoon intensity is inferred to have been increased before ~5ka and then intensity decreased where Mn/Ti reaches a minimum ~4ka (Nakamura et al., 2016). These data show instead of an abrupt 4.2ka event, a monsoonal weakening pattern over at least 500y that could have led to decreased precipitation in the region.

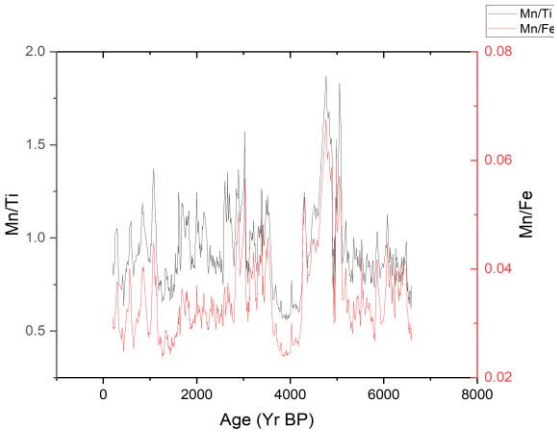


Figure 10: Mn/Ti and Mn/Fe ratios from Lake Rara between 0-7ka. Data from Nakamura et al., 2016.

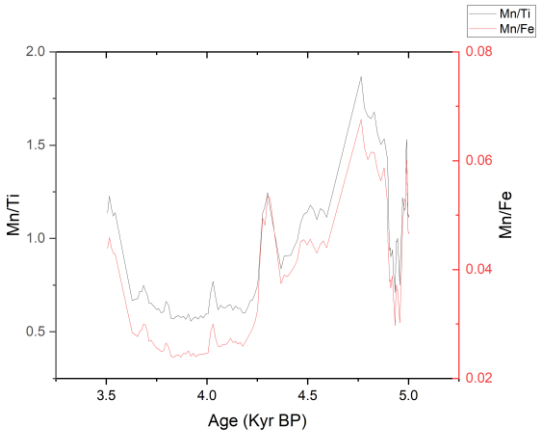


Figure 11: Mn/Ti ratios from Lake Rara between 3.5-5.0ka. Data from Nakamura et al., 2016.

Karsandi Palaeolake, 300m

Levels of precipitation and evaporation were inferred in this core from the oxygen isotopes and deuterium of the gypsum (Dixit et al., 2018). At 5.1ka, there was higher clastic deposition and a decrease in gypsum in the assemblage, alluding to increased precipitation levels (Dixit et al., 2018). The exact date of the onset of aridification here is difficult to ascertain due to the lack of material able to be dated in the unit (Dixit et al., 2018). An estimated date is after 4.4ka and the dry conditions are thought to extend until 3ka as the deposition remains sandy but shifts to high gypsum content with a lack of ostracods and gastropods within the assemblage (Dixit et al., 2018). The lake is thought to have been saline and shallow as its maximum during this time. The lake here became a playa ~3.2ka where the core shows predominantly aeolian sand and remains desiccated at present day (Dixit et al., 2018).

Kotla Dahar Palaeolake

Dixit et al. (2014) looked at oxygen isotopes of gastropods in aragonite deposits of this lake in Haryana, India. During a more humid phase between 6.5-5.8ka the 18 O levels indicate the lake was deep with low salinity. As decreases in precipitation associated with a weakening of monsoon rainfall is associated with high shell $\delta^{18}O$, it highlighted that between 5.8-4.2ka the ISM was potentially weaker (Dixit et al., 2014; Berkelhammer et al., 2012). The salinity during this period also rose, as indicated by the increased populations of gastropods and ostracods that live in saline waters and the $CaCO_3$ decreased to ~37% (Dixit et al., 2014). At ~4.1ka $\delta^{18}O$ rapidly increased from -0.1‰ to 4.4 ‰ and $CaCO_3$ decreased further to ~10% as ostracods disappeared from the assemblage. This showed an abrupt shift towards higher levels of evaporation and lower precipitation in the region (Dixit et al., 2014).

Lunkaransar Playa Lake, 195m

This playa is situated on the edge of the Thar desert and was once a groundwater and rain fed lake (Enzel et al., 1999). This region is under the influence of the ISM, but the study proposed that winter precipitation would be required to sustain a perennial lake here (Enzel et al., 1999). The lake waters increased ~6.3ka, with the humid phase of climate but started to decline ~5.5ka and became a dry playa ~4.8ka. Dated to this time, Zone 4 of the core was predominantly silt, sand and mud cracks with no laminar structure, alluding to a mostly dry or ephemeral lake (Enzel et al., 1999). There was an abrupt load of aeolian sand, not seen in the

previous record of 5000y, that demonstrated dune instability caused by significant change in climate conditions (Enzel et al., 1999).

Didwana Lake

There are two different zones in this core at Didwana Lake that are of interest, 6.2-4.2ka (D5) and post-4.2ka (D6). D5 is marked by pollen of *Calligonum* replacing *Cosmarium* and desmids, and a decrease in *Typha* (Singh et al., 1990). These populations show that lake levels decreased to a moderate depth, which led to an increase in sedges. By 5ka, *Oldenlandia* and *Artemisia* values decreased which gave rise to graminae and trees (Singh et al., 1990). The lake did not desiccate or lower dramatically during this time as *Typha* was still present and halophytic taxa was not seen to increase (Singh at al., 1990).

However, in D6, after 4.2ka there were only 3 pollen samples due to the lake becoming ephemeral (Singh et al., 1990). The ephemeral nature was shown by a mixture of non-laminated, poorly laminated and silty deposits (Wasson et al., 1984; Singh et al., 1972,1974). Within the 3 samples was *Oldenlandia* and *Artemisia* that decreased in levels by 4ka whereas *Calligonum* had higher levels, indicating falls in both summer and winter precipitation (Singh et al., 1990). However, the evaporation rate was not so extreme as to leave the lake hypersaline, during this time period from 4.2ka to now, the lake remains ephemeral (Singh et al., 1990).

Bap-Malar Playa

Bap-Malar had two sources as a lake, rainfall and groundwater but shows desiccation ~6ka which is 2ka before the proposed 4.2ka event. This is indicated by evaporates of gypsum, silt and sand (Deotare et al., 2004).

Kanod Playa, 480m

Similar to Bap-Malar, Kanod playa experienced drying conditions well before 4.2ka. Between 7.5-5.8ka, the lake was ephemeral and then became completely dry ~5.5ka, as shown by gypsum and silty sand in the core, as well as an absence of pollen (Deotare et al., 2004).

Sambhar Playa Lake, 365m

The core in this region gives evidence that this lake actually expanded during the humid phase but also remained at a high stand afterwards, between 6.8-2.5ka (Sinha et al., 2006). It was only after 2.5ka that levels dropped due to more arid conditions and the changing of the monsoons which is shown in the assemblage of the core as higher sulphate minerals (Sinha et al., 2006). At no point did the lake completely desiccate, and conditions up until present are ephemeral. Interestingly, Didwana and Lunkaransar lakes which are in a similar region, were dry between 4-3ka (Sinha et al., 2006).

4.1.3.2 Ocean cores

SO90-39KG and SO90-56Kaf

These cores were examined for planktonic foraminifera (looking at oxygen isotopes), as well as alkenone producing coccolithophores (as a proxy for SST) (Doose-Rolinski, 2001). Between 4.6-3.3ka, sea surface temperature (SST) was seen to change by up to 3˚C and salinity decreased. Doose-Rolinski (2001) suggests that during this time period evaporation levels decreased as the South-West (SW) monsoon (ISM) weakened and the North-East monsoon (winter monsoon) strengthened. Andruleit et al. (2000) looked at sediment trapping close to this site and found that coccolithophore populations (Especially *F. profunda* and *E. huxleyi*) profoundly increased at the start of the SW monsoon and throughout the NE monsoon, mostly due to maxima of SST (Doose-Rolinski, 2001).

63K

The ocean core analysed from this location mapped planktonic oxygen isotope ratios over the last 6ka close to the Indus delta. $\delta^{18}O$ levels in G. ruber increased from 4.2ka which could highlight a decrease in SST and enhanced salinity at this time (Staubwasser et al., 2003). Giesche et al. (2019) looked at this data alongside *Neogloboquadrina dutertrei* that live in the thermocline and found enhanced surface mixing between 4.5-4.3ka, which they attributed to a stronger winter monsoon. However, at 4.1ka when the study proposes the ISM and winter monsoon declined, the biggest drop in precipitation is predicted to have occurred. Giesche et al. (2019) do agree with the G. ruber findings in Staubwasser et al. (2003) but suggest that decreases in Indus River discharge started earlier, by 4.8ka. Staubwasser et al. (2003) put forward the idea that solar variability could be one major cause of precipitation changes in the

area during the Holocene. This is suggested by the change in production of ^{14}C, seen to reach a maximum around 4.2ka showing that reduced solar radiation may link with heavier $\delta^{18}O$, meaning more arid conditions (Staubwasser et al., 2003).

Indus-11C

This 6ka record of planktonic foraminifera in the Arabian Sea provides proxies for several climate factors. Species of radiolarian and jellyfish that have population increases in warmer, eutrophic conditions were seen to decrease during the period that this studies labels as Early Neoglacial Anomalies (ENA), markedly between 4.5-3.0ka (Giosan et al., 2018). However, in this interval, dinoflagellates and fungi that thrive in nutrient rich waters peaked during a time of probable increased winter mixing (Giosan et al., 2018). These proxies point towards a longer climate interval where the winter monsoon increased in intensity while the ISM weakened, there is no signal of an abrupt 4.2ka event (Giosan et al., 2018). Giosan et al. (2018) put forward the theory of push-pull migration of the Harappans, where populations moved from areas negatively affected by the aridification caused by the lessened summer rains to regions experiencing enhanced precipitation from the supposedly strengthened winter monsoon. The argument for an enhanced winter monsoon, where other studies suggest a weakening, is that ancient DNA and *Globigerina falconensis* provide more accurate proxies for marine ecosystem changes caused by the shifting monsoons (Giosan et al., 2018).

M5-422

Beginning ~4.025ka (plus/minus 150y), there was an increased flux of dolomitic aeolian sediments in the M5-422 core which alluded to increased aridity across the nearby landmass (Cullen et al., 2000). Values increased from a maximum of 0.43g/cm2/k.y to 0.97g/cm2/k.y and calcium carbonate increased from 19% to ~39% in the assemblage (Cullen et al., 2000). This study has $\delta^{18}O$ values for *G. ruber* but there is not a sharp signal in these data compared to the $CaCO_3$ and dolomite (Cullen et al., 2000).

Bay of Bengal (VM29-19)

The data here shows patterns of reduced rainfall between 5.3-4.2ka and 4.8-4.6ka as $\delta^{18}O$ values shifted positively (Rashid et al., 2011). Due to low resolution, timings from this study

cannot be precise and sit between 4.8-4.2ka for proposed timing of when the ISM weakened (Rashid et al., 2011).

4.1.3.3 Cave Speleothems

Sahiya Cave, 1045m

Around 4ka, the speleothem at Sahiya Cave showed slow growth, and the $\delta^{18}O$ had increased variability which gives evidence towards gradual change of climatic conditions, rather than a rapid onset event (Kathayat at al., 2017). In the record, the trend towards cooler, more arid conditions began around 4.1ka and the study has the highest resolution of data for a proxy that helps give insight into the fluctuations of the ISM (Kathayat et al., 2017). In *figure 12*, the $\delta^{18}O$ reached a minimum at ~4.0ka after a pattern of decreasing values started ~4.6ka which indicates wetter conditions. Between 4.0-3.5ka, as $\delta^{18}O$ rose to more positive values, climate became drier, and values levelled out and then proceeded to increase until ~2.75ka (*Figure 12*).

Kathayat et al. (2017) inferred from these data that the ISM weakened and meltwater from the Himalayas decreased in volume leading to drier conditions in the Indus Valley as westerly precipitation reduced.

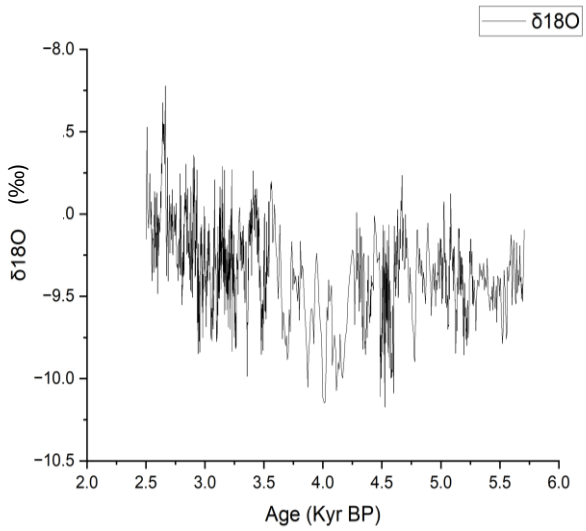


Figure 12: $\delta^{18}O$ (‰) of Sahiya Cave Speleothem from 2.5-5.7ka. Data from Kathayat et al., 2017.

Mawmluh Cave, 1255m

Speleothem records at Mawmluh Cave indicated sharp aridification as there was a significant increase of $\delta^{18}O$ to heavier isotopic values at ~4.2ka (*figure 13*) (Berkelhammer et al., 2012;

Walker et al., 2018). High values appear between 4.3ka and ended at 3.88ka, where they then drastically decline. The stalagmite then ceased growth at 3.6ka (Berkelhammer et al., 2012). The high resolution of this data (~5 years) offers a strong picture of conditions at the time and makes this proxy one of the most important data sources for the 4.2ka event. Many other proxies have much lower resolution and thus make it more difficult to discern a viable short-term climate event such as the one proposed to have occurred ~4.2ka. The suggested reasoning for the high $\delta^{18}O$ values and hence a strong shift to drier conditions, is that a southward shift of the ITCZ caused a weakening of the ISM which is estimated to have had its lowest strength between 4.07-3.88ka (Walker et al., 2018). The 1.5‰ increase of $\delta^{18}O$ is thought to represent a 20-30% drop of rainfall from monsoon origins (Walker et al., 2018).

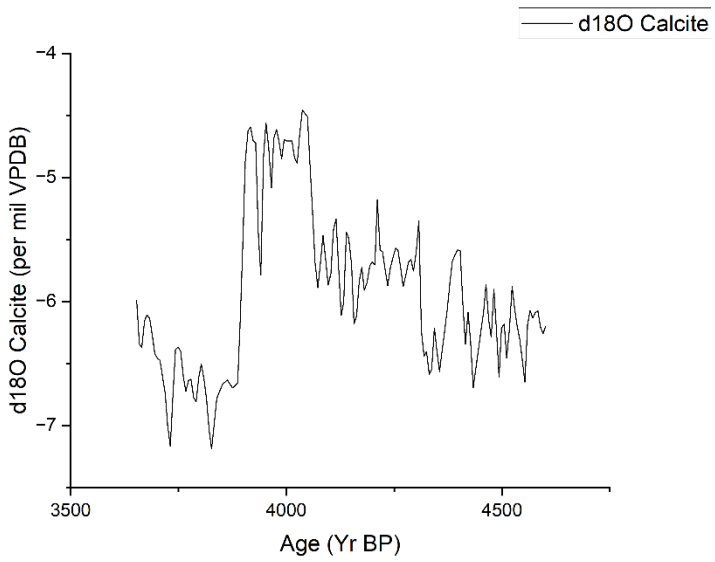


Figure 13: $\delta^{18}O$ of Calcite (per mil VPDB) from speleothem in Mawmluh Cave between 4.5-3.6ka. Data from Berkelhammer et al., 2012.

Summary

Tso Moriri and Lake Rara to the North, on the edge of the Himalayas showed arid conditions commencing between 4.75-4.35ka until 3.75-3.45ka, thus lasting ~1ka (Dutt et al., 2018; Nakamura et al., 2016). Karsandi palaeolake, the lake furthest east (other than Lake Rara), did show heightened aridity from ~4.4-3.2ka. This however was more of a long shift than an abrupt event (Dixit et al., 2014). Many of the lakes closer to the Thar desert showed aridity signals much sooner at ~6.0-5.5ka with either heightened salinity or complete desiccation (Kotla Dahar, Lunkaransar, Kanod Playa, Bap-Malar) (Dixit et al., 2014; Enzel et al., 1999; Deotare et

al., 2004). The only exceptions were Sambhar Playa which was at high stand between 6.8-2.5ka before the region increased in aridity and Didwana which had a signal at ~4.2ka as lake levels decreased from reduced precipitation in both summer and winter seasons (Sinha et al., 2006; Singh et al., 1990). However, both of these lakes are on the margins of the Thar desert area which may account for this (Sinha et al., 2006; Singh et al., 1990).

SO90-39KG, SO90-56Kaf and 63K cores are in a similar location but do show different trends. The SO90 cores suggest the area experienced decreased salinity between 4.6-3.3ka and the study explains this through the SW monsoon weakening and the NE monsoon strengthening (Doose-Rolinski, 2001). However, the 63K core had increased $\delta^{18}O$ at 4.2ka which the study interpreted as decreased SST and increasing salinity. Giesche et al. (2019) put forward that therefore both monsoons weakened. The study of the Indus-11C core looked more at organism populations, and saw that populations that thrive in warm, eutrophic waters decreased between 4.5-3ka (Giosan et al., 2018). They proposed that as the ISM weakened, the winter monsoon increased during this time as populations thriving in nutrient rich waters peaked due to enhanced winter mixing (Giosan et al., 2018). The furthest core to the West, M5-422 dated increased aridity to ~4.025ka as it saw increased aeolian and calcium carbonate deposits in the assemblage (Cullen et al., 2000).

Both of the speleothem proxies had very high resolutions, Mawmluh cave boasting 5y intervals and thus giving the highest resolution picture (Walker et al., 2018; Kathayat et al., 2017). At Sahiya cave, Kathayat et al. (2017) found that there was slow growth in the speleothem and increased variability in the $\delta^{18}O$ at around 4ka, alluding to a gradual climatic shift rather than an 'event'. Mawmluh cave speleothem also showed more arid conditions starting ~4.3ka and lasting for over 400y but said the shift happened abruptly (Walker et al., 2018). The researchers suggested the main weakening of the ISM occurred between 4.07-3.88ka (Walker et al., 2018).

The majority of these studies investigated the strength of the ISM over the last 6ka, and most did theorise a weakening between 4.8-4.0ka (Rein, 2007; Nakamura et al., 2016; Singh et al., 1990; Doose-Rolinski, 2001; Giesche et al., 2019; Giosan et al., 2018; Rashid et al., 2011; Kathayat et al., 2017; Walker et al., 2018). A few studies believe a shift in intensity of the ISM occurred ~1ka earlier starting from ~5.8-5.5ka (Dixit et al., 2014; Enzel et al., 1999). Giesche et al. (2019) and Singh et al. (1990) both put forward that the winter monsoon weakened at a similar time period, however Doose-Rolinski (2001) and Giosan et al. (2018) suggested the winter monsoon was more asynchronous and instead increased in intensity. Therefore, it seems likely that the ISM weakened between 4.8-4.0ka, leading to more arid conditions around

the Indus River Valley, although the Thar Desert may have experienced aridification earlier from ~6ka (Giosan et al., 2018; Dixit et al., 2014). More studies may be needed looking at proxies showing the winter monsoon patterns more accurately, in order to decipher the winter seasonal influence ~4.2ka. Most of the studies also do not show an abrupt 4.2ka 'event' but instead trends of drying climate over timescales of 400-1000y (Giosan et al., 2018; Dutt et al., 2018). These patterns of aridification seem to start in the West, in locations such as the Thar Desert ~6.0-5.0ka and then move East ~4.5-3.8ka (Dixit et al., 2014; Walker et al., 2018).

4.1.4 Mesopotamia

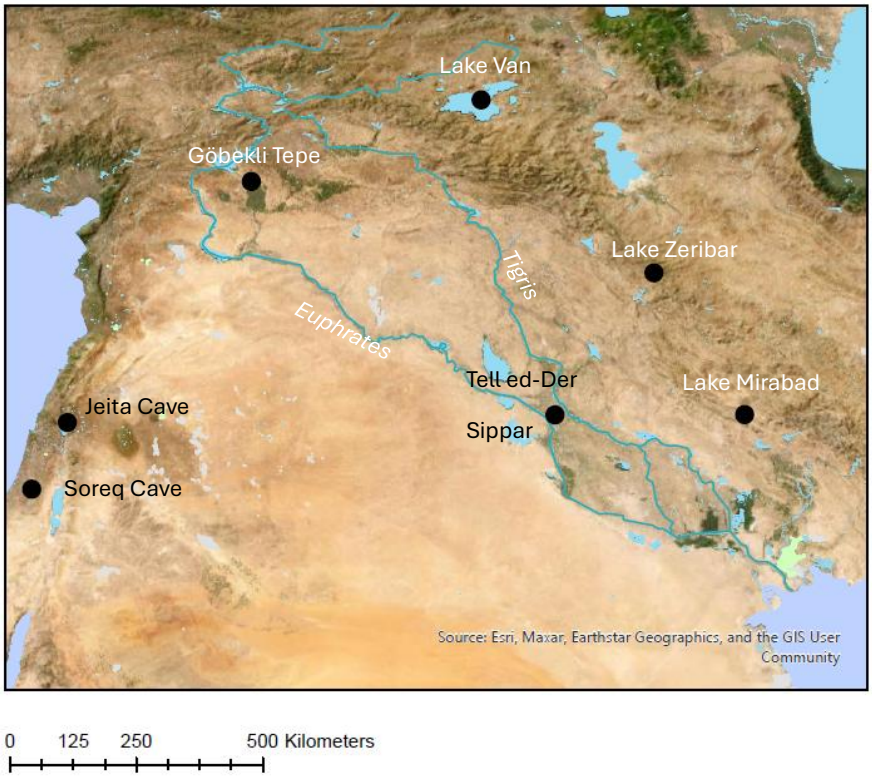


Figure 14 : Map of proxy sites across Mesopotamia. Data from Stevens et al., 2006; Stevens et al., 2001; Wick et al., 2003; Verheyden et al., 2008; Barr-Matthews et al., 1999; Haeyvaert and Baeteman, 2008; Riehl et al., 2009.

4.1.4.1 Sediment cores

<u>Tell ed-Der and Sippar, 40m</u>

During the Uruk and Akkadian periods in Mesopotamia, the Tigris and Euphrates river channels were used for both irrigation and transportation (Heyvaert and Baeteman, 2008). At the sites Tell ed-Der and Sippar, channels were used to go between the two ancient cities, and thus

evidence here of both natural avulsion and anthropogenic activity can help identify how the hydrology of this area changed through time (Heyvaert and Baeteman, 2008).

Avulsion is the process of a river diverging into a new channel which can occur naturally during events like flash floods, where the water level exceeds natural levees and thus flows into lower lying ground (Heyvaert and Baeteman, 2008). This can also happen when an existing channel fills with silt and therefore the river finds a more efficient route. However, human impacts can also lead to avulsion. For example, making breaks in levees which can help to reduce flooding as water is funnelled into flood basins lower down on the plain (Heyvaert and Baeteman, 2008). For irrigation, some natural crevasses are made bigger and also people have tried to prevent avulsion by creating artificial levees (Heyvaert and Baeteman, 2008).

From evidence of avulsion of palaeochannels at these sites, one channel (which is unknown as to whether it belongs to the Tigris, Euphrates or both) seems to have been abandoned ~5ka (Heyvaert and Baeteman, 2008). Whereas a younger belt of the Euphrates between Tell ed-Der and Sippar seemed to be in use from ~5-3ka and then subsequently was also abandoned (Heyvaert and Baeteman, 2008). Increased avulsion could perhaps have been from increased flash floods during a more humid phase ~5ka or a change in the irrigation pattern could have channelled water away from this area. However, in addition to the proposed aridification of Mesopotamia ~4.2ka, avulsion of palaeochannels of the Tigris and Euphrates river systems could also explain desertion of some of the ancient cities, that would no longer be as close to water sources.

Göbekli Tepe, 780m

At this site in modern day Turkey that would have been Northern Mesopotamia, pedogenic carbonate coatings of stones were analysed as well as the isotopic carbonate of plant macroremains (Riehl et al., 2009). Pedogenic carbonate is used as an environmental proxy as the $\delta^{13}C$ and $\delta^{18}O$ vary due to CO_2 in the soil and the isotopic oxygen of the precipitation (Cerling, 1984; Amundson et al., 1989; Cerling et al., 1989). The data shows that between 5-4ka, the moisture availability increased, and temperatures were relatively high and at ~4ka there is an aridification signal in the moisture availability (Riehl et al., 2009). This is more pronounced by the carbonate coating ceasing growth at ~4ka (Riehl et al., 2009).

This study also analysed the seed assemblages of both wild and crop plants at the archaeological site as well as the isotopic carbon of ancient plant macroremains (Riehl et al.,

2009). Between ~5.4-4ka barley dominates the assemblage, free-threshing wheat rather than hulled wheat and an abundance of lentil, flax and domesticated peas (Riehl et al., 2009). Flax and pea are both susceptible to drought and what is seen between 4-3.6ka is a complete lack of flax in the assemblage which would indicate drier conditions (Riehl et al., 2009). However, there is a rise in bitter vetch and grass pea, which are more drought tolerant while cultivation of grapes is seen to decline (Riehl et al., 2009). These plant assemblages highlight increased soil moisture until ~4.2ka, a short rapid decrease between 4.2-4.1ka and then rapid increase between 4.1-4ka before returning to a pattern of reduced soil moisture availability (Riehl et al., 2009). The $\delta^{13}C$ record here demonstrates an increase in soil moisture availability between 5-4ka as $\delta^{13}C$ increases but then as it decreases at ~4ka, there is pronounced water stress until ~3.2ka when $\delta^{13}C$ slightly increases and remains at this moderate level today (Riehl et al., 2009).

4.1.4.2 Lake sediment cores

Lake Mirabad, 1270m

In the lake sediment core, dated between 4.2-3.4ka, there is a decrease in $\delta^{18}O$ as well as an abrupt increase in the population of *Plantago lanceolata* (Stevens et al., 2006). The $\delta^{18}O$ levels are interpreted as a potential predominance of winter precipitation rather than an overall increase in rainfall, but the values still seem to be consistent with the early Holocene Mediterranean precipitation regime (Stevens et al., 2006). The population change of *p. lanceolata* is an indicator of increased human activity at the lake basin but due to the low resolution of the data, these theories are based on longer trends rather than showing any unique climate patterns or human activity in the 200y around 4.2ka (Stevens et al., 2006). Stevens et al. (2006) do suggest that during the 800y beginning at 4.2ka, the data shows disruption to the spring moisture flux and perhaps a premature commencement of northwesterly winds across the Zagros Mountains which could have led to less run-off from the Tigris during spring and summer months. However, a higher resolution proxy would be needed to evaluate whether a 4.2ka event signal can be shown in this region.

Lake Zeribar, 1285m

On the other side of the Zagros Mountains across from Lake Mirabad, the Lake Zeribar core also highlighted a decrease in $\delta^{18}O$ between 4-3.5ka (Stevens et al., 2006). Before this, ~4.5ka, the lake had a high level which supported the oak forests of the region and the climate was similar to that of today (Stevens et al., 2006). This was shown by high $\delta^{18}O$, indicating high precipitation levels during the spring (Stevens et al., 2001). However, by 4ka, there was an increase in *Salix* pollen (Willow trees) found in the core as well as mineral debris which indicated that lake levels lowered up until 3.5ka from decreased spring precipitation (Stevens et al., 2001). These changes seem to coincide with the Akkadians abandoning several farms in northern parts of Mesopotamia, although the dating of this data could be more robust as the resolution was not very high (Weiss et al., 1993; Stevens et al., 2001).

Lake Van, 1645m

In this region of former Anatolia, just north of Mesopotamia, there is evidence that between 6.2-4ka the forest-steppe biome reached maximum extent and thriving populations of pistachio and *Quercus* (oak) denoted prime soil conditions and climate (Wick et al., 2003). The relative humidity was presumed high at this time as low charcoal amounts from wildfire were found until 4ka (Wick et al., 2003). *Juniperus* (Juniper) populations increased at 5ka in the normally oak dominant woodlands, which could either be due to thriving in the new climatic niche or possible anthropogenic degradation of the woodland's oak population (Wick et al., 2003). Between 4.2-3.5ka, the Mg/Ca ratio and charcoal values increased as the woodland environment declined perhaps from aridification of the regional climate (Wick et al., 2003). There may have been some sort of anthropogenic influences at this time, especially considering that the *P. lanceolata* values indicate that grazing around Lake Van began ~3.8ka. Between 4-2.1ka, oak pollen values show up less and less as $\delta^{18}O$ increased. Specifically between 4.2-4ka, Mg/Ca and $\delta^{18}O$ changes show lower humidity levels as the lake reduced in water level and the oak populations diminished (Wick et al., 2003). Charcoal values in the assemblage increased, indicating drier spring growing seasons but there was no evidence of cropping until 600y ago (Wick et al., 2003). Therefore, the decline of oak seems to be correlated to the decline of spring rainfall rather than anthropogenic influences and thus there was an aridity signal here between 4.2-4ka, if not longer (Wick et al., 2003).

4.1.4.3 Cave Speleothem

Jeita Cave, 95m

Stalagmites are used as proxies for precipitation and vegetation cover, with $\delta^{18}O$ used for the former and ^{13}C for the latter (Frumkin et al., 2000; Bar-Matthews et al., 1999). At Jeita Cave, the stalagmite at 6.4ka increased in $\delta^{18}O$ by 0.5‰ over 500y which highlighted a reduction in precipitation (Verheyden et al., 2008). There was a brief increase in precipitation at 5.9ka, marked by temporarily lower $\delta^{18}O$ levels which then continued to increase by 0.6‰ and continue at this higher level until 1.1ka (Verheyden et al., 2008).

$\delta^{13}C$ followed a similar pattern with increasing values at 6.5ka, but with two brief declines of up to 0.5‰ at 5.9ka and also between 3.5-3ka (Verheyden et al., 2008). Between 5.9ka and 1.1ka (the most recent data point in the stalagmite), values generally increased by 1.2‰ which alludes to reduced vegetation cover (Verheyden et al., 2008). At 4ka, there was a brown layer in the stalagmite which was created from quick transferral of impurities within the cave due to flooding, therefore wetter conditions are inferred between 4-3ka (Verheyden et al., 2008). However, the inferences of these data may not have a high level of accuracy due to the low resolution of 180y which may fail to capture short-term climate events (Verheyden et al., 2008).

Soreq Cave, 400m

The speleothem of Soreq Cave are perhaps one of the best known palaeoclimate proxies associated with the 4.2ka event and offer high resolution oxygen and carbon isotope data (Bar-Matthews et al., 1999). As seen in *figure 15*, the maximum value of $\delta^{18}O$ appeared ~5.2ka and then decreased by 1.6‰ to reach a minimum by 4.7-4.6ka (Bar-Matthews et al., 1999). This pattern indicated drier conditions at 5.2ka which grew wetter over ~500y, as a signalled by the decreasing $\delta^{18}O$ (Bar-Matthews et al., 1999). Then between 4.6-4.2ka, $\delta^{18}O$ values increased up to similar levels as 5.2ka in 400y, indicating aridification of the climate (Bar-Matthews et al., 1999). This was followed by changes in the isotopic values of only 0.4‰ over 3000y between 4.0-1.1ka which demonstrated no further humid phases within the proxy timeline (Bar-Matthews et al., 1999).

With $\delta^{13}C$ showing vegetation changes, the data highlighted a delay following precipitation changes shown by $\delta^{18}O$ (Bar-Matthews et al., 1999). The minimum $\delta^{18}O$ at 4.7-4.6ka is reflected in $\delta^{13}C$ data by 4.4-4.3ka where $\delta^{13}C$ reached a minimum and then increased over the next ~400y (*Figure 16)*. ~ 4ka, there was a maximum in $\delta^{13}C$ as conditions became very arid following the decreased precipitation shown by the rapid rise of $\delta^{18}O$ (*Figures 15 and 16) (*Bar-Matthews et al., 1999*).*

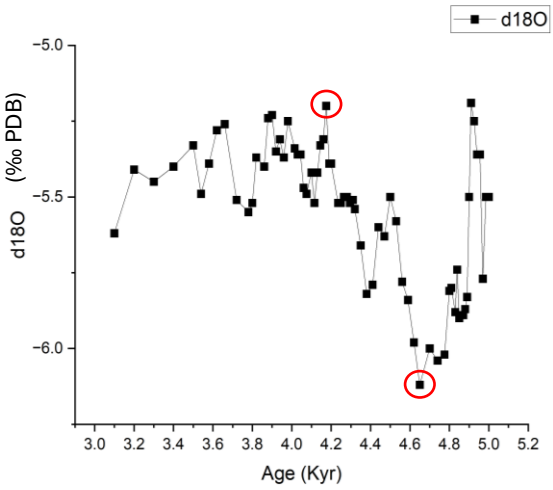


Figure 15: Graph of $\delta^{18}O$ (‰ PDB) from Soreq Cave Speleothem. Data from Bar-Matthews et al., 2003.

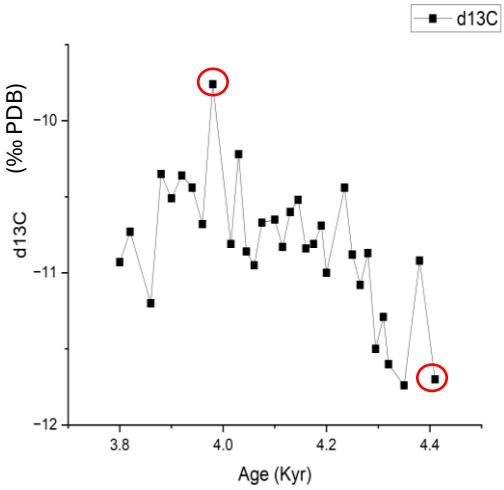


Figure 16: Graph of $\delta^{13}C$ (‰ PDB) from Soreq Cave Speleothem. Data from Bar-Matthews et al., 2003.

Summary

Starting with Northern Mesopotamia and Anatolia, there seems to be a more general shift ~4ka from wetter conditions to those more arid. This is shown by the reduced oak populations and increased charcoal at Lake Van as well as plants at Göbekli Tepe shifting to more drought resistant species (Wick et al., 2003; Riehl et al., 2009). East of the Tigris, both Lake Zeribar and Lake Mirabad highlight a longer pattern of aridification between ~4.2-3.4ka as spring/summer rains declined, and lake levels dropped. Although, it must be taken into consideration that these are low resolution proxies, so a rapid event may not appear in the record (Stevens et al., 2001; 2006). In Southern Mesopotamia, palaeochannels of the Tigris and Euphrates rivers underwent avulsion either due to aridification, flash flooding or changes in the irrigation system causing abandonment of the ancient cities of Tell ed-Der and Sippar by 3ka (Heyvaert and Baeteman, 2008).

In the Levant to the West, the low-resolution data of Jeita cave picked up on a shift at 5.9ka of drier conditions as well as rapid flooding ~4ka but again, perhaps the resolution does not allow for a short climate event to be seen in the record (Verheyden et al., 2008). However at Soreq

cave, where the resolution was much higher, the climate patterns shown were a wet phase between 5.2-4.7ka and a rapid decline of precipitation between 4.6-4.2ka that is further emphasised by less vegetation in the region up to 3.9ka (Bar-Matthews et al., 1999). This proxy with the highest resolution in the region, highlights aridification began at 4.6ka, reached a peak at 4.2ka and then continued with little variation until the end of the proxy ~3.6ka (Figure 15).

Therefore, from these data, there is evidence of a shifting in climate in Mesopotamia to more arid conditions that could have begun as early as 5ka and certainly by 4ka this affected species of trees and crops, lake levels, soil moisture and hydrology (Heyvaert and Baeteman, 2008; Riehl et al., 2009; Stevens et al., 2001). Many of the records agree that these conditions continued either until ~3ka or even as recent as 1ka (Stevens et al., 2001; Verheyden et al., 2008). Only the Soreq cave speleothem gives evidence for the 4.2ka event but lasting for 400y so more high-resolution proxy data is needed in this region (Bar-Matthews et al., 1999). This would allow a more fully formed assessment of whether Mesopotamia only experienced gradual aridification over several thousands of years or if indeed there was a 4.2ka event.

4.2 Climate modelling data

To investigate climate ~4.2ka further, where regions may have had few proxy sites or limited resolution, climate modelling was used to illustrate trends in precipitation, evaporation, temperature, river output and monsoon strength.

For putting precipitation data into context, it should be acknowledged that drought susceptible species of crops such as flax, pea, free threshing wheat and barley require ~300-450mm/year of water. However, although drought resistant species like millet, bitter vetch, grass pea and lentil average at 250-300mm/year, they can grow in drier regions with irrigation and often need less water in more mature phases of growth (Tokarz et al., 2020).

4.2.1 Egypt & East Africa

4.2.1.1 Precipitation

Nile River Basin, Egypt (*Figure 17*)

The most southern sites of Faiyam Oasis, Khufu branch and Saqqara oscillated between 15-40mm/year of precipitation over the 1000y time period. There was a downtrend beginning at 4ka where levels dropped from ~30-35mm/year to a period of lower variation ~15-20mm/year

for 50-100y at ~3.9ka. The other sites further north in Egypt; Lake Manzalla, Tanta and the Rosetta branch had higher precipitation levels varying between 105-270mm/year. They appeared to have more stable variation that ebbed and flowed in 200-300y cycles. Although technically the lowest precipitation for all 3 occurred ~3.9ka, it was only the lowest by ~5-10mm/year. None of the Egypt sites made the precipitation threshold for drought resistant crops but the Old Egyptian Kingdom relied on irrigation and flooding of the Nile and thus could have had successful harvests of crops particularly in the more northerly sites (Butzer, 1984; Bard, 1993; Tokarz et al., 2020). However, for this region, it is more important to analyse the precipitation of the Ethiopian highlands, in which the Nile sources are situated.

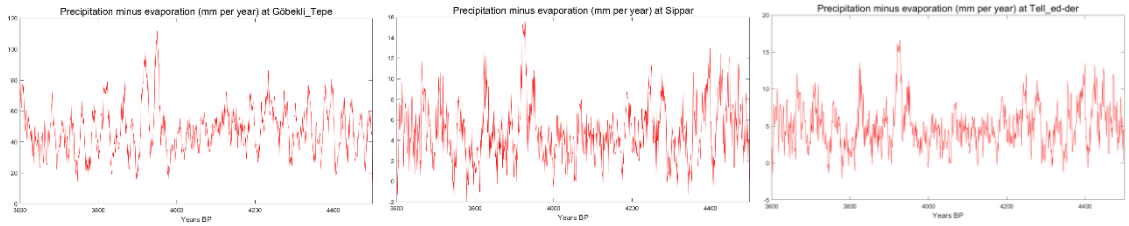


Figure 45 : 10y average of Precipitation minus Evaporation (mm/year) of archaeological sites of Mesopotamia from 4.5-3.6ka.

East African Lakes (*Figures 18 & 19*)

Lake Abiyata boasts the highest precipitation of the three Ethiopian lakes, between 1000-1300mm/year. Although there does seem to be less amplitude of variation at 4.1-4.0ka between 1050-1100mm/year, this is similarly seen at 4.5-4.4ka and thus does not appear abnormal from the pattern of natural variation. Lake Tana has slightly lower precipitation levels between 800-1100mm/year and although there is a dip at 4.1-4.0ka at ~900-950mm/year, it is similar to other precipitation variation during the 1000y interval. Lake Abhe further South has lower precipitation between 280-440mm/year, probably due to the site's lower altitude. Again, this site has a low in precipitation just before 4ka to ~300mm/year but that is not dissimilar to other lows in the 1000y period. All of these sites are above the threshold requirement of precipitation for drought resistant crops although it is less relevant in this location due to the rainfall being the driver of the Nile river flow and flooding in Egypt rather than for in situ agriculture.

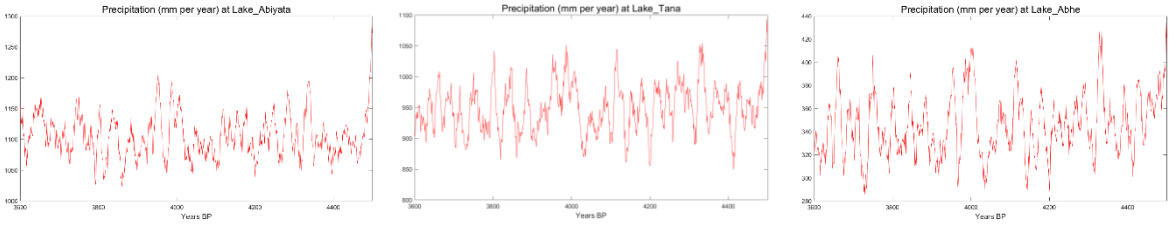


Figure 18: 10y average of Precipitation (mm/year) of Lakes in Ethiopia from 4.5-3.6ka.

There are two different sites for Lake Victoria due to its vast size but precipitation for both ranges between 1000-1450mm/year. Between 4.5-4.0ka, there seems to be 200-300y cycles of increasing/declining precipitation but post-4ka, variation looks more erratic. ~4.1ka does see the lowest amplitude but not by much more compared to other declines in precipitation.

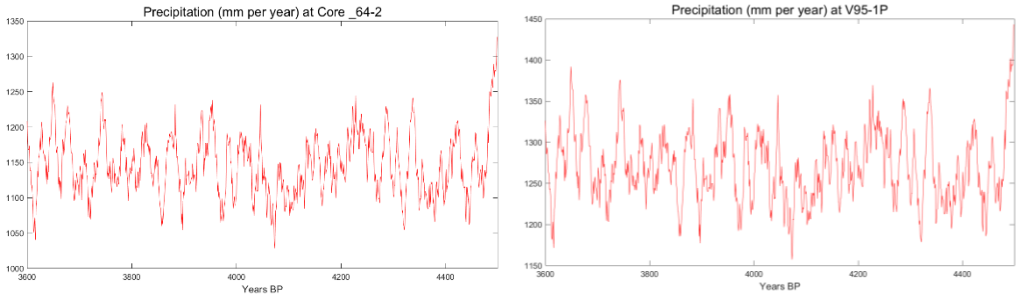


Figure 19: 10y average of Precipitation (mm/year) of Lake Victoria from 4.5-3.6ka.

Mapping precipitation

By mapping 100y averages of precipitation data from the climate model, this gives insight into whether certain areas were affected by a precipitation change. The two time periods compared were 4.3-4.2ka and 4.2-4.1ka, to try and investigate whether a centennial scale shift to aridification took place at 4.2ka. The changes were relatively small (< -36.5mm/year or -0.1mm/day) but highlight change in East Africa between the sources of the White and Blue Nile and also North-East of the Nile Delta (*Figure 20*). Looking closer at *figure 21*, this would have affected the Nile Delta itself too, to a lesser extent. The significance of these centennial changes are discussed at the end of the results section.

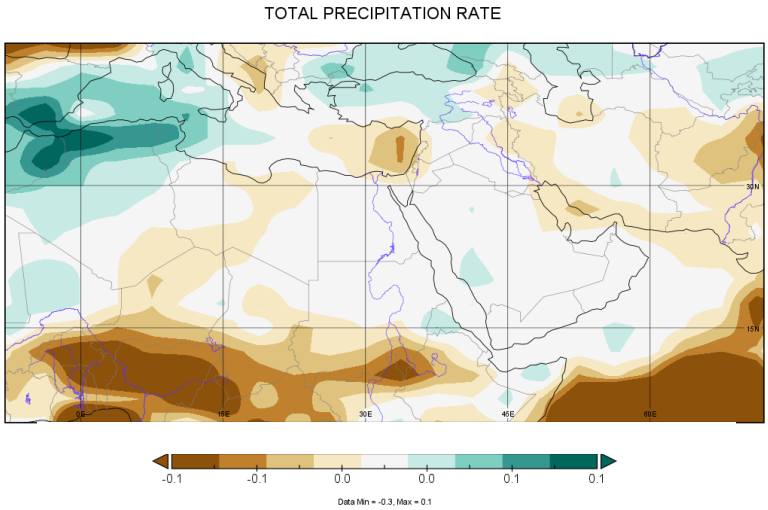


Figure 20: Precipitation difference (mm/day) between 4.3-4.2ka and 4.2-4.1ka.

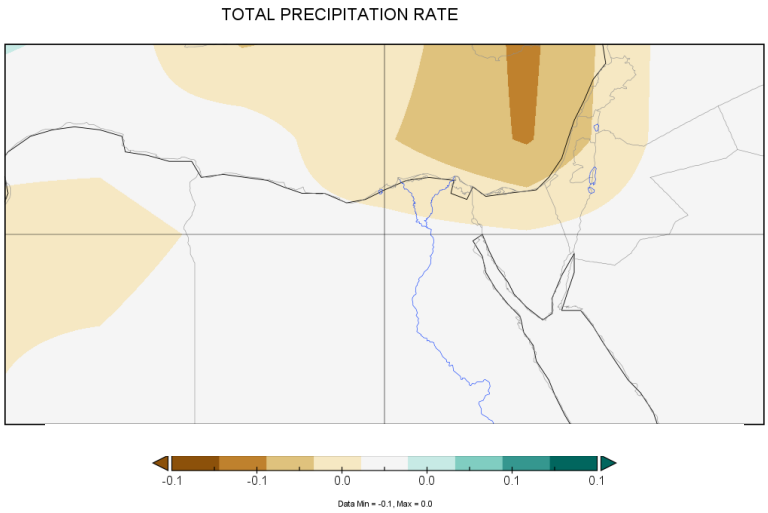


Figure 21: Map of precipitation change (mm/day) over Egypt between 4.3-4.2ka and 4.2-4.1ka.

4.2.1.2 Precipitation minus evaporation

Nile River basin, Egypt (*Figure 22*)

Lake Manzalla and the Tanta and Rosetta branches of the Nile showed similar patterns in the precipitation minus evaporation data. The largest fluctuation for all three sites being at ~3.9ka where the highest level of evaporation was experienced between -305 to -445mm/year which then quickly retreated to between -250 to -350mm/year before the pattern seemed to normalise again. Khufu, Saqqara and Faiyam Oasis with their lower precipitation levels also experienced smaller changes in P-E but with very similar fluctuations to each other. The main

trend in the data for all three of these sites was positive P-E just after 4.4ka at ~2.5mm/year which went negative to ~-1.5mm/year by 4.35ka. Although the figure displays a large change, the small scale must be noted as it is only ~4mm/year change.

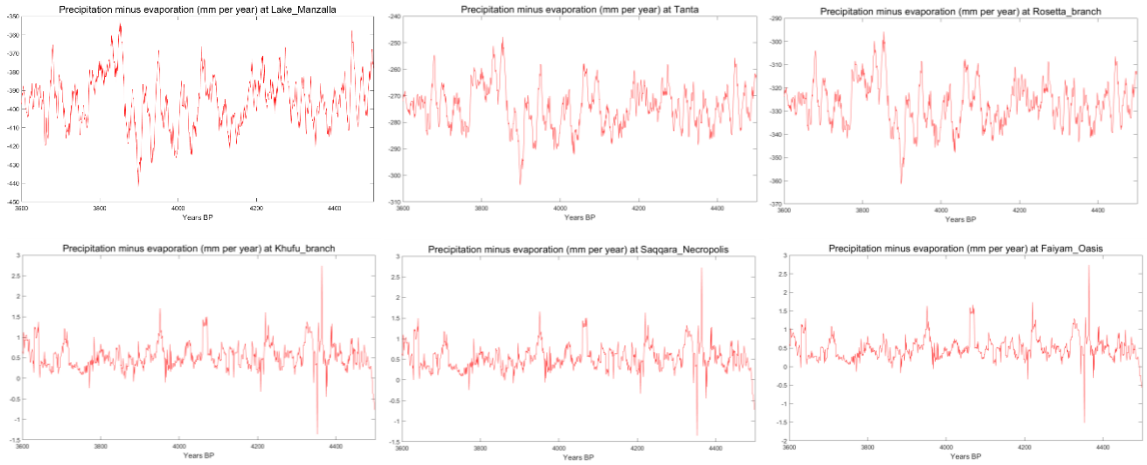


Figure 22: 10y average of Precipitation minus evaporation (mm/year) of sites in Egypt from 4.5-3.6ka.

East African Lakes (*Figures 23 & 24*)

All three of the East African lakes have quite different scales of P-E and varying patterns in the data but all of them are positive, meaning precipitation outweighs evaporation. Lake Abiyata's highest level of P-E was at 4.5ka at ~325mm/year and Lake Tana was also at the same time but at ~150mm/year. The main drop in P-E (higher evaporation) for Lake Abiyata occurred just after 4.4ka and went down to ~135mm/year but was not too dissimilar to other bouts of higher evaporation across the millennium. Lake Tana had a similar trend but down to ~80mm/year where for ~50y variation remained low.

Lake Abhe however had the highest evaporation level at 4.4ka down to ~10mm/year P-E. Otherwise in the timeline, low P-E values were ~25mm/year including one at ~4ka which was sandwiched between two of the lowest evaporation levels (high P-E) going up to ~55mm/year.

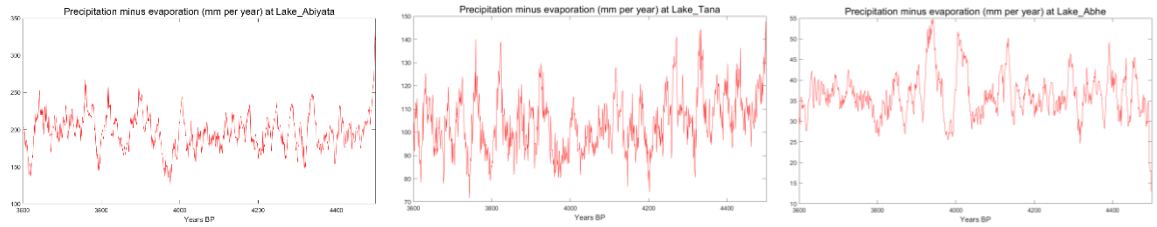


Figure 23: 10y average of Precipitation minus evaporation (mm/year) of Lakes in Ethiopia from 4.5-3.6ka.

For Lake Victoria, there is a lot of variance but no obvious trends. The two different sites across the lake have lowest evaporation at P-E = 320 and 240mm/year respectively and go up to the highest evaporation levels when P-E = ~150 and 90mm/year respectively.

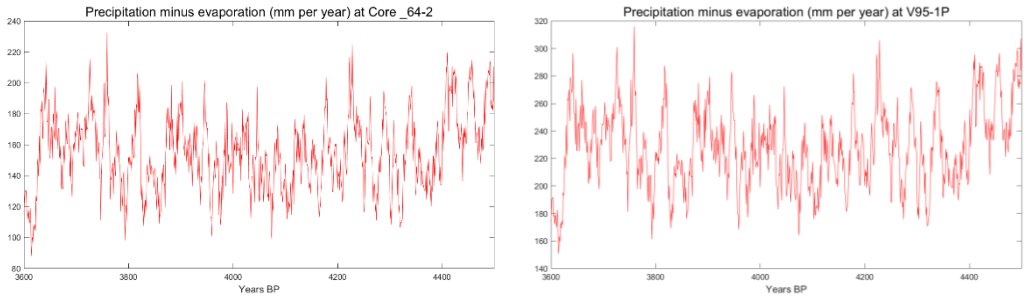


Figure 24: 10y average of Precipitation minus evaporation (mm/year) of Lake Victoria from 4.5-3.6ka.

4.2.1.3 Temperature

Nile River basin, Egypt (*Figure 25*)

All of the sites in Egypt had the same temperature profile, just with slightly different scales. They experienced their highest values at 4.2ka and a second highest at 4.05ka. For Lake Manzalla in the North, this was 20.6℃ and then Tanta and Rosetta being close together had similar values of 21.4 ℃ and 21.5 ℃ respectively. Khufu and Saqqara had the same maximum temperature of 21.8 ℃ but Faiyam Lake, the furthest South had the highest maximum temperature of 22.3 ℃. The lowest temperature values occurred around 3.6ka and between 4.35-4.3ka, with the second lowest peak being at 4ka. The lowest temperature being at Lake Manzalla (19.4 ℃) and the highest of the lows being at Faiyum (21.1 ℃) whereas the other sites fell between 20.1-20.6 ℃. Between, 4.2-4ka, there seemed to be increased variability that could allude to a climate event.

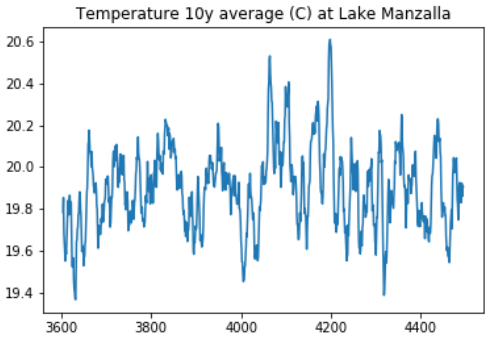


Figure 25: 10y average of Temperature (˚C) of sites in Egypt from 4.5-3.6ka. Lake Manzalla is shown but all other sites have the same temperature profiles, with the varying scale of temperature given in the text above.

East African Lakes (Figures 26 & 27)

Both Lake Abhe and Tana reached a peak at 4.15ka Tana of 20.2 ˚C and Abhe with 26.5 ˚C. There is a potential temperature event in these locations between 4.2-4.1ka shown as the peaks in the temperature profiles in *figure 26*. Abiyata, more central in Ethiopia has several peaks at 3.8ka, 3.7ka, 4.15ka and 4.3ka of 18.8 ˚C, so a less obvious pattern compared to the others. Lake Abhe has a low from 4.3-4.25ka going down to 24.75 ˚C whereas for Lake Tana, the lowest temperature of 19 ˚C occurs between 3.80-3.75ka and has some other similar lows. Lake Abiyata has its lowest value at 4.1ka but lots of similar lows just like Tana.

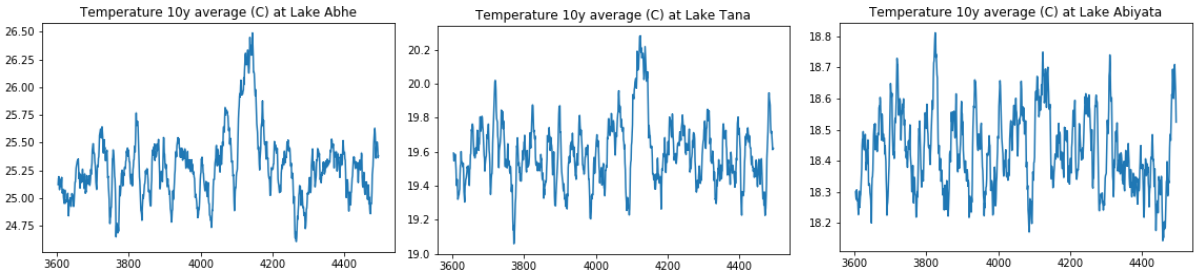


Figure 26: 10y average of Temperature (˚ C) of Lakes in Ethiopia from 4.5-3.5ka.

At Lake Victoria, the highest temperature occurs at 4.5ka, 4.1ka and 3.7ka, reaching ~22.5-22.6 ˚C with a second highest value at ~4.3ka of 22.4 ˚C. Then the lowest temperature of 21.3 ˚C is reached several times, 4.4ka, 4.2ka, 3.85ka and 3.6ka with some values close behind within 0.1 ˚C around 4.5ka, 4.35ka and 4.3ka. Lake Victoria's temperature profile is more similar to Lake Abiyata, as it does not show a clear peak ~4.1ka but instead has a lot more variability. This could show that a temperature event between 4.2-4.1ka was more prevalent in the North of Ethiopia, therefore does not show in the more southerly sites whether that be in Ethiopia or further south where Lake Victoria is situated.

Lake Victoria

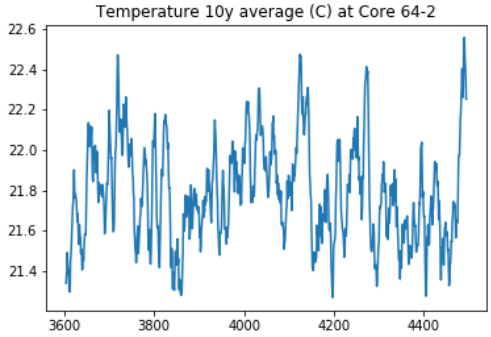


Figure 27: 10y average of Temperature (C) of Lake Victoria from 4.5-3.6ka.

4.2.1.4 River output

Nile River Output (*Figure 28*)

The river output for the Nile over the time period 4.5-3.6ka does not show a discrete event at 4.2ka but instead a shift over a longer timeframe. From 4.5-4.2ka, there is variation in output averaging at about 15000 m^3s^{-1} with a peak value of 17000 m^3s^{-1} being reached at ~4.35ka. Then, at 4.2ka values decline and by 4.15ka, there is a new average of below 14000 m^3s^{-1} – a drop in average output of ~1000 m^3s^{-1}. The dips between 4.2-4ka are at ~4.15ka and ~4.05ka respectively, both reaching lows of below 13000m^3s^{-1} which is the first time over the period we see values this low. However, The lowest value of ~12500 m^3s^{-1} is only reached at 3.6ka.

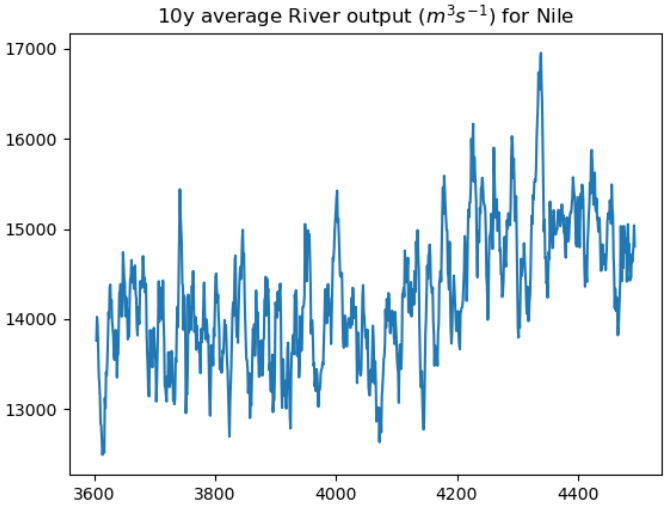


Figure 28: 10y average of River Output (m^3s^{-1}) for the Nile from 4.5-3.6ka.

4.2.1.5 Monsoon Index

East African Monsoon (*Figure 29*)

It must be noted that as the monsoon index was created with centennial averages, the dated year BP on the X axis denotes the midpoint year, for example 4ka shows 4.5-3.5ka. From the plotted EAM monsoon index, there is a stable pattern between ~6-5ka followed by a strengthening ~5ka which would align with the AHP. Then between ~4.5-4ka the trend is slightly lower than pre 5ka, followed by a rapid drop ~4ka which alludes to a swift weakening of the monsoon. Post 4ka, the index is more stable again with less variation but at a new lower strength. There is a slight strengthening between 3-2.75ka where the index is seen to increase before dropping to more stable variation once again.

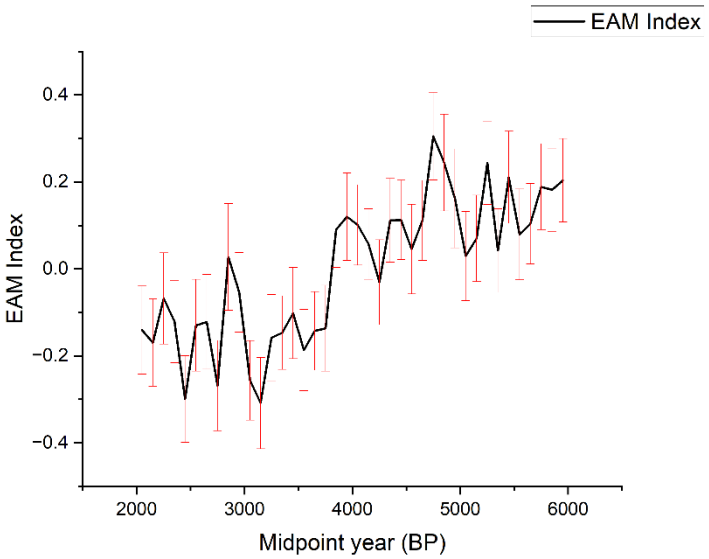


Figure 29: Centennial average of the monsoon index of the East African Monsoon from 6-2ka. A normalised MSLP based index with error bars marking the standard error of the centennial averages.

Summary

In Egypt, sites in the South of the Nile delta had very low precipitation in general across the 1000y plotted time period. Some of the sites further North like Lake Manzalla, Tanta and Rosetta had precipitation levels just about the threshold for drought resistant species (~270mm/year), although it must be taken into account that agriculture was mostly based on Nile flooding rather than rainfed (Butzer, 2012). The largest declines in precipitation occurred ~3.9ka but could have just been internal variation as the decline was by ~35mm/year over a scale of 50-100y. This did coincide with higher evaporation levels shown by the P-E plots. The Nile river flow output experienced a lower average post 4.2ka as it declined between 4.3-4.2ka. Although temperature values peaked at 4.2ka, this was not reflected in the evaporation levels and they did not remain high for long, as by 4.1ka, temperature levelled out again, with another slightly lower peak occurring ~4.05ka. In this region, there did not seem to have been an event ~4.2ka shown in the climate modelling data with temperature, precipitation and P-E. However, the Nile river output may allude to a more longstanding change of climate that began at 4.2ka as aridity increased in the region. This shows as lasting until at least 3.6ka in the plots, but without further climate modelling, it cannot be known if the area became wetter again before becoming Egypt as we know it today, a dry desert climate.

The Ethiopian lakes showed a reduction of precipitation between 4.1-4.0ka but evaporation seemed low across the wholetime period probably due to high altitude of most of the lakes.

This is surprising as temperature peaked at this time by ~1˚C more than the average before which would be thought to increase evaporation rates. Tana and Abiyata precipitation averaged at 1000mm/year or more whereas lower altitude Abhe was ~280-440mm/year but all have no clear decline at 4.2ka. At Lake Abiyata further South however, temperatures were stable ~4.2ka before peaking at ~4.15ka and experiencing a sharp drop ~4.1ka. For Lake Victoria even further South, precipitation was also above 1000mm/year with 200-300y cycles of variation but again no clear 4.2ka signal as the precipitation dip at 4.1ka was only slightly more than other similar declines across the 1000y. Again, evaporation was low due to high altitude and high precipitation, but the temperature values were seen to peak ~4.3ka and 4.1ka and drop at 4.2ka. However, it must be noted that in the 1000y profile, these patterns were among other peaks and troughs to values of the same number and thus the trends are not overwhelmingly large. Comparing these data with the monsoon index, this also appears to match with a rapidly weakening monsoon between 4.5-3.5ka (midpoint 4ka).

4.2.2 Indus River Valley

4.2.2.1 Precipitation

Lakes (*Figure 30*)

A majority of the sites (Karsandi, Lunkaransar, Kanod, Didwana, Bap Malar, Sambhar and Kotla Dahar) had two main features within their precipitation figures. The first occurred ~4.35-4.3ka where precipitation dropped with varying scales across the sites, as low as 20mm/year (Kanod playa) but also ~300mm/year (Kotla Dahar) with most others ~75mm/year. For context, the average of these sites before this is just about the threshold for drought resistant cropping and the decline takes most of them well below it. Then, very quickly the highest precipitation was observed (525mm/year for Kotla Dahar, ~70mm/year for Kanod playa but most ~300mm/year. The second feature that a majority of these sites experienced was just after 4ka where there was a slightly bigger drop in precipitation. This ranged from ~10mm/year (Kanod Playa) to ~250mm/year (Kotla Dahar) but most averaging ~50-75mm/year. All of these bar Kotla Dahar would be below the threshold for producing drought resistant agriculture.

The two more different precipitation figures were Tso Moriri and Lake Rara which are both close to the Himalayas and thus would have very different climatic influences. Tso Moriri lake had more extreme fluctuations in precipitation post-3.8ka with highs of nearly 875mm/year

and going down to ~550mm/year. Lake Rara however, had variation but the data did not seem to highlight any key trends.

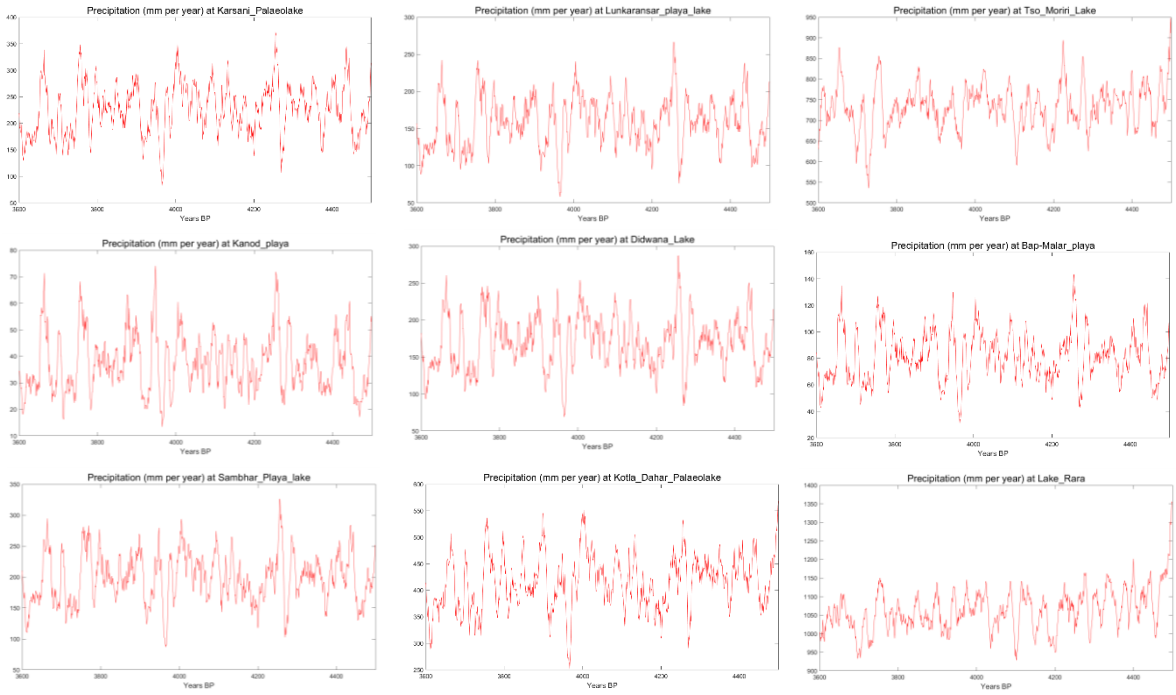


Figure 30: 10y average of Precipitation (mm/year) for lake sites around the Indus River Valley from 4.5-3.6ka.

Ocean sites (*Figure 31*)

All of the ocean sites do not have very distinct trends in their precipitation profiles except that for 63K, Indus 11C, M5-422 and the S090s there seems to be an increase in the amplitude of variation post-4.2ka.

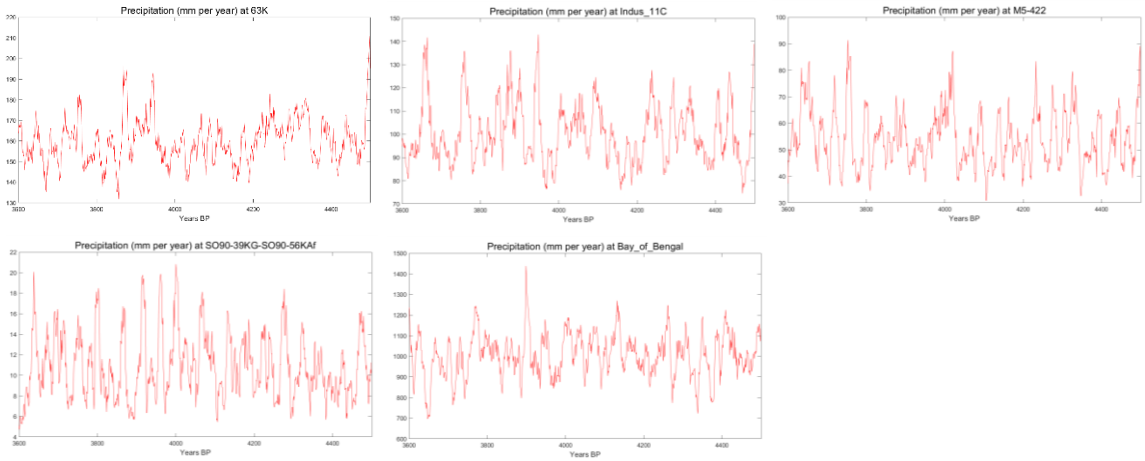


Figure 31: 10y average of Precipitation (mm/year) of Ocean sites close to the Indus River Valley from 4.5-3.6ka.

Caves (*Figure 32*)

For both Sahiya and Mawmluh cave, there is a lot of variability but both had a decline in precipitation that was slightly bigger than other trends. For Sahiya, this occurred ~3.95ka going down to ~575mm/year where other dips were mostly above 600mm/year. For Mawmluh, this happened later ~3.85ka at ~1300mm/year compared to other declines above 1400mm/year. Both the sites are well above the threshold for drought tolerant crops for the whole 1000y plot.

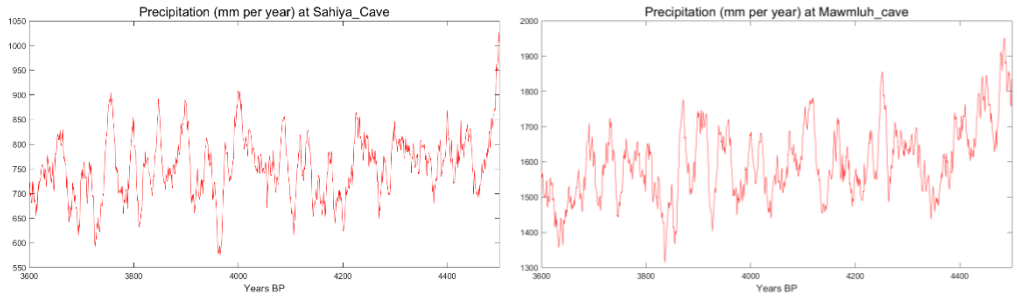


Figure 32: 10y average of Precipitation (mm/year) of caves close to the Indus River Valley from 4.5-3.6ka.

Mapping precipitation (*Figure 33*)

Similar to the mapping of precipitation over Egypt and East Africa, there is not a large change in precipitation between the 4.3-4.2ka 100y average and 4.2-4.1ka (< -36.5mm/year or -0.1mm/day). However, it is useful to see how the trends map onto the land and *figure 33* highlights the divide of the subcontinent of the drier North vs the wetter North-East and East. Considering the locations of the sites, the most significant drying zones would perhaps contain Tso Moriri Lake and Sahiya Cave and then sites in the Thar desert were drier by a lesser extent. The significance of the centennial variations are explored at the end of the results section.

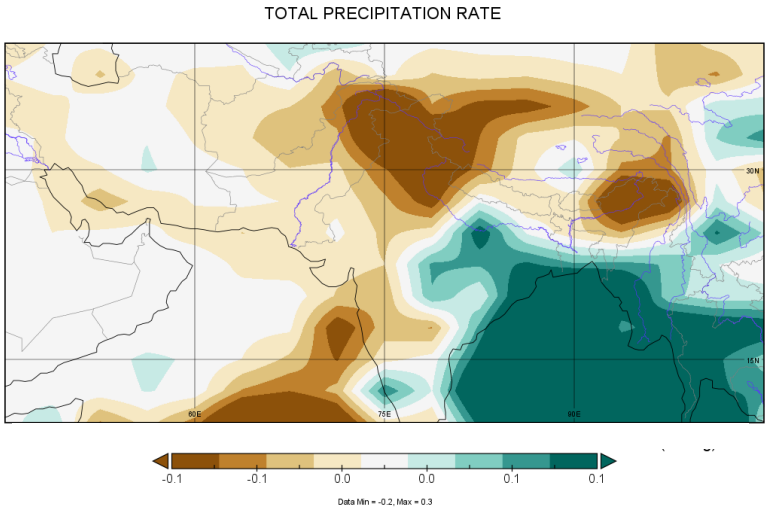


Figure 33: Precipitation difference (mm/day) between 4.3-4.2ka and 4.2-4.1ka in the region of the Indus River valley.

4.2.2.2 Precipitation minus evaporation

Lakes (*Figure 34*)

There is a lot of variation in the P-E and hence evaporation trends of the lake sites but no obvious patterns. There does appear to be a slightly longer decline in P-E (higher evaporation) just after 4ka, this is especially evident at Kotla Dahar and Lake Rara.

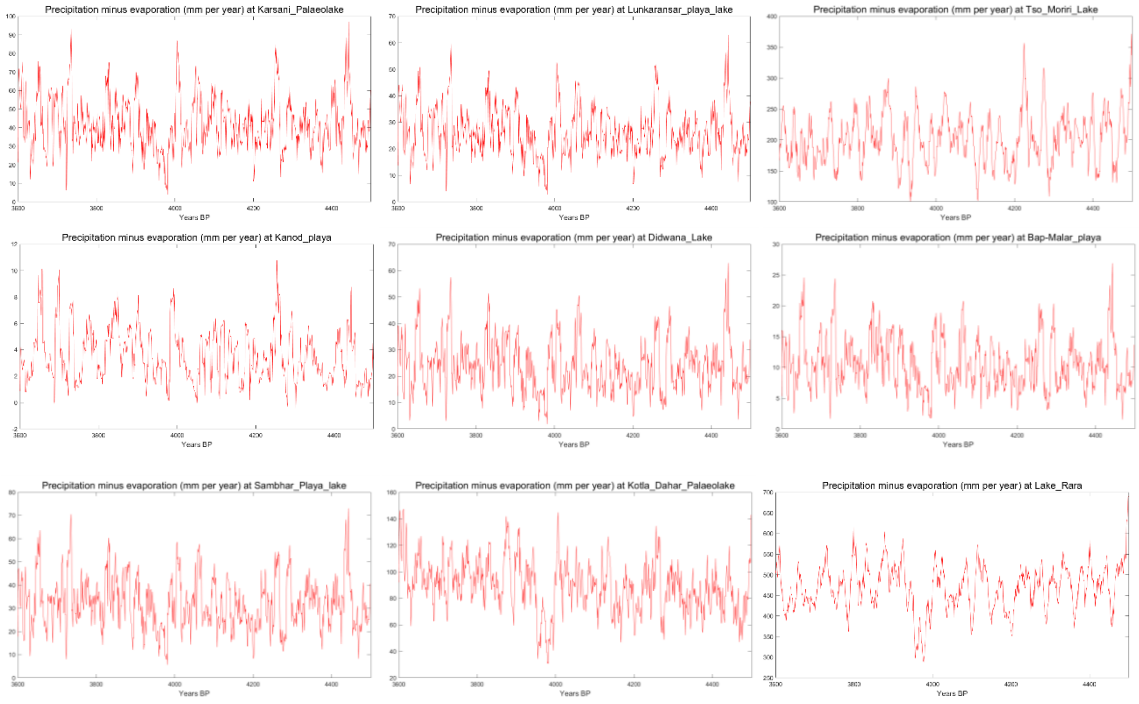


Figure34: 10y average of Precipitation minus Evaporation (mm/year) of sites further from Indus River Valley from 4.5-3.6ka.

Ocean sites (*Figure 35*)

For three of the ocean sites (Indus-11C, M5-422 and 63K), the main pattern appears to be that the average in P-E shifts to more positive values (lower evaporation) over time. The only ocean site that shows a more obvious trend is Bay of Bengal, as the plot highlights further negative P-E (higher evaporation) post-4ka, which then shoots up to the most positive P-E (lower evaporation) before levelling out at a lower average of P-E. The SO90s appear to have a very small window of fluctuations in P-E, going between 2 and -0.5mm/year, with the smallest variation post-3ka.

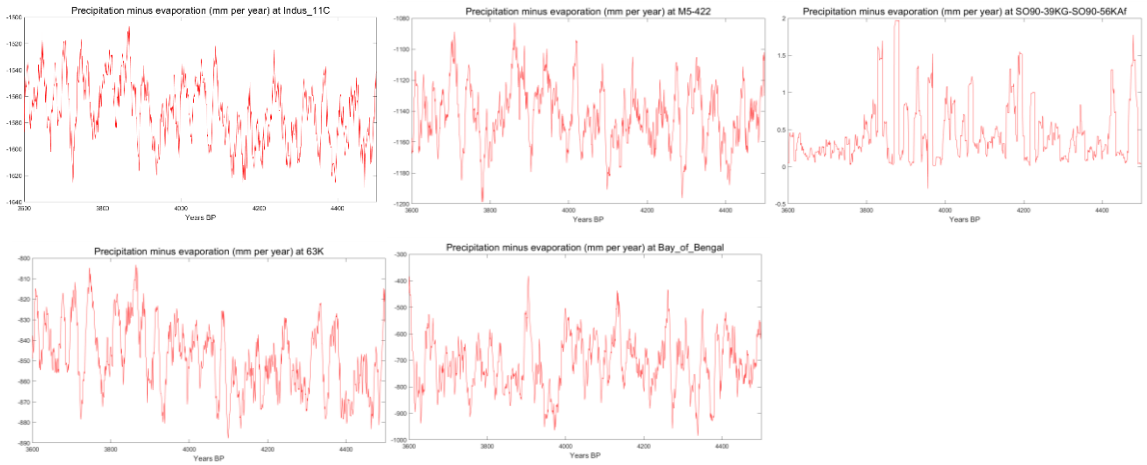


Figure 15: 10y average of Precipitation minus Evaporation (mm/year) of Ocean sites close to Indus River Valley from 4.5-3.6ka.

Caves (*Figure 36*)

For Sahiya cave, the average in P-E increases over time until 4ka where it drops from nearly 400mm/year, down to 50mm/year. This higher evaporation lasts for ~50y before stabilising at a new higher average between 250-400mm/year. Mawmluh cave however shows an opposite trend where P-E values reduce between 4.5-4.0ka, going from ~800mm/year to ~250mm/year. Therefore evaporation is seen to increase but then post-4ka, fluctuations stabilise between 300-500mm/year.

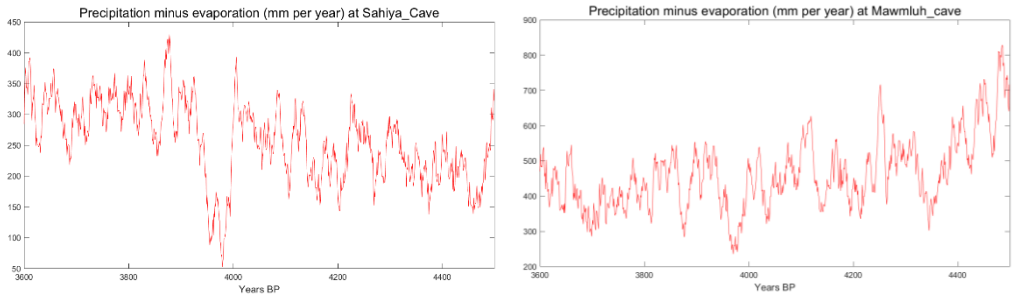


Figure 36: 10y average of Precipitation minus Evaporation (mm/year) of caves close to Indus River Valley from 4.5-3.6ka.

4.2.2.3 Temperature

Temperature was only calculated for the central sites. Karsandi, Lunkaransar and Sahiya all had peaks in temperature at 4.1ka (*Figure 37*). For the first two sites, they had the same values of 25.5˚C, compared to their average values of ~24.25˚C. For Sahiya, this peak was lower at 13.4 ˚C whereas it had lower values at 4.5ka going down to 12.3˚C. Tso Moriri Lake had a lot more variability throughout the time period. The only peak was ~3.7ka at -3.4˚C whereas it usually had an average of -4.2˚C.

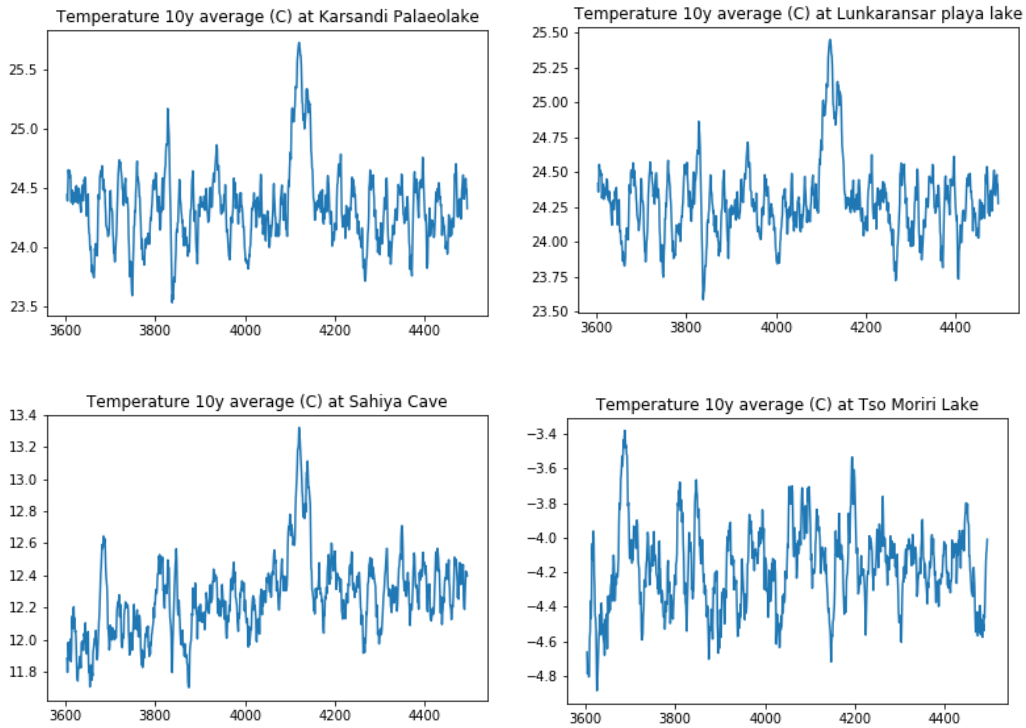


Figure 37: 10y average of Temperature (C) of sites close to Indus River Valley from 4.5-3.6ka.

4.2.2.4 River output

Indus River output (*Figure 38*)

For river output of the Indus river, there seems to be a trend of 3-4 cycles of variation over the whole timeframe. The first uptrend occurs between 4.5-4.2ka, peaking at 4500 m^3s^{-1} just before 4.2ka. By 4.2ka, values drop to 2500 m^3s^{-1} and then the next uptrend lasts until 4ka to ~4400 m^3s^{-1} and then drop to 2250 m^3s^{-1} just after 4ka. The next uptrending pattern is much faster, beginning around 3.85ka and peaks at ~3.75ka to above 4500 m^3s^{-1} before dropping down to nearly 2000 m^3s^{-1} by 3.7ka and the last increasing trend returns to values ~4250 m^3s^{-1} at around 3.65ka.

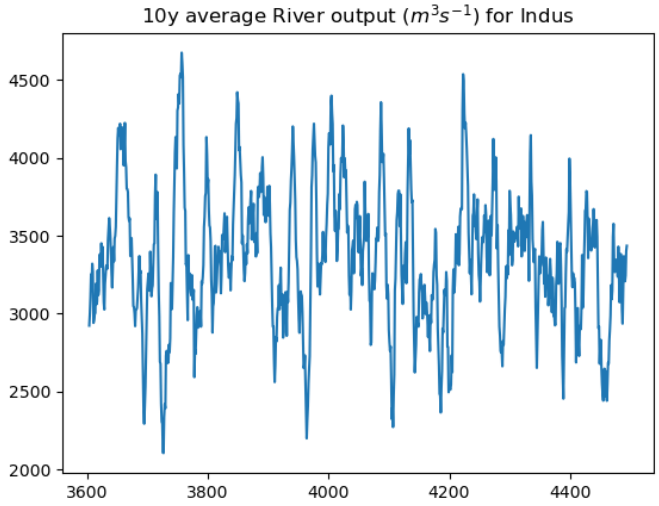


Figure 38: 10y average of River output (m^3s^{-1}) for the Indus from 4.5-3.6ka.

4.2.2.5 Monsoon index

Indian Summer Monsoon (*Figure 39*)

By plotting the monsoon index for the Arabian branch of the ISM, it can be seen that there is a general trend of weakening of the ISM between 5.5-3.0ka as the index decreased. The first more rapid drop appears at ~4.75ka followed by a more stable trend before dropping again just before ~4.2ka until ~4ka. Therefore, although the monsoon index shows the ISM weakening on a millennial scale, between 4.75-4.0ka there were two events of more rapid weakening that could have had more drastic effects on a shorter timeframe.

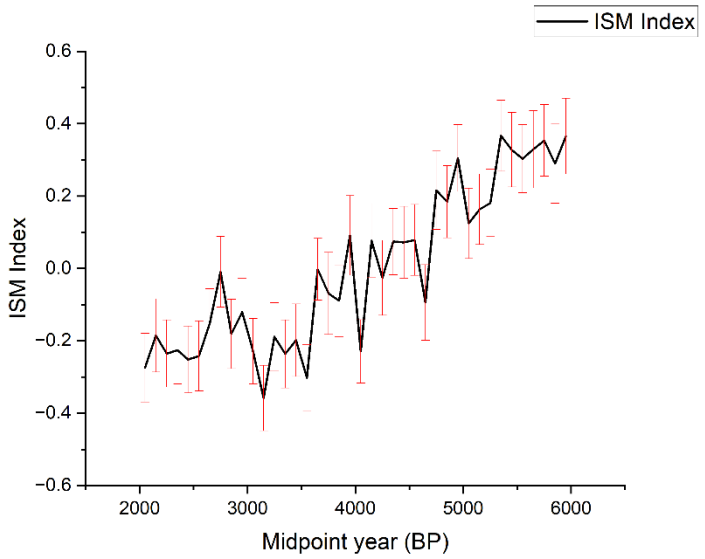


Figure 39: Centennial average of monsoon index for the Arabian Sea branch of the Indian Summer Monsoon. A normalised MSLP based index with error bars marking the standard error of the centennial averages

Summary

The river output of the Indus was at its highest just before 4.2ka but during this time, only the Palaeolakes in the Thar Desert had an increase in precipitation. River output values then declined at both 4.2ka and 4.1ka. Whereas, precipitation trends of the lake sites highlighted precipitation declines at 4.35-4.3ka and 4ka but not 4.2-4.1ka. These declines averaged at 75mm/year for the former and 60mm/year for the latter which is well below the threshold for cropping drought resistance plant species. Whereas, before the declines in precipitation most of the sites had been just over the threshold. Only Kotla dahar remained above this during these periods of decline with between 250-300mm/year at each drop. The Himalayan lakes had higher precipitation above the threshold (up to 875mm/year) but showed less clear trends. The monsoon index of the Arabian branch of the ISM showed a general weakening over the 1000y period with a more rapid drop ~4.2-4.0ka. Despite a ~1˚C increase in temperature centrally at 4.1ka, lake sites only had slightly higher evaporation levels just after 4.0ka which also occurred at Sahiya Cave but with a larger trend lasting ~50y where P-E declined from 400mm/year to just 50mm/year. However, the cave precipitation data only demonstrated declines between 3.95-3.85ka with no clear signal at 4.2-4.0ka. Further South, the ocean sites

had a lot of variation in precipitation but no clear trends other than the amplitude increasing post-4.2ka and the evaporation levels actually declined over the timescale for most of the sites.

Although river output was at its lowest at both 4.2ka and 4.1ka, it did rise again in between and thus was not low for the whole 100y period. No other data highlighted a 4.2ka specific event but some sites displayed trends of lower precipitation/higher evaporation before or after. Sahiya cave had the most prominent heightened evaporation pattern, but this was at 4.0ka and also the location of the cave is beneath the Himalayas and shown in the regional precipitation map as being within the drier region. It must be taken into account that the sites closest to the Indus River Valley were in the Thar Desert with low precipitation levels and the sites not in the desert were further East. These data can give us an idea of climate at the time but sites closer to the river itself would have been even more accurate.

4.2.3 Mesopotamia

4.2.3.1 Precipitation

Archaeological sites (*Figure 40*)

All three of the archaeological sites show similar trends in precipitation across the 1000y plotted. Values decline between 4.5-4.2ka, for Sippar/Tell-ed-der these go from ~130 to 70mm/year and for Göbekli Tepe, from ~460 to 320mm/year. Precipitation fluctuations then stabilise until ~3.8ka, where there is an increase in variability. Only Göbekli Tepe remains above the threshold for drought resistant crops.

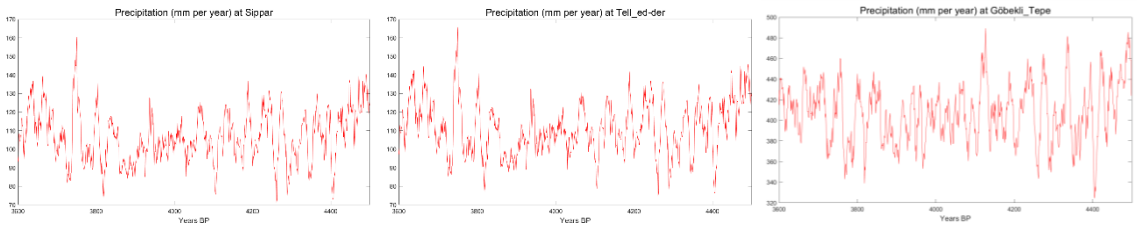


Figure 40: 10y average of Precipitation (mm/year) at archaeological sites of Mesopotamia from 4.5-3.6ka.

Lakes (*Figure 41*)

The three lakes across Mesopotamia have increased variability in precipitation between 4.5-4.2ka, with a low at 4.4ka which is more pronounced at Lake Van and Lake Zeribar. Then while Lake Mirabad and Zeribar have a drop of ~80mm/year at ~4.1ka, Lake Van actually demonstrates an increase of ~80mm/year in precipitation. Fluctuations decrease ~4ka before increasing again ~3.8ka. All three would remain above the threshold for drought resistant plant species except Lake Mirabad at 4.1ka.

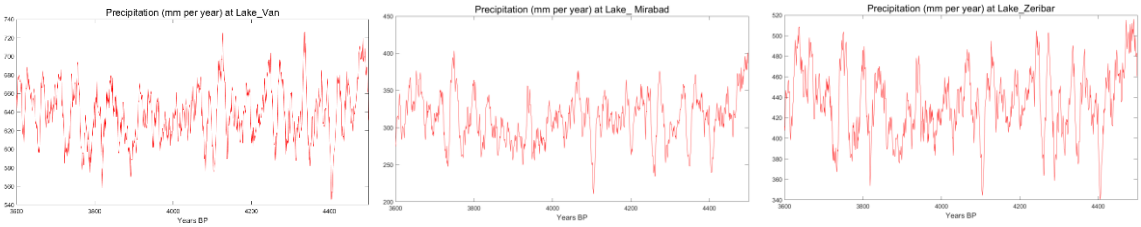


Figure 41 : 10y average Precipitation (mm/year) for lakes in Mesopotamia from 4.5-3.6ka.

Caves (*Figure 42*)

There are no obvious trends at Jeita or Soreq cave in the precipitation plots, other than fluctuations of roughly 300y cycles. They have very similar plots, just with Jeita cave having a maximum value of 390mm/year versus 330mm/year for Soreq. Both remain above the threshold for drought resistant cropping across the whole timeframe.

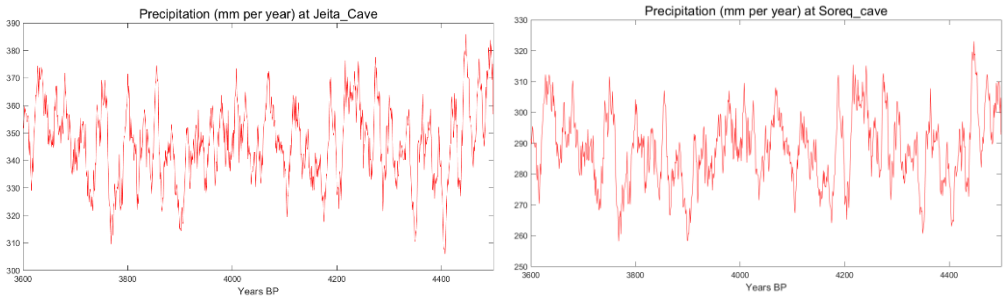


Figure 42: 10y average Precipitation (mm/year) of caves close to Mesopotamia between 4.5-3.6ka.

Mapping precipitation (*Figure 43*)

Similarly to the other maps of precipitation, there is little change (< -36.5mm/year or -0.1mm/day) but it is useful to see how the changes mapped onto the region of Mesopotamia. The drier areas appear to be East of the Tigris-Euphrates, but the changes are not as large here as the aridification North of the Nile Delta. Whereas there appear to be wetter regions to the North-West. With the sites' locations in mind, Göbekli Tepe would be the only site close to the wetter Northern region and Tell-ed-Der/Sippar is in a neutral zone with no/little change. Jeita and Soreq Cave would be in a dry zone of the coastal Levant, and the Eastern lakes would all be in/near drier regions.

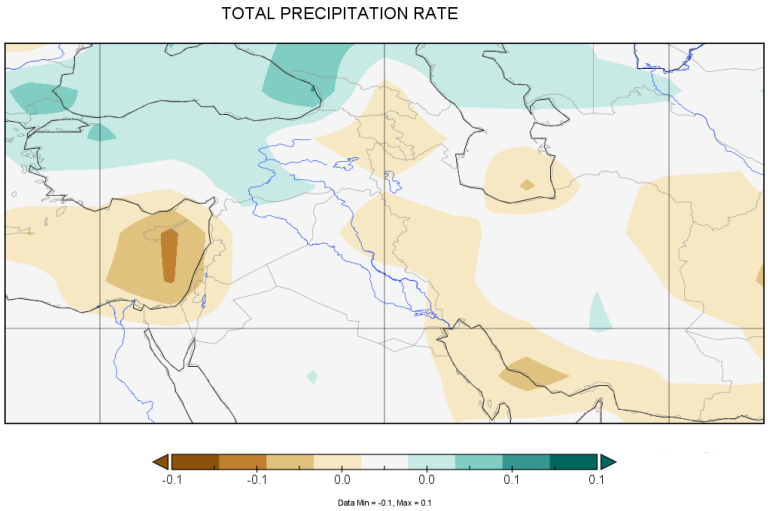


Figure 43: Map of precipitation difference between 4.3-4.2ka 100y and 4.2-4.1ka 100y averages in mm/day across Mesopotamia.

From *Figure 44*, it is evident that between 4.3-4.2ka and 4.2-4.1ka there is a decline in precipitation over Egypt between 0 to 0.025mm/day but the f-test shows this as significant change for this area. Whereas, the monsoonal highlands of Ethiopia and Lake Victoria demonstrate insignificant change, probably as those areas encounter a lot of variability of precipitation.

The region of the Indus River Valley is within the 0 to -0.075mm/day centennial change and the f-test shows this as significant change whereas the wetter North-East towards the Ganges has insignificant change due to the variability seen at the location.

Mesopotamia appeared to have some areas of significant centennial change centrally and some which were insignificant to the South and North.

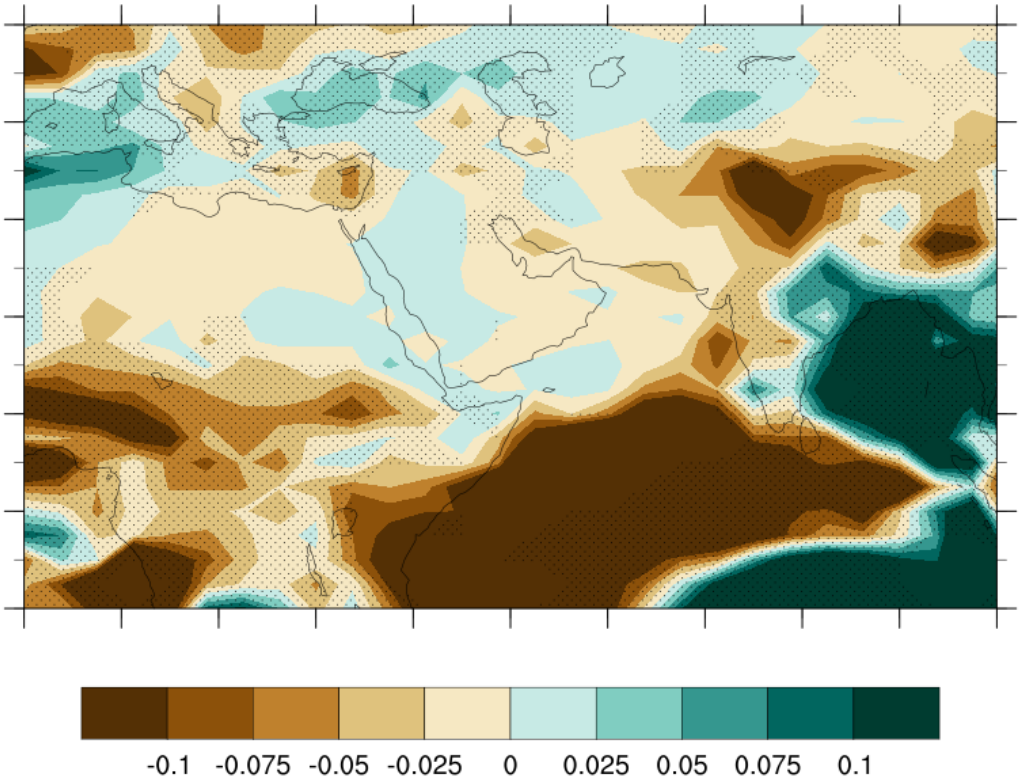


Figure 42: : Map of precipitation difference between 4.3-4.2ka 100y and 4.2-4.1ka 100y averages in mm/day across all three regions with f-test for significance (Shaded parts insignificant change).

4.2.3.2 Precipitation minus evaporation

Archaeological sites (*Figure 45*)

The P-E of the three archaeological sites follows similar trends across the period. Variation seems to decline between 4.2-4.0ka before a peak ~3.9ka (lower evaporation). This is followed by increased fluctuation in P-E, but it also must be acknowledged that the scale is small for all three sites but especially Sippar/Tell-ed-der.

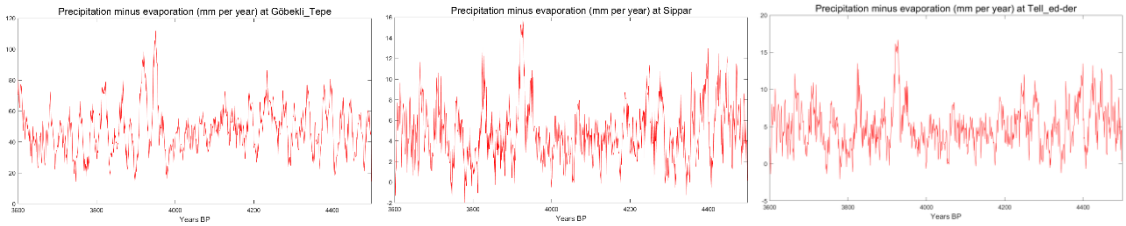


Figure 45 : 10y average of Precipitation minus Evaporation (mm/year) of archaeological sites of Mesopotamia from 4.5-3.6ka.

Lakes (*Figure 46*)

The pattern of higher P-E (lower evaporation) ~3.9ka also appears in the plots of the lakes. Aside from that, there are not many clear trends in the data.

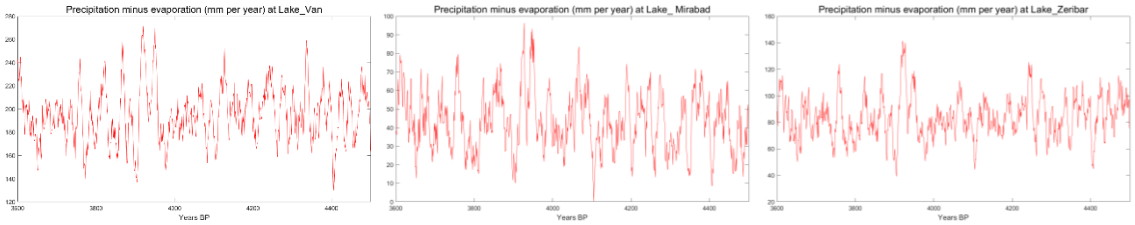


Figure 46: 10y average Precipitation minus Evaporation (mm/year) of lakes in Mesopotamia from 4.5-3.6ka.

Caves (*Figure 47*)

Just like the precipitation plots, for P-E the two caves appear to have the same pattern but also to the same scale. The main trend is increased variability post-4ka, skewing more negative (higher evaporation). This is followed by the highest P-E values just before 3.8ka before returning to more average fluctuations.

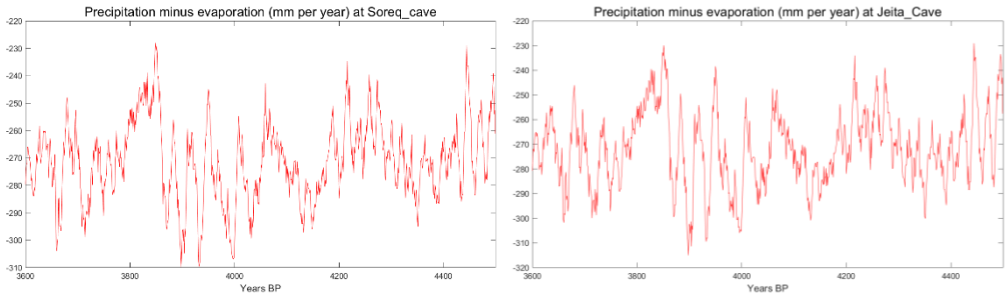


Figure 47: 10y average of Precipitation minus Evaporation(mm/year) for caves near Mesopotamia from 4.5-3.6ka.

4.2.3.3 Temperature (*Figure 48*)

For Tell ed-der/Sippar and Soreq cave, both have high temperatures at 4.2ka of 21.8˚C and 19.2˚ C respectively. Soreq has another peak at 4ka of similar temperature and for Tell ed-der/Sippar, this second peak is at 3.8ka. For all 3, there is a lot of variation and no other obvious patterns other than a slight declining trend from 3.8-3.6ka. For Göbekli Tepe, the only main peak is just before 3.8ka, to 15˚C and similar decline 3.8-3.6ka.

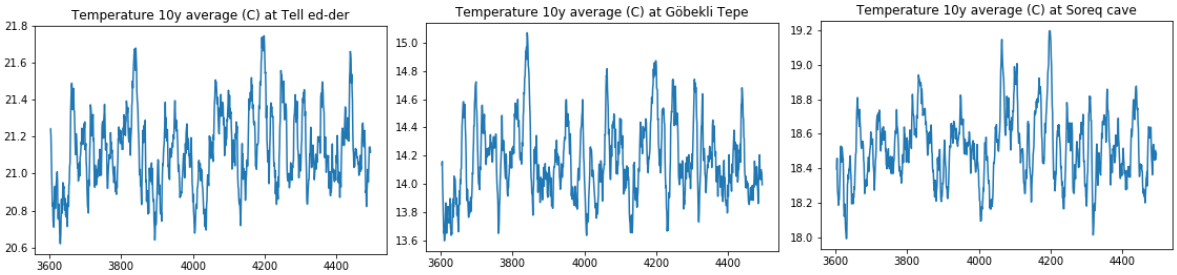


Figure 48: 10y average of Temperature (˚C) for key sites in Mesopotamia from 4.5-3.6ka.

4.2.3.4 River output

Tigris-Euphrates River output (*Figure 49*)

For the river output of the Tigris-Euphrates river system, the largest peak is at 4.45ka (~2400 m^3s^{-1}) and this drops to its lowest value by 4.4ka (800 m^3s^{-1}). There is a lot of variation at both ends of the time period, between 4.5-4.2ka and ~3.8-3.6ka. Between 4.2-3.8ka, variation is mostly smaller with a few peaks and troughs. Most of the low values are ~1100 m^3s^{-1} between 4.4-4.2ka and then between 4.2-3.9ka there are two dips going down to 1000 m^3s^{-1}. Around 4.2ka, there are three peaks going up to ~2200 m^3s^{-1}, so there does not seem to be a dry period reflected in the river output at this time but there is a slight downtrend during the period of small variations between 4.2-3.8ka.

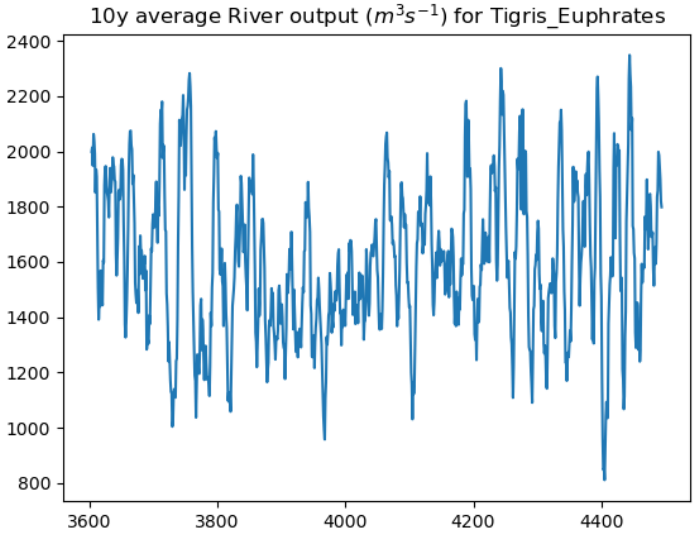


Figure 49: 10y average of River output (m^3s^{-1}) of Tigres-Euphrates from 4.5-3.6ka.

4.2.3.5 Oscillation index

North Atlantic Oscillation (*Figure 50*)

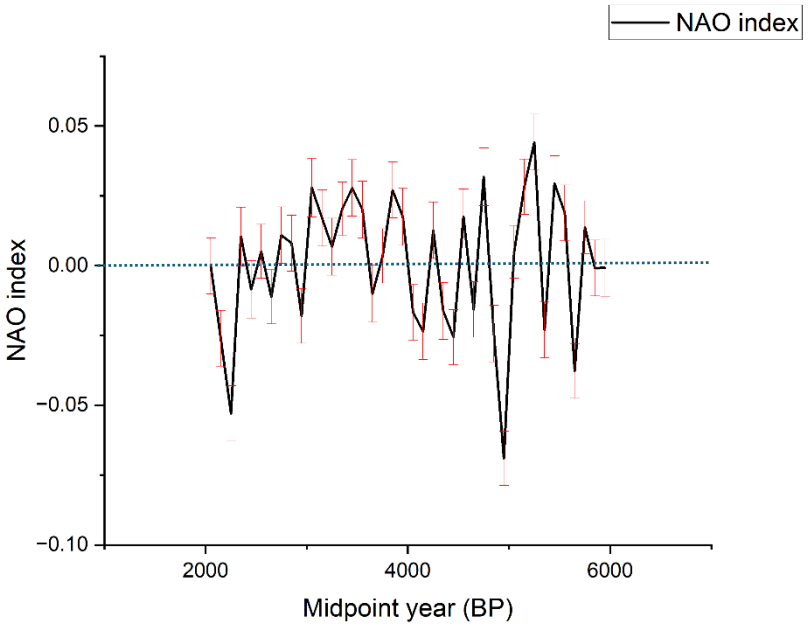


Figure 50: Centennial average of the North Atlantic Oscillation (NAO) Index between 6-2ka. A normalised MSLP based index with error bars marking the standard error of the centennial averages.

By plotting the centennial average of the NAO index from 6-2ka, it demonstrates neither a positive nor negative phase NAO during the period, as the index is always close to 0. It would be expected to reach near 1 or -1 to be a significant phase.

Summary

For the archaeological sites of Mesopotamia, precipitation declined over ~300y between 4.5-4.2ka and the amplitude of variation of P-E was lower between 4.2-4.0ka before reaching the highest evaporation levels at 3.9ka. Sippar/Tell-ed-er were never above the threshold for drought tolerant crops and Göbekli Tepe remained above the threshold for the whole timeframe. The lake sites also experienced higher evaporation at 3.9ka and had similar trends in amplitude of variation of precipitation but two precipitation declines at 4.4ka and 4.1ka. The two caves had no clear precipitation trends other than roughly 300y cycles of variation and evaporation was highest here between 4.0-3.8ka. Tell-ed-der and Sippar being the only sites of actual Mesopotamian settlements were the only two sites (other than Lake Mirabad at 4.1ka) to have precipitation levels below the threshold of agriculture using drought resistant species of plants. Temperature centrally, was highest ~4.2ka but lower between 4.1-4.15ka. The river output for the Tigris-Euphrates river system mirrored the pattern in variation of precipitation as the amplitude of variation of the river output was also smaller between 4.2-4.0ka. River output average also declined between 4.2-3.9ka which matches up with highest evaporation levels being at 3.9ka. The NAO index gave no indication of strong positive or negative phase so therefore it could be presumed that there were negligible effects caused by the NAO during the 4.2ka time period.

4.3 Archaeological data

4.3.1 The Egyptian Old Kingdom

4.3.1.1 Political/Economics

The political and economic situation during the 9th and 10th dynasties was one that led to power and wealth decentralising from its usual pharaonic pattern and instead spreading to the provinces (Bard, 1993). This would be the end of the pharaohs of the Old Egyptian Kingdom and usher in a new age of the First Intermediate Period (Bard, 1993). This shift was highlighted by the change in burial practice, from centralised tombs in Memphis during the Old Kingdom,

to provincial tombs on rich landholders' own land. Some old elites at the time wrote moral stories in reaction to being disturbed by the new social order (Seidlmayer, 2003; Butzer, 2012). There seemed to be an increase in the number of bureaucrats being buried in tombs during the 5th and 6th dynasties which alluded to wealth being spread beyond the pharaoh's inner circle and also would've taken a toll on expenditure on building mortuary amenities (Bard, 1993). This would then result in officials of the crown with lower or even middle ranking eventually losing funding for their own tombs (Bard, 1993).

In the middle of the 6th dynasty, there had also been a policy put in place to encourage loyalty for elites in the provinces which included land donations from Pepi II, an example was written by Sabni I in Elephantine who was gifted land in Upper and Lower Egypt (Jiménez-Serrano, 2023). By the 9th dynasty, lack of centralised governance meant a breakdown of both order and tradition, the governor Ankhtifi's tomb mentioned tombs being violated and even the elite experiencing hardship (Butzer, 2012). During this time of lack of strong succession following the death of Pepi II, it seemed the provinces took advantage in order to gain more power and steer wealth into their locality (Butzer, 2012).

Another area that drove economic downturn for the crown and rippled down the chain was a collapse of foreign trading, items like wood imported for boat building or luxuries of olive oil and wine (Butzer, 2012). Naturally, the pharaoh would have reaped the benefits of trade with other nations but during Pepi II's reign, Byblos (In modern day Lebanon) was invaded by the Akkadians which halted trade with Egypt and thus diminished the capital of the crown (Saghieh, 1983; Butzer, 2012). This also coincided with the end of Egypt's hegemony over Nubia, where they previously received imports of gold, ivory and ebony (Bard, 1993). This diminution of the crown's wealth from lack of trade aligned with a time of change in agricultural resources, suggesting one or multiple feedback loops were responsible for Egypt reaching its tipping point into 'collapse' or renewal.

4.3.1.2 Environment and Agriculture

The economy of Egypt until this point in time was based on irrigation fed agriculture hoarded by the state as the pharaoh assumed a god-like persona in providing sustenance physically but also divinely in the sense of seeming to control the weather and conditions for good harvest (Butzer, 1984; Bard, 1993). After the AHP came more intermittent flooding with change in inundation level, and which areas of the Nile river basin received floods (Butzer, 2012). However, as much as there were possible climatic factors, human impact also needs to be

considered and could've independently as well as in tandem with climate, led to the decline of the Egyptian Old Kingdom. Across this period, populations of wild species declined from predation, more land was used for growing crops and grazing animals enhanced desertification (Bard, 1993). The Nile flow itself was altered by channel cutting as irrigation was used to change the pattern of flooding, to maximise water level and duration of floods (Butzer, 2012). Pepi II's own influence was change of land use, with more areas taken as mortuary land to celebrate dead kings and therefore less available for agriculture (Bard, 1993). These occurrences would mean in a drier climate, less meat was available, animals had less grazing land available which would also affect dairy produce, and less land was available or conducive for growing crops (Bard, 1993). The crown would cease to have surplus grains and thus would no longer seem all-powerful as they became unable to feed the masses (Bell, 1971; Bard, 1993).

4.3.1.3 Famine

In several governor's tombs there is writing of hunger and famine around the time of Pepi II (Elkashef, 2023). Ankhtifi's tomb claims 'All of Upper Egypt died because of hunger, every man eating his (own) children; but I never let death happen because of hunger in this nome. I gave a loan of Upper Egyptian barley to Upper Egypt, and I gave to the north.' Although, it is necessary to allow room for potential hyperbole in claims of the scale of famine and of cannibalism (Eyre, 2002; Elkashef, 2023). Some interpretations state the writings mention Nile failure causing starvation, death and migration to greener pastures (Butzer, 2012). Documents of Heqanakht also mention famine and additional claims of cannibalism: 'Look, one should say hunger (only) about (real) hunger. Look, they've started to eat people here' (Allen, 2002; Elkashef, 2023). Finally, famine features in the autobiography of Qar, a 6th dynasty nomarch (~2345-2181 BC or 4.345-4.181ka) who was in role under Merenre, and then through Pepi II (Daressy, 1917; Elkashef, 2023).

4.3.1.4 Invasions and Violence

There are numerous accounts of civil unrest or invasions of foreign cities that would have impacted trade around the time of 2200 BC or 4.2ka. During Pepi II's reign, there were tensions between the Egyptians and Wawat-Irtjet (Of Lower Nubia) as described by Harkhuf (A 6th dynasty governor) while using the land route to trade with Iam (Jiménez-Serrano, 2023). Pepy-

nakht Heqaib I, a subsequent governor during Pepi II's reign, was sent by the pharaoh to attack Lower Nubia, killing the heirs of rulers and taking captives to present to the king. This was thought to be a tactic to enable safer trade routes as the alternative desert routes at the time were just as dangerous and the coastal route had also had issues (Jiménez-Serrano, 2023). Ankhtifi, another Old Kingdom governor, had written evidence in his tomb of civil war and there seems to be various inferences of this, both direct and indirect in the archaeological record (Butzer, 2012). This would have impacted the crown's power, capital and ability to provide for the population.

Summary

The archaeological record in Egypt highlights that during Pepi II's reign, there was decentralisation that led to there being many provincial kings after no clear succession – meaning that power structures were no longer pharaonic and thus what was known as the Egyptian Old Kingdom came to an end (Bard, 1993; Butzer, 2012). This shift of power and land ownership to the provinces was especially evident with the change to local burials (Butzer, 2012). At the same time, Egypt and the crown suffered from decreased trade with foreign cities due to invasions or hostility, which would've impacted the elite economically. On top of this, there was also loss of agriculture due to land use, climate and hydrological change (Bard, 1993; Butzer, 2012). With the state's loss of wealth and hunger rife in the Egyptian nomes, there is no wonder that the god-like nature of a central pharaoh may have been questioned or unable to be maintained (Butzer, 2012; Elkashef 2023). Whether there was one main trigger or catalyst to the decline of the Egyptian Old Kingdom or the experience of many simultaneous factors, it is unclear. What is obvious is that the state was not robust enough to handle it and therefore the region underwent 'collapse' or decline to then rise again in a very different socio-political structure. This would then become known as the Intermediate Period (Butzer, 2012; Elkashef, 2023).

4.3.2 The Harappan Civilisation

4.3.2.1 Environment and Agriculture

During the Mature Harappan phase, the Indian Summer monsoon started to weaken, which brought more consistent rainfall until ~2200 BC (4.2ka) (Petrie et al., 2017). At this time, populations shifted to North-East India where climate was more favourable as the monsoon

continued to weaken (Madella and Fuller, 2006; Giosan et al., 2012a). It became much harder for both rain-fed and floodplain agriculture, and previously perennial rivers became ephemeral or completely parched (Giosan et al., 2012a). The first evidence of hydrological change around this time period came 2500 BC (4.5ka), around the cusp of the Early Harappan phase, into the Mature phase, in the Cholistan part of the Thar desert, where the Hakra (Saraswati) river flowed (Mughal, 1990; Giosan et al., 2012a). Around this time, flood intensity became less and less, which at first aided agricultural intensification and city growth until a certain threshold (Giosan et al., 2012b). Then, later ~2100 BC (4.1ka), water channelled from the Sutlej (Satluj) river reduced enough to cause migration of settlements nearer better water sources (Mughal, 1990). The Beas river, also in the North-West, showed hydrological stress in palaeoclimate models during the reduced monsoon, which would've directly impacted Harappa, the city (Robbins Schug et al., 2013). Therefore, it seems likely there was a shift in population towards the North-East of the plain, where precipitation was higher, as early as 2500 BC (4.5ka) but perhaps amplified further ~2200-2100 BC (4.2-4.1ka) (Petrie, 2017; Petrie et al., 2017; Green and Petrie, 2018). This is highlighted in the map of sites created by Dutt et al. (2018) where sites dated to the Mature Harappan Phase are marked in yellow and are more widespread whereas sites dated to the Late Harappan Phase move easterly towards the Ganges and Yamuna rivers *(Figure 51*).

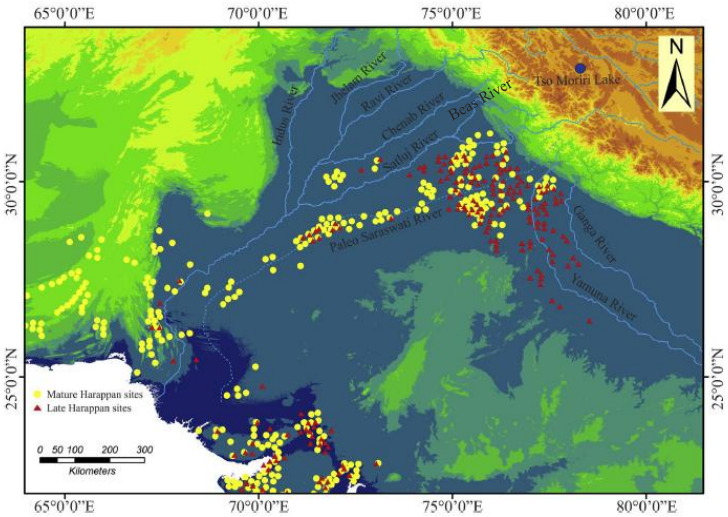


Figure 51: Map of sites from the Mature and Late Harappan phases and river systems from Dutt et al. (2018).

However the changing monsoon affected the Indus valley, whether it was excessive flooding, drought or a combination, one example of both evidence for changing climate and resilience to this was crop diversification (Madella and fuller, 2006; Giosan et al., 2012a; Sarker et al., 2016).

It is theorised that even in the Early Harappan Phase, agricultural practices adapted with climate and water availability, so perhaps the civilisation was used to adjusting their cropping pattern (Petrie et al., 2016; 2017; Petrie, 2017; Petrie and Bates, 2017). This was seen particularly in the Mature Harappan phase across the North-West of the region, where there is also more evidence of hydrological change (Petrie, 2017; Petrie et al., 2016, 2017; Bates et al., 2017a, 2017b; Petrie and Bates, 2017). Wheat and barley went from making up ~60% of agriculture, to just 20%, in favour of more drought-resistant species like millet and rice (Giosan et al., 2012b; Sarker et al., 2016). Although increased diversity of crops may have been used in earlier phases to allow surplus stocks to mitigate years of failed/lesser harvests, switching to summer crops with lower yields during the late Mature/Late phase may have been a catalyst for the decentralisation of agriculture (Fuller and Madella, 2001; Weber, 2003; Fuller and Stevens, 2009; Weber et al., 2010; Sarker et al., 2016). As large cereal storage would no longer be required, food storage and processing could be localised in the household and thus households could be further from economic centres (Fuller and Madella, 2001; Weber, 2003; Fuller and Stevens, 2009; Weber et al., 2010; Sarker et al., 2016). This could have led to the decline in social complexity as there would have been less connection between agriculturalists and cities, and thus village settlements would have run as localised systems (Giosan et al., 2012b). This dissolution of urban living would in turn have economic effects, but not everyone in society would feel these equally, with the most vulnerable groups being the ones already marginalised (Robbins Schug et al., 2013).

4.3.2.2 Population growth, violence and disease

There is more research and knowledge about the growth of urbanisation within the Harappan civilisation and less about how social structures changed once settlements spread further from city cores and populations declined (Kenoyer 1997; Possehl, 2002; Wright, 2010). How did these societies of agriculturalists and pastoralists but also artisans interact post-urbanisation? The archaeological sites dated to the Mature phase were far fewer compared to the Early phase which emphasises this retraction of the civilisation away from urban centres and to specific, sometimes new settlements (Giosan et al., 2012b; Green and Petrie, 2018). Some earlier period mounds were even restored, and this continued a snowballing effect of decentralisation as migration occurred due to climate/economic/social reasons, but further populations left cities due to the de-urbanisation itself, especially in the North-West (Green and Petrie, 2018). Some researchers also suggest Aryan invasion as a theory for settlement changes, although there seems to be little evidence put forward for this, but instead

interpersonal violence within the civilisation itself (Sarker et al., 2016). Perhaps people retreated to rural living partly due to increased violence which would have been exacerbated by economic struggles, affecting the marginalised communities the most (Robbins Schug et al., 2013). As surpluses dwindled, those of lower social standing would have been the first to suffer, causing further oppression and leading to further violence in urban cores (Robbins Schug et al., 2013). Although, these theories must be evaluated with reservations, as the complexity of early civilisations cannot always fit the projections of our modern lens on societies (Green and Petrie, 2018).

Another factor that would have impacted marginalised groups much more than others was disease (Robbins Schug et al., 2013; Sarker et al., 2016). Bodies from cemeteries dating to ~2000 BC (4ka) were examined and showed evidence of leprosy and tuberculosis near the Indus Valley (Robbins Schug et al., 2013). 160 individuals were analysed and showed evidence of lesions from infectious disease but also infections related to suspected violent injury (Robbins Schug et al., 2013). The rate of infection and disease was higher in these cemeteries from the Late Harappan Period compared to earlier phases which highlights increased violence, poverty and perhaps a decline in living conditions/hygiene (Robbins Schug et al., 2013). One of the burial sites that was located just outside of the city walls, found more individuals who perished from injury and disease, and it is thought they were perhaps living in poverty or could have been stigmatised in Harappan society (Robbins and Schug et al., 2013).

Summary

The Harappan civilisation thrived and expanded for centuries but its growing population in urban centres could not be sustained through the changing of the monsoon (Madella and Fuller, 2006; Robbins Schug et al., 2013; Petrie et al., 2017). When the ISM weakened, precipitation in the North-West was less reliable, rivers dried up and agriculture became increasingly difficult over the span of 2500-2100 BC (4.5-4.1ka) (Mughal, 1990; Giosan et al., 2012a). In response, settlements shifted North-East to moister regions closer to the Ganges through modern day Punjab, Haryana and Uttar Pradesh (Madella and Fuller, 2006; Giosan et al., 2012a). Crop growing adapted with summer varieties such as rice and millet, which grew with less rain but also had lower yields and thus there was less surplus to maintain the large population (Fuller and Madella, 2001; Weber, 2003; Fuller and Stevens, 2009; Weber et al., 2010; Giosan et al., 2012b; Sarker et al., 2016). With settlements mostly situated away from urban cores, the previous urban centred economy crashed perhaps instigating increased levels

of violence, poverty and disease within dwindling cities (Mughal, 1990; Robbins Schug et al., 2013; Sarker et al., 2016). This would have pushed more people to leave for rural villages, leading to further decentralisation and the disintegration of urbanism within the Harappan civilisation (Robbins Schug et al., 2013). Therefore, as much as the Harappans tried to mitigate the weakening monsoonal effect on their agricultural systems, it seems the expansive urbanism they inhabited successfully for centuries could not be sustained (Fuller and Madella, 2001; Weber, 2003; Fuller and Stevens, 2009; Weber et al., 2010; Giosan et al., 2012b; Sarker et al., 2016). Although the Late phase came to an end, the Harappans around the time of 4.2ka were not eradicated but instead shifted to a more sustainable way of living through the shifting climate with local food production in more humid rural regions (Mughal, 1990; Sarker et al., 2016).

4.3.3 The Akkadian Empire

4.3.3.1 Environment and Agriculture

Research in the late 1990's put forward the theory that volcanic activity was the cause of aridification across Mesopotamia, causing urban cities to be left to the desert, although this would require large-scale feedback and climate tipping points to produce a widespread permanent change. More recent research favours theories of natural climate change interconnected with unsustainable agriculture practice (Courty and Weiss, 1997; Weiss and Courty, 1993; Weiss et al., 1993, Ur, 2010; Tainter in Centeno et al., 2023). Mesopotamian society was one built on the back of canal systems and irrigation in a reasonably dry climate, but this also left it vulnerable to climate events such as drought or flooding (Wilkinson, 1994;1997, Ur, 2010; Butzer, 2012). The latter could cause damages across urban settlements, open new natural channels away from canals, fill waterways with silt or cause saltwater intrusion (Butzer, 2012). Man-made hydrological structures required workers and capital to be built and sustained over time so therefore, they were also vulnerable to economic change and migration away from urban centres (Butzer, 2012). In areas along the network where canal management broke down, agriculture could no longer be maintained and with no human influence, the desert would take over once more (Butzer, 2012). However, this degradation was also possible with too much human influence. If land was over-grazed or cropping not managed well, desertification would ensue and is evidenced in archaeobotanical data and thus this necessitated a shift to mobile pastoralism (Wilkinson, 1994;1997; Lawrence, 2021). Some areas were within the range of ~300mm of annual precipitation which could allow for rainfed

cropping practices, but this could not be relied upon due to precipitation changes even on an annual scale could mean harvests were not always very fruitful (Lawrence et al., 2021).

One example of the coupled effect that agriculture/pastoralism and population had on each other was the urban centre of Ebla (Lawrence et al., 2021). Within texts, it speaks of the elite control of livestock, which could be pastured in drier regions, and a shift away from flax to wool. This allowed more fertile land to be used for crop agriculture which is thought to have been another catalyst for population growth and the expansion of urban cities (Lawrence et al., 2021). With these changes, it is thought Ebla was able for a time to mitigate problems associated with the drying climate by using animals that could thrive like sheep/goat rather than cattle and also placing them further from water sources, freeing up land where crops could grow more productively (Lawrence et al., 2021). These changes were evident in the archaeological record, as with the rise of livestock came the decline of wild native species and tracks can be seen by satellite where domestic herds were intensively moved across the plains (Altaweel, 2004; Ur, 2003; Wilkinson, 1993; 2003; Zeder, 1998; 2003).

However, with growing population and urbanisation, more and more pressure was put upon rural areas for produce to sustain the masses and it was inevitable that eventually the carrying capacity would be overshot (Ur, 2010; Lawrence et al., 2021). Lawrence et al., 2021 used agricultural modelling and archaeological data to find that between 2600-2000 BC (4.6-4.0ka), urban cores could not produce enough food for their growing populations and therefore needed surplus from the hinterlands, often taken through taxes. When taxation of rural settlements grew too high, populations shifted to semi-pastoralism, herding more nomadically and thus away from the pressures growing on supplying urban cores (Butzer, 2012). Populations also migrated away from the more arid zones and toward higher rainfall regions, meaning not only de-urbanisation of cities but also de-population of certain villages and settlements (Lawrence et al., 2021).

4.3.3.2 Politics/Economics

Rainfall and food production are quite obvious factors in the survival of a civilisation, but Wilkinson et al. (2007) used settlement and agricultural data alongside cuneiform records to identify the labour force to also be a significant factor. Thus, it is important to consider the ramifications of both the shift to mobile pastoralism and also depopulation of settlements (Lawrence et al., 2021). Deurbanisation is also assumed to bring the decline of social/political

complexity and is put forward as the telltale sign for the ‘collapse’ of societies (Lawrence et al., 2021).

Wilkinson (1994) analysed the carrying capacity of ancient cities and found that a settlement would reach its limit on food production for its own population at just over 2600 people. Once surplus was needed from the hinterlands, another threshold would be met at populations of ~11,700-14,300 inhabitants where the economy could not function if impacted by external factors such as climate aridification (Wilkinson, 1994). Lawrence et al., 2021 puts forward that even without climate change, rapid growth of this ancient civilisation would have eventually reached a limit that could not no longer be sustained.

There is a lot of dispute, specifically in the case of Mesopotamia as to whether shifts away from urbanisation were ‘collapses’ after all, as some suggest the civilisation often functioned in a decentralised capacity even when large cities were maintained (Adams, 1978; Weiss and Courty, 1993; Van de Mieroop, 1999; Chapter 1 in Centeno et al., 2023). There is evidence of large city walls, religious buildings and palaces that allude to top-down society with elite or state reign, but researchers claim these rulings could have been for short periods of time and governing still may not have been centralised (Van de Mieroop, 1999; Ur, 2010; Scott, 2017). This theory points to evidence of having many smaller palaces, artworks rarely with imperial/state propaganda and using tribal systems (Stein, 2004). Adams (1978) puts forward that the theory of elite power over Mesopotamia does not seem plausible when nomadic herding was a possible route of existence outside of governance and these groups were valuable to both the economy and civilisational politics (Durand, 2004; Fleming, 2004)

When Mesopotamia is reconstructed with these theories in mind, power can be assumed to have been spread among not only at the top of institutes but to households across the plain, including those living mobile pastoral lifestyles (Ur, 2010). How this changes the perspective of civilisational shifts, is that a decentralised society could perhaps deurbanise more effectively to deal with both exogenous and endogenous factors of hardship in a large urban civilisation (Wilkinson et al., 2007). Mitigation techniques for surviving aridification, overpopulation and saturated land-use could have been retreating to village settlements and mobile pastoralism, and therefore requiring fewer hands for farming, diversifying crops more rapidly but also being able to rely on each other in community (Wilkinson et al., 2007). Therefore, although deurbanisation and abandonment of urban centres are signs of civilisational collapse, those living rurally or nomadically may not have felt like their quality of life was lacking when the pressures of urban life ceased (Wilkinson et al., 2007).

Summary

Throughout time, Mesopotamia experienced cycles of de-urbanisation and urbanisation lasting ~400y, so what was so different about this last stage of de-urbanisation? Thought to have lasted between 100-200y, perhaps the most recent urban growth stage before it had been more rapid and larger than before and hence the carrying capacity was met much sooner and it deteriorated much faster (Ur, 2010; Lawrence et al., 2021). Another theory could be that climate was a much more significant exogenous factor than ever before and that combined with overpopulation, urban Mesopotamia would not rise from the desert again (Weiss et al., 1993). Unlike other civilisations of the time, there seems to be a lack of evidence of disease, famine or violence in the record for this population, so perhaps the inhabitants spread out from urban cores across to more productive regions without the high mortality rate that was seen elsewhere (Sarker et al., 2016; Lawrence et al., 2021). This society that was suspected as having a decentralised structure most of the time even though urban phases, perhaps was able to mitigate better for a time but if the land became unliveable with low annual rainfall and the land was reclaimed by the desert, conceivably the people migrated to more promising lands and thus there was no further re-population in the time of Akkad (Wilkinson et al., 2007; Butzer, 2012; Lawrence et al., 2021).

5.0 Discussion

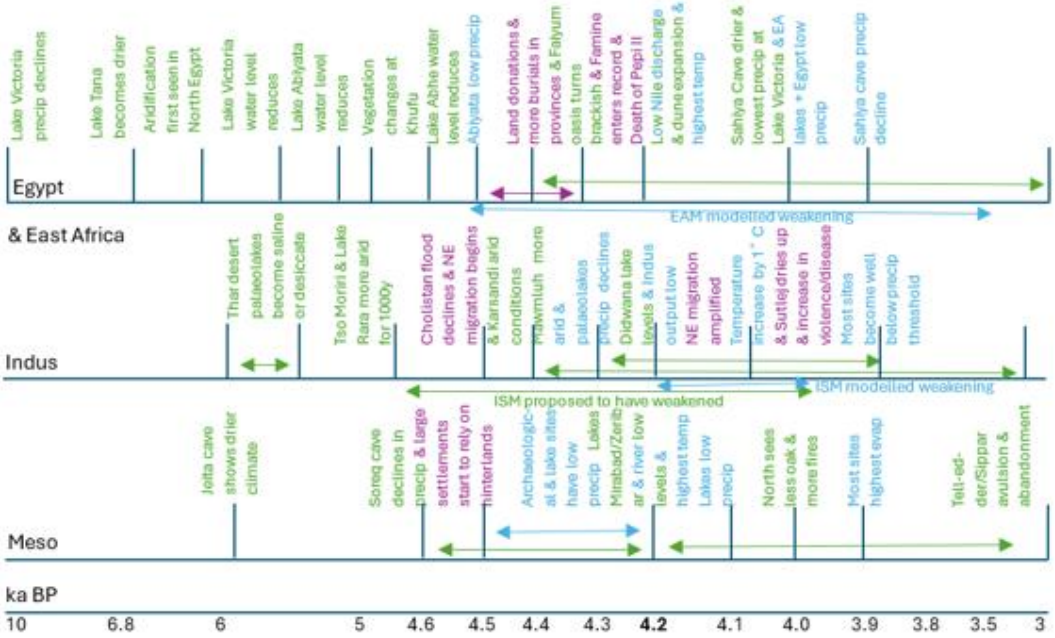


Figure 52: Timeline of all three civilisations/regions with key dates across proxy, climate modelling and archaeological data.

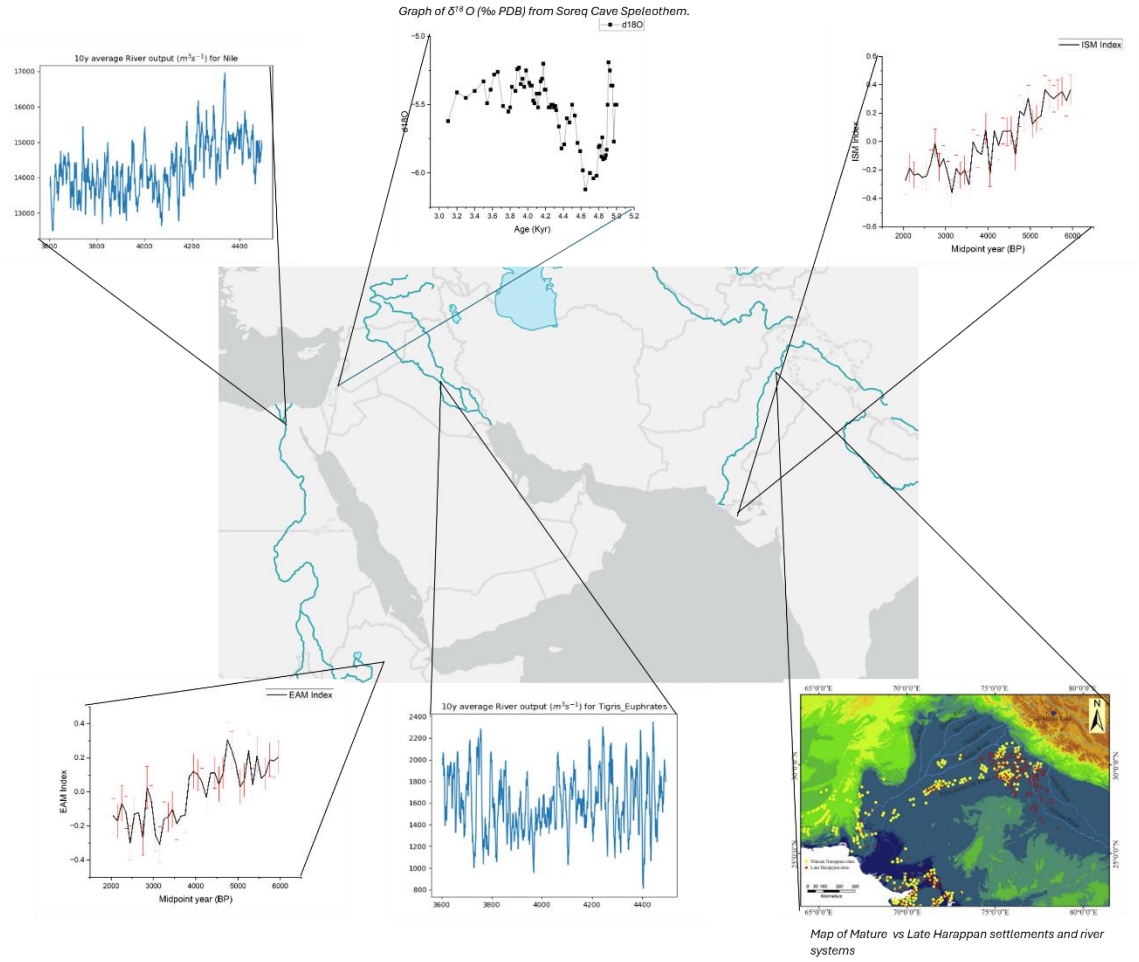


Figure 53: Map of all three civilisations/regions with key figures across proxy, climate modelling and archaeological data.

5.1 Proxy and climate data compared

5.1.1 Egypt and East Africa

The proxy data of the Nile Delta alluded to low Nile discharge between 4.25-4.05ka (Stanley et al., 2003) and the climate modelling data simulated agreed with this estimate, as the river output showed low values between 4.2-4.05ka (*Figure 52)*. However, post-4ka there seemed to be a new regime of lower river output from the Nile which suggests a climate shift rather than a brief event (*Figure 53*). The timing of this aligned with the simulated EAM rapidly weakening between 4.5-3.5ka (*Figure 53*). Faiyum Oasis proxy data illuminated brackish conditions between 4.4-3.0ka which may correlate more with a longer shift in climate rather than a rapid excursion (Marks et al., 2018) Other proxies estimated aridification in this region from as far back as 6.1ka in the North of Egypt, and vegetation changes were inferred at Khufu

~5ka (Sheisha et al., 2022). Although dune expansion evidenced in sediment cores was thought to have occurred ~4.25ka, simulated precipitation at several Egypt sites actually demonstrated declines between 4.0-3.9ka in line with higher levels of evaporation and only temperature increased at 4.2ka (Hassan et al., 2017). When mapped geographically, it was seen that the whole Nile Delta was in a dry zone when comparing the 100y averages of 4.3-4.2ka with 4.2-4.1ka and that the variation was significant for the region.

The proxy data from Lake Manzalla in Egypt demonstrated a switch from White Nile dominant sediments to Blue Nile taking place ~4.2ka, therefore the monsoonal region of East Africa at the sources of the Nile needed to be examined (Stanley et al., 2003). Lake Tana, the source of the Blue Nile was estimated to begin having a drier climate ~6.8ka in the proxy studies and for nearby Ethiopian lake Abiyata this was 5.4ka – both outside of the climate simulation timeframe (Chalié and Gasse, 2002; Marshall et al., 2011). In the climate data, Lake Tana (as well as Abiyata and Abhe) declined in precipitation ~4.1-4.0ka but evaporation levels were not high despite temperature simulating an increase by a whole 1˚C. The highest evaporation levels for all three lakes occurred in the model ~4.4ka, and only Lake Abiyata's precipitation plots coincided with a low at this time. Further South at the White Nile source of Lake Victoria, proxy data alluded to water level and precipitation decline ~10ka until between ~4-2.6ka but this larger scale picture was outside the scope of the climate simulation run. However more rapid changes were picked up on with precipitation declining ~4.1ka but there appeared to be an oscillation of 200-300y of increase and decline rather than a discrete event (Berke et al., 2012). Although the precipitation and evaporation data was only analysed between 4.5-3.6ka, the monsoon index running from 6-2ka highlighted the longer weakening pattern of the monsoon that would have affected Egypt and monsoonal East Africa, as seen in the proxy data as far back as 10ka. The more rapid decline in the strength of the EAM at the midpoint of 4ka may be evident in both the proxy and climate modelling data but there is no clear '4.2ka event' seen in the data runs between 4.5-3.0ka (*Figure 52*). The monsoon index post-4.2ka appeared to stabilise but at a new weaker equilibrium, which is also more indicative of a changing climate regime.

5.1.2 Indus River Valley

The proxy sites the furthest North in this region were theorised to have become arid ~4.75-4.35ka until 3.75-3.45ka (Dutt et al., 2018; Nakamura et al., 2016). When the climate simulation precipitation data was mapped, the North of the subcontinent showed the greatest

drying when comparing the 100y averages of 4.3-4.2ka and 4.2-4.1ka. The simulated temperature of the sites was highest ~4.1ka, where it increased by 1˚C, and the lake sites did show higher evaporation by 4.0ka. The Thar desert proxy research predicted the area became drier ~6.5-5.5ka (*Figure 52)* which was outside of the timescale of the climate model data, but simulated precipitation had two main declines at 4.35-4.30ka and 4.0ka (Enzel et al., 1999; Deotare et al., 2004; Dixit et al., 2014). The implications of these falls in precipitation must be acknowledged as on average the sites were just at/above the threshold for drought resistant cropping (~250mm/year) and during these declines, values fell to well below the threshold (60-70mm/year). Locations like Didwana Lake were estimated from proxy data to have had decreased water levels ~4.2ka and the simulated river output matched with declines at 4.2ka and 4.1ka. The Mawmluh Cave Speleothem had very high resolution that estimated aridification beginning ~4.3ka for 400y and most proxy studies suggested the ISM weakened between 4.8-4.0ka, with a few estimating 1000y earlier ~5.8-5.5ka (Rein, 2007; Nakamura et al., 2016; Singh et al., 1990; Doose-Rolinski, 2001; Giesche et al., 2019; Giosan et al., 2018; Rashid et al., 2011; Kathayat et al., 2017; Walker et al., 2018; Dixit et al., 2014; Enzel et al., 1999). However, the monsoon index calculated for the Arabian branch of the ISM indicated general monsoon weakening between 6-3ka but more rapidly between 4.75-4.5ka and 4.2-4.1ka (*Figures 52 and 53).* The simulated Indus River output had the most variability compared to the other rivers across the civilisations so although there was a drop ~4.2ka, it was less clear, and the river seems to have a pattern of increasing/decreasing output every 200y. The proxy data alluded to an aridification pattern starting earlier in the West and moving East (more specifically in relation to the Thar desert) and this was evident in the data-model comparison as the Thar desert lake sites experienced an earlier precipitation drop ~4.35-4.30ka whereas more eastern sites like Sahiya Cave had declining rainfall between 3.95-3.85ka which may explain the eastward migrations *(Figure 53*).

5.1.3 Mesopotamia

Northern Mesopotamia had proxy evidence of drier conditions ~4ka from increased charcoal from wildfire and declining populations of oak overtaken by more drought resistant species (Wick et al., 2003; Riehl et al., 2009). However, in the climate modelled data the archaeological sites had declining precipitation earlier between 4.5-4.2ka and highest evaporation as late as 3.9ka. Soreq Cave was estimated to have had wetter conditions between 5.2-4.7ka and then rapidly drier conditions between 4.1-4.0ka (Bar-Matthews et al., 1999). Lake Zeribar and

Mirabad proxy data highlighted that they experienced drier climate between 4.2-3.4ka and in the climate modelling data, these sites experienced precipitation decreases at 4.4ka and 4.1ka and then the highest evaporation level at 3.9ka (Stevens et al., 2001). The simulated river output for the Tigris-Euphrates was interesting as river output was high ~4.2ka but low by 4.1ka and again after 4.0ka but there was much less variation in the data between 4.2-3.8ka (*Figure 53).* There was also an even lower output value at ~4.4ka which was also reflected in the precipitation plots. The proxy studies alluded to longer aridification between 6-3ka, with perhaps more intense drying ~4.2-3.9ka (Only evidenced in high resolution proxy of Soreq Cave) (*Figure 53).* The climate modelling data was able to highlight two separate excursions in climate at ~4.4ka and ~4.1-4.0ka. However, it must be said that climate conditions did not seem to return to average between the two dates and therefore they may not have been discrete events but rather slightly more extreme parts of a longer period of aridification. Predictions in the literature theorised that it was the NAO either in a strong positive or negative phase at this time which affected the precipitation brought to Mesopotamia from the Westerlies, however, the NAO index calculated from simulated climate data highlighted a neutral phase NAO which would have had negligible effects on the climate of the region.

5.2 Archaeological insights to data

5.2.1 Egypt

The Egyptian Old Kingdom relied heavily on the Nile river for agriculture and transport. Thus it was vulnerable to intermittent flooding, change in water level and change in locations of floods, but these factors could be enhanced or mitigated by channel cutting (Butzer, 2012). The proxy studies at Saqqara highlighted flash floods and mudflows ~4.2ka which would have influenced use of that specific area in Egypt (Welc and Marks, 2014). Saqqara was once a thriving location for pyramid building and funerary architecture as the Nile river was used to transport materials between 4.6-4.2ka but by ~4.25ka the Western Desert began encroaching as dunes expanded across the area (Hassan et al., 2017). At this time, the simulated river output of the Nile declined between 4.2-4.05ka and did not recover, at least within the simulated time period ending at 3.6ka (*Figure 53)*. Some inferences of tomb writings suggest Nile failure was quoted to have caused famine, and this is mentioned as far back as ~4.4ka (Butzer, 2012).

However, other endogenous factors were present at this time and some that also increased desertification. The land use for agriculture and animal husbandry when overexploited allowed deserts to expand or drier regions were used more due to land being needed which were then more vulnerable to drought (Bard, 1993). During the reign of Pepi II, a lot of land was sectioned off for tombs that could then not be used for food production, or land was gifted to the provinces to gain their favour (Bard, 1993). There were writings of war and civil unrest and this power struggle for pharaonic rule came to a crux when Pepi II died (Butzer, 2012; Jiménez-Serrano, 2023). Aridification of the Nile Delta was perhaps a major reason for the end of the Egyptian Old Kingdom but also came at a time of diminished foreign trading (with some foreign cities even invaded by the Akkadians of Mesopotamia), failed administration and complex politics (Butzer 2012; Saghieh, 1983; Bard, 1993). Therefore, perhaps the civilisation was not robust enough to withstand not only several endogenous failures but also the biggest exogenous factor of all: climate change. However, it does not seem that this region experienced a discrete '4.2ka event' in climate but instead a more gradual drying that perhaps came to a crux ~4.2-4.0ka when the EAM weakened further.

5.2.2 Indus River Valley

Across the region examined for the Indus river valley, proxy data highlighted aridity signals from the Thar Desert as early as 6.0-5.5ka and archaeological studies noted the effects when at 4.5ka, the Cholistan part of the Thar desert grew drier (Mughal, 1990; Enzel et al., 1999; Deotare et al., 2004; Dixit et al., 2014). As the Hakra river output declined, flooding intensity decreased which was at first beneficial to agricultural growth and the expansion of the Harappan civilisation (Mughal 1990; Giosan et al., 2012b). This was until a threshold of aridity, when water levels and flood intensity became too low to operate in the region (Giosan et al., 2012a; 2012b). From even the Early Harappan Phase (~5.2ka), there seemed to be diversification of crops in the archaeological record which perhaps showed that the Harappans had previously adapted to changes of climate, as this aligned with a weakening in intensity of the ISM as shown by the calculated monsoon index (*Figure 53)* (Madella and Fuller, 2001).

Then during the Mature phase (4.6ka) and Late phase (4.2ka), perhaps these kinds of adaptations were even more important as the ISM had two sharper declines in strength at the midpoints ~4.75ka and ~4ka, affecting 5.25-4.15ka and 4.5-3.5ka (*Figure 53)*. in the Late Mature Phase, farming became more localised which in a way helped mitigate the effects of climate conditions shifting but also aided in the further decentralisation of economic centres

(Fuller and Madella, 2001; Weber, 2003; Fuller and Stevens, 2009; Weber et al., 2010; Sarker et al., 2016). Mortality rates and migration were theorised to have increased, with populations moving North-East in line with the monsoonal changes (Giosan et al., 2012a; Petrie et al., 2017). Migration was first evident in the record in line with the Late Mature phase (~4.5ka) when the Thar desert became more arid, as highlighted in the simulated precipitation plots (Petrie, 2017; Petrie et al., 2017; Green and Petrie, 2018). Average precipitation otherwise was just at the threshold for drought resistant crops and during these two key points, levels fell well below and thus this would have impacted the region's agricultural productivity significantly. This was further emphasised in the mapping of precipitation 100y averages between 4.3-4.2ka and 4.2-4.1ka, when migration was amplified as the North/North-West became drier and showed the North-East wetter (*Figures 33 and 52*). Those who did not migrate by 4.0ka, were left in urban centres that saw increased violence and disease, possibly due to scarcity driven by the climate changes seen in the proxy data and simulated climate data (Robbins Schug et al., 2013).

So in the Indus River Valley, there appears to have been two more prominent climate excursions as seen in the changing intensity of the ISM ~4.5ka and 4.1-4.0ka (*Figure 53)*. However, the ISM pattern is also seen to gradually decline over time concurrently. Even if these two points in time were not extreme climate events, precipitation levels falling below the thresholds for drought tolerant agriculture would have made a dramatic change locally and hence was followed by the mass migration of settlements (*Figure 53) (*Petrie, 2017; Petrie et al., 2017; Green and Petrie, 2018).

5.2.3 Mesopotamia

Similar to the Indus, in Mesopotamia there was a rise in urbanisation ~4.6ka which lasted until ~4.3ka in the South and 4.2ka in the wetter North (Akkermans and Schwartz, 2003; Stein, 2004; Wilkinson, 1994; Lawrence et al., 2021). Conditions could have become drier as soon as 100y after the establishment of larger settlements (4.5ka) where simulated precipitation declined for archaeological sites from 4.5-4.2ka which would have put more pressure on the hinterlands to provide for growing populations. When the precipitation change was mapped between 4.3-4.2ka and 4.2-4.1ka, the North-West appeared wetter in climate so may have been a migration route as aridification amplified. As a civilisation built on man-made canals and irrigated agriculture, there was already a vulnerability when it came to extremes of drought or flooding which would've been particularly relevant when the Tigris-Euphrates river output was

simulated to reach a low ~4.1ka (*Figure 53)* (Wilkinson, 1994;1997, Ur, 2010; Butzer, 2012). There may have been evidence however of adaptation in agriculture as macroremains of drought resistant plant species were found at Göbekli Tepe between 4.0-3.6ka, similar to how the Harappans reformed their cropping practices around the same time (Madella and Fuller, 2001; Riehl et al., 2009). At the proxy sites of Tell-ed-Der and Sippar, it was thought the rivers were in use between 5-3ka until avulsion occurred ~3ka either due to climate or anthropogenic influence (Heyvaert and Baeteman, 2008).

All civilisations reach a threshold of function even without external climate forcings, and for Mesopotamia, the extent of growth of its urban cores is theorised to have been its downfall (Butzer, 2012; Lawrence et al., 2021). As populations increased, large urban centres and their associated agriculture were established in drier areas, potentially increasing exposure to the droughts that occurred in the region (Lawrence et al., 2021). At a certain size, the population required more and more from the hinterlands for food surplus but also those living in cities started to opt for mobile pastoral lifestyles supposedly away from taxation (Butzer et al., 2012; Lawrence et al., 2021). Even during times of rapid urban growth, the Akkadians were theorised to have lived in quite decentralised structures with power spread amongst institutions but also households (Wilkinson et al., 2007). Therefore, when dealing with both endogenous and exogenous factors like climate change and overpopulation, perhaps they were better equipped to deal with them, even if ultimately, they could not sustain large urban centres (Wilkinson et al., 2007). So although the Akkadian Empire came to collapse, this was perhaps different compared to the end of the Egyptian Old Kingdom and the Harappans of the Indus River Valley as there seemed to be lacking evidence of violence or disease (Sarker et al., 2016; Lawrence et al., 2021).

6.0 Conclusions

The objectives of this study were to investigate if a climate event ~4.2ka was evident in proxy data across the expanse of three ancient civilisations, whether simulated climate data agreed with the proxy findings and if the archaeological record further emphasised aridification ~4.2ka or if any other factors could have responsible for civilisational collapse.

Proxy data and inferences from studies were collated regionally, some of these at locations where settlements once stood but mostly the closest lakes and caves were used. In Egypt, dune expansion was evident in sediment cores ~4.25ka and there were signs of low Nile river output

~4.2ka which alluded to aridification and expansion of the desert (Stanley et al., 2001; Hassan et al., 2017). This drying of the climate was suggested to have occurred earlier in the Ethiopian lakes between 6.8-5.4ka but evidence in Egypt was also scattered between 6.1-3.0ka. For example, vegetation changes occurred around Khufu ~5ka and Faiyum Oasis was brackish by 4.4ka, which continued until 3.0ka (Marks et al., 2018; Sheisha et al., 2022). Similarly, sites close to the Indus river valley also showed a pattern of aridification beginning thousands of years before 4.2ka, at ~6ka (*Figure 52)*. Even excluding the Thar desert lakes which may have experienced an earlier drying ~6.0-5.5ka where they became desiccated or saline, proxy sites gave evidence across a time span of 4.75-4.0ka. This matched up with the predicted ISM weakening between 4.8-4.0ka (Rein, 2007; Nakamura et al., 2016; Singh et al., 1990; Doose-Rolinski, 2001; Giesche et al., 2019; Giosan et al., 2018; Rashid et al., 2011; Kathayat et al., 2017; Walker et al., 2018). The highest resolution proxy, Mawmluh cave still alluded to 400y of aridity which would not necessarily constitute a discrete '4.2ka event'. Across in Mesopotamia, the Soreq cave proxy also implied at least 400y of precipitation decline from 4.6ka and in the North/Anatolia, vegetation changes and increased fires were marked ~4.0ka (Bar-Matthews et al., 1999; Wick et al., 2003; Riehl et al., 2009). However, other proxies showed lake levels still low at 3.4ka (after nearly 800y) and avulsion occurring ~3.0ka (Stevens et al., 2001; 2006). Furthermore, in Mesopotamia the proxy data was too spread across more than 1000y to constitute a discrete 4.2ka climate excursion.

To examine further, a climate model simulation was run between 5-3ka, but data was analysed closer to the date of interest between 4.5-3.6ka. Proxy site locations were used to estimate local precipitation, evaporation and temperature trends and evaluate if findings matched the proxy study inferences. River output was plotted for the three major rivers, and monsoon indices were calculated for the ISM and EAM, as well as an index of the NAO. Climate modelling data mapped several sites in Egypt as having lower precipitation ~4.0-3.9ka and higher evaporation ~3.9ka. Although, the highest temperature across the 1000y did occur at 4.2ka and coincide with the lowest Nile river output ~4.2-4.05ka. However, post 4.0ka, the average Nile output did not increase again, and this was simultaneous with the rapid weakening of the EAM. This was also seen in the data in Eastern Africa where precipitation was low between 4.5-4.4ka and 4.1-4.0ka and evaporation was highest ~4.4ka. In the literature, the NAO was theorised to have influenced the ITCZ to be more southerly, causing monsoonal change but the NAO index calculated did not demonstrate a strong positive or negative phase, so this is unlikely. The Indus sites, particularly close to the Thar desert appeared to have two separate climate excursions in the precipitation data ~4.4-4.3 and ~4ka and the Indus river output declined at 4.2ka but

seemed to have regular 200y patterns of increase/decline which could have coincided at 4.2ka. These trends in the region of the Indus River Valley aligned with the calculated ISM index which highlighted a general weakening of the monsoon between 6-3ka but most rapidly at the centennial midpoints of 4.5ka and between 4.2-4.1ka. During these points in time, precipitation specifically fell below the threshold needed for even drought resistant cropping and thus could have been why migration seemed to occur ~4.5ka and then increased again ~4.2ka. In Mesopotamia, precipitation appeared to decline in the plots from 4.5-4.2ka and then higher evaporation was seen later ~3.9ka. Between 4.2-3.8ka, the Tigris-Euphrates river output had lower variation with lows at both 4.1ka and 4.0ka. As the calculated NAO index was close to 0, these climatic changes are unlikely to have been influenced by the phase of the NAO, therefore there was likely to be internal variability and local factors affecting the climate.

To evaluate if climate changes were evident in the archaeological record or if the collapse of the civilisations was due to other factors, archaeological studies were collated. Inferences were then compared with the climate data to highlight matching/contrasting timelines and give context to both the effects of climate and additional endogenous factors of collapse. In Egypt, Nile failure was referenced in tombs and said to have led to extreme famine across the lands (Butzer, 2012). As a kingdom that relied on regular floods for agriculture, drier conditions with flash flooding would have impacted food production, as well as the dune encroachment estimated at 4.25ka (Welc and Marks, 2014; Hassan et al., 2017). However, at the time of pharaoh Pepi II, there was ineffective land-use management where less land was used for agriculture and more and more put aside for burials or gifted to provincial elites (Bard, 1993). There became a lack of foreign trade as well as war/power struggles with nearby nations, reducing the crown's capital (Saghieh, 1983; Bard, 1993; Butzer 2012). Within this context, the end of pharaonic rule of the Egyptian Old Kingdom could have been caused by a drying climate and/or other economic/political factors at the time. The question is, would collapse have occurred at the same time (~4.18ka or 2184BC) if it had not coincided with the death of Pepi II?

In the Early Harappan Phase (~5.2ka or 3200 BC), crop diversification appeared in the Indus River Valley which demonstrated previous climate adaptations and aligned with an earlier rapid weakening of the ISM in the calculated index (Madella and Fuller, 2001). So when this mitigation technique appeared again during a rapid weakening of the ISM in the Late Mature Phase (4.2-3.9ka), it was evident the civilisation had some level of resilience to exogenous factors like climate. The change to smaller scale farming could have also been more robust too, as crop failures would be on smaller scales and more varied species across plots would have more chance of successful harvest (Madella and Fuller, 2001). The migration of settlements

toward the Ganges in the wetter North-East correlated with precipitation maps as the drier regions close to the Thar Desert were gradually abandoned (Giosan et al., 2012a; Petrie et al., 2017). Urban cores experienced higher levels of violence and disease during deurbanisation which appeared in the archaeological record but could have been a result of scarcity of resources brought about by drought (Robbins Schug et al., 2013). The Late Harappan Phase did last from 3.9-3.0ka which suggests perhaps collapse for the Harappans was slower compared to the other civilisations, and this was perhaps due to higher levels of resilience built into their systems of agriculture (Giosan et al., 2012b).

As a society that relied on irrigation and man-made channels in a relatively dry climate, Mesopotamia was perhaps always vulnerable to climate change (Butzer, 2012). With urban expansion building into even drier regions, this would have been enhanced further (Lawrence et al., 2021). Similarly to the Harappans, there was evidence of adaptation by using drought resistant species between 4.0-3.6ka, however it seems Mesopotamia was less robust overall (Riehl et al., 2009). Although people inhabited Mesopotamia post-4.2ka, it was no longer the Akkadian Empire. Perhaps the threshold of growth of this civilisation would have been reached around this time without the additional factor of climate shifts but also growth into desert regions would have left them more vulnerable to collapse (Lawrence et al., 2021). At least there seemed to be less evidence of violence and disease in the archaeological record for the Akkadians, perhaps their more decentralised power structures allowed for a smoother transition to smaller scale rural settlements (Wilkinson et al., 2007; Sarker et al., 2016; Lawrence et al., 2021).

To conclude, in Egypt and East Africa, there did not appear to be a discrete ‘4.2ka event’ but rather a slower aridification after the AHP that was then influenced by a more rapid weakening of the EAM between 4.5-3.5ka. This caused the Nile river output to reduce and remain low as the monsoon index remained weaker post 4ka. Famine became evident in the archaeological record ~4.4ka and highlighted not only environmental but also social/political issues of the time (Butzer, 2012). However, the reason Egypt may have been assumed to have experienced collapse due to a ‘4.2ka event’ may be due to the death of Pepi II which brought an end to the pharaonic rule of the Old Kingdom (Butzer, 2012; Jiménez-Serrano, 2023). In the Indus River Valley there also was not evidence of a rapid ‘4.2ka event’ but similarly a pattern of degradation in monsoon strength of the ISM between 6-3ka. There were more rapid declines in monsoon strength ~4.75-4.5ka and 4.2-4.1ka which was also illustrated in the precipitation data. It seemed that the Thar desert region experienced drier climate earlier and thus pushed settlements to migrate towards the wetter North-East, beginning ~4.4ka and increasing ~4.2ka

(Petrie, 2017; Petrie et al., 2017; Green and Petrie, 2018). At these points in time, precipitation fell from just above to below the threshold needed for drought tolerant crops which may have been the reason for settlements shifting as agriculture began to fail. Comparably, Mesopotamia also had two main climate excursions ~4.4ka and 4.1-4.0ka but this also seemed to be part of a larger scale climate shift from 6-3ka. As urbanisation increased intensely ~4.6ka, larger settlements had to push into drier regions and thus with growing populations, they were more vulnerable to drought (Lawrence et al., 2021).

7.0 Limitations and Further Research

One main limitation of all three sections within the thesis but also in the wider literature is being vulnerable to 'suck-in' or 'smear', terms coined by Baillie (1991) where in this case both environmental and archaeological events in history occur at similar times and thus are 'sucked-in' or combined to be assumed as the same event or correlated. 'Smear' works similarly but inversely, where due to radiocarbon dating errors, one event may appear as an extended period when data appears to be spread through time, but the discrete event actually occurred over a rapid timeframe (Baillie, 1991). It could be argued that the 4.2ka event was smeared, which is why it has been difficult to confirm when data varies between ~3.9-4.6ka but due to confirmation bias, it seems more likely that the 4.2ka event has been victim to suck-in within palaeoclimate studies which has been further over-emphasised by the collapse of ancient civilisations occurring circa the same time period (Baillie, 1991; McKay et al., 2024).

An example of this in the proxy record is when comparing the 8.2ka with the 4.2ka event where the 8.2ka event has evidence of forcing at a discrete point in time whereas this is more unclear for 4.2ka and excursions also occur between ~3.9-4.6ka which is an example of suck-in. Especially when considering the level of variation seen, this could have happened at any different point of the Holocene due to variability of climate at the time (Mckay et al., 2024). Although it must be recognised that even climate variability that is not large enough to be considered an event could have locally had big effects on ancient civilisations within the fluctuations of Holocene climate (McKay et al., 2024). Another limitation of proxy data is that often there can be site-level excursions away from average climate variation that can be interpreted as 4.2ka event but at more regional/global levels, seeing the same fluctuation is rarer and is more likely to be temperature based rather than precipitation (McKay et al., 2024).

Within the climate modelling aspect of the research, in future to explore if signals ~4.2ka were actually natural variability, there could be multiple runs of the simulation with alternative start points in order to gauge if variability would still show a peak/trough in the data at the same point. Due to there being no major forcing, it could show that the transition of wetter to drier climate could have happened at a different time, and that perhaps the overlap of the three regions' climate shift was partly coincidental and still slightly asynchronous. Although two monsoon indices and an index for the NAO were calculated, other atmospheric/oceanic indices could have been explored such as the winter monsoon/NW monsoon over India, the Indian Ocean Dipole and ENSO. The archaeological data had limitations in dating due to imprecise radiocarbon dating, where layers are dated rather than objects themselves or pottery is used to estimate time periods (McKay et al., 2024). Archaeological literature can be based on interpretations and hence biases rather than concrete evidence, which must be acknowledged. This includes where only a small sample of sites are found; there can be overrepresentation of certain artefacts or settlements or populations (McKay et al., 2024).

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