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The Holocene

The 4.2 ka event: a review of palaeoclimate literature and directions for future research

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Abstract:	In recent years, much evidence has been presented on the 4.2 ka event. A review of 317 palaeoclimate papers shows that dry conditions were common during the event, especially from Eastern Mediterranean to India. The 4.2 ka event was not, however, a global drought event. Wet conditions were reported especially for central/northern Europe and sub-Saharan Africa. The 4.2 ka event is typically characterized either as short (4.2-4.0 ka) or long (4.4-3.8 ka) episode, possibly developing over an extended interval of time, in keeping with the North Atlantic forcing and correlating with the Bond 3 event of ice-rafted debris. This forcing is understood to drive a southward migration of the Inter-Tropical Convergence Zone (ITCZ), resulting in decreased rainfall over most of the Asian monsoon region, with possibility that an interplay of El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) has modulated the global circulation. Cold conditions were also reported but less frequently, in comparison to the 8.2 ka event, Dark Ages Cold Period and Little Ice Age. Some high-resolution records show a double peak structure of which two anomalies are tree-ring dated to 4.14-4.05 ka and 3.97 ka. Accurately and precisely dated high-resolution records indicative of various climatic variables, especially outside of the traditional study region (Mediterranean–Middle East–India–China), including reconstructions of the ENSO and NAO histories and ITCZ migrations, are crucially needed for rigorous examination of the global scale characteristics of the 4.2 ka event and its forcings. Such research seems to be just beginning.

Introduction

Holocene climate history is characterized by distinct climate variability at the millennial and centennial timescales (Mayewski et al., 2004; Wanner et al., 2008, 2011; Solomina et al., 2015). One of the frequently cited climatic episodes dates back around four millennia and is commonly termed the 4.2 ka event or 4.2 ka BP event (Rousseau et al., 2019). Research of this event has its own history that goes back decades. Early studies recognised reductions in monsoon precipitation and coinciding weakening of the Indus Valley civilisation (Singh, 1971). Synchronous increases in aridity (Figure 1a) around same time in the Mesopotamia, Aegean, Egypt, Levant and the Indian subcontinent are generally understood to have driven the documented collapses of the ancient rain-fed agriculture civilisations (Weiss et al., 1993; Cullen et al., 2000; deMenocal, 2001). The same region extended to China, climate-culture nexus and drastic changes in monsoon circulation have all remained in the core of the multidisciplinary research focussing the 4.2 ka event since those days (Ran and Chen, 2019). In this context, a wider spread of the coinciding droughts and apparent global linkages have been illustrated also for North American sites (Booth et al., 2005).

More recently, an isotopic ($\delta^{18}O$) excursion recorded in Mawmluh Cave speleothem in northeast India (Figure 1), reflecting the reduction in monsoon rainfall during the 4.2 ka event (Berkelhammer et al., 2012), was formally ratified as Global Boundary Stratotype Section and Point (GSSP) for the lower boundary for the Meghalayan Stage/Age, and accordingly the boundary between the Middle and Late Holocene, by the Executive Committee of the International Union of Geological Sciences (Walker et al., 2018, 2019a, 2019b). The ratification was supported, among other evidence, by a dataset that had been collated by Mayewski et al. (2004), who had described synchronous rapid climatic disruptions with wide spatial distribution between 4.2 and 3.8 ka, in connection with major atmospheric circulation changes typified as a ‘‘cool poles, dry tropics’’ pattern. Apart from droughts, however, wet conditions seem to characterize the 4.2 ka event at high latitudes, including the

Mount Logan ice-core succession that constitutes an auxiliary stratotype for the Mawmluh Cave (Figure 1b) (Fisher et al., 2008; Walker et al., 2019b), as well as in parts of sub-Saharan Africa (Booth et al., 2005; Walker et al., 2012; Railsback et al., 2018, 2022). Moreover, advances of Northern Hemisphere glaciers over the same period, in keeping with cooling in the North Atlantic sector, have been identified (Denton and Karlén, 1973; Solomina et al., 2015). With these regards, the foregoing papers (deMenocal, 2001; Mayewski et al., 2004; Booth et al., 2005; Solomina et al., 2015), like several other authors, have discussed the 4.2 ka event in the context of a North Atlantic events of ice-rafted debris as recorded by Bond et al. (1997, 2001). The North Atlantic data show a cold-water pulse commonly referred to as Bond 3 event at around 4.2 ka and suggesting reduced solar radiation as driver of the Bond events over Holocene time scales (Figure 1c). Putatively, such forcings in addition to ENSO-driven (El Niño–Southern Oscillation) sea surface temperature patterns (Booth et al., 2005) could explain the global extent of the event, although the teleconnections involved and actual physical mechanisms underlying the possible linkages (Gupta et al., 2021; Banerji and Padmalal, 2022; Renssen, 2022) remain to be further explored.

More critical views of the event have also been expressed. No convincing support for the global spread of the event was found in a multi-proxy study (Wanner et al., 2008). A global analysis of speleothem records did not detect notable isotopic excursions around 4.2 ka (Parker and Harrison, 2022). These authors concluded that the lack of consensus about the event could stem from its spatial complexity, poor age constraints and/or its weak climatic signals. Similar to criticism on palaeoclimate indications of the 4.2 ka event, worries about the Middle–Late Holocene boundary, concerning its dating accuracy together with its' putative global spread, have been created (Voosen, 2018).

Clearly, there seems to be a need for studies that aim to delineate the evidence presented for the 4.2 ka event. This paper constitutes a review of evidence on climate variability during the 4.2 ka event (Table S1). A literature search for “4.2 ka event” and for its various synonyms (Table S2) was performed (Google Scholar (http://scholar.google.com/), accessed 26 June 2023) and all papers citing the term with new proxy indications of climatic or environmental evidence on the event, published in international English-language peer-reviewed journals, were included in this review. The number of explored papers totalled 317 and exceeds by ~tenfold the number of papers included in previous literature collections (Booth et al., 2005; Railsback et al., 2018). Pure literature syntheses were not included. Archaeological papers without natural proxy data were excluded to avoid mismatches arising from differing scales of human responses to any potential climatic driving mechanisms (Jaffe et al., 2021).

Characterizing the 4.2 ka event literature

It seems the actual phrase “4.2 ka event” was first used by Staubwasser et al. (2003) who discussed the Holocene drought/monsoon cycles and the demise of the Indus Valley civilization around that time. The literature that follows constitutes the foundation and rationale for examining the characteristics of this event and how it has been detailed using a large set of palaeoclimatic records. With these regards, there is a notable increase of literature citing the 4.2 ka event since 2018 (Figure 2a). Interestingly, this is the year of the formal ratification of the Meghalayan GSSP (Walker et al., 2018). It appears plausible that the ratification increased the interest on, or at least awareness of, climatic/environmental variations pertaining to the 4.2 ka event.

The sites encompassing China, India and the Mediterranean/Levant account for approx. two thirds of the studies (Figure 2b). Proxy indications were adopted as reported in the reviewed literature. Dry conditions, recorded as droughts or increases in aridity, were the most common (47% of the studies) proxy indication (Figure 2c), such conditions dominating (>50% of the indications) especially in India and Middle East/Eastern Mediterranean (Figure 3). The 4.2 ka event was not, however, a global dry event but wet conditions (16%) were also reported, especially in central/northern Europe, sub-Saharan Africa, and in parts of China. This means that moist conditions have been reported also from the Asian monsoon region. This would agree with the previously defined tripolar precipitation pattern whereby rainfall decreased over India and southern and northern China and increased over central China (Tan et al., 2018; Zhang et al., 2018; Lin et al., 2022). Cold (19%) conditions were also reported but less frequently. This differentiates the 4.2 ka event from other major Holocene climate episodes, the 8.2 ka event (Alley and Ágústdóttir, 2005; Rohling and Pälike, 2005), Dark Ages Cold Period (Helama et al., 2017, 2021) and Little Ice Age (Lamb 1995; Grove 2004) which were dominated by cold conditions. Clearly, the 4.2 ka event was prominently a hydroclimatic episode and certainly not a warm period almost anywhere (2% of the studies).

Many of the studies were based on multiple proxies (40%) (Figure 2d). Materials were mostly dated either using radiocarbon (^{14}C) determinations (77%), followed by uranium–thorium (14%) and optically stimulated luminescence methods (9%). The starting and ending years and peak/mid-point of the event were adopted as reported in the original studies. The mid-point was on average dated to 4.16 ka. A large number (46) of papers reported the date of the event simply as “4.2 ka”. More detailed chronological examination showed an average starting and ending dates of 4.37 ka and 3.81 ka for the event, respectively. Rounded to 100 years, the most common starting years were 4.2 ka (44 studies), 4.3 ka (32) and 4.4 ka (30), the most frequent ending years being 3.8 ka (35), 4.0 ka (31) and 3.9 ka (24) (see Figure 4a).

In the literature, the 4.2 ka event appears either short, with a duration of 200 years, or long, in which case it could span over half-a-millennia. That is, the most usual chronological positions of the event were 4.2-4.0 ka (11 studies), 4.3-3.8 ka (10) and 4.4-3.8 ka (9). The most common durations of the event were 200 (29), 400 (21), and 500 (20) years.

Hydroclimatic events and those recorded in the Asian monsoon region seemed to have both started and ended slightly later than other events (Figure 4b). In the monsoon region, the events had ended ~110 years later than elsewhere, which could possibly reflect findings that the drought of the Indian summer monsoon may have markedly extended over the early Late Holocene (Gupta et al., 2021; Scroxton et al., 2023). Even so, this difference was not found to be statistically significant (t test, $p > 0.05$).

Not all published data appears to concur with the evidence of the 4.2 ka event. These studies do not seem to be clustered at any one type of proxy or region (e.g. Swindles et al. 2013; Mishra et al., 2015; Jaouadi et al., 2016; Fritz et al. 2018; Li et al., 2018a; Ön et al., 2018; Hang et a., 2020; Li et al., 2021; Yang et al., 2021).

Multiple phases within the event

Several papers have illustrated and discussed climate anomalies within the nucleus (4.2-4.0 ka) of the 4.2 ka event. A double-peak structure has been described at least in the following studies (see right-hand plots in Figure 1): dry pulses at 4.03 and 3.96 ka in the Yangtze Valley, China (Zhang et al., 2023), high foraminifer $\delta^{18}O$ values at 4.1 and 3.95 ka in the Arabian Sea indicative of weak Indian monsoon (Giesche et al., 2019), three aridity events at 4.19, 4.11, and 4.02 ka reconstructed for north India (Giesche et al., 2023), two wet anomalies from 4.16 to 4.01 ka in Namibia (Railsback et al., 2018), and anomalously wet/overcast conditions at 4.14-4.05 ka and 3.97 ka in northern Europe (Helama and Oinonen, 2019), which the latter authors called Meghalayan anomaly. Moreover, Weiss (2022) construed a series of the Indian monsoon megadroughts at 4.2-4.17 ka, 4.14-4.08 ka, and 4.06-3.97 ka from the palaeoclimate literature. This set of literature shows that double-peak conditions recorded in India and China were dry, while those in northern Europe and southern Africa were wet. Notably, the second stage of the double peak would appear temporally consistent with indications of climatic disturbances specifically at 4.0 ka, as previously discussed in fewer literature sources under the terms ‘4000 BP event’ (Perry and Hsu, 2000) and ‘4.0 ka event’ (Armitage et al., 2015).

Regarding the poor age constraints minded by Parker and Harrison (2022), it is obvious that reliable comparisons of the described short-term anomalies are becoming increasingly limited by uncertainties inherent to radiometric dating techniques. While uncertainties of only 10-30 years are reported in some studies (Railsback et al., 2018; Walker et al., 2018), calendar-year age ranges for calibrated ^{14}C dates around 4.2 ka typically are of order 80-150 years (Guilderson et al., 2005), for which additional uncertainties inherent to age-depth models (Telford et al., 2004) are to be added in the case of sedimentary records. Accepting the exact tree-ring dates at 4.14-4.05 ka and 3.97 ka (Helama and Oinonen, 2019) would stand as an alternative form of chronological assessment, against which the radiometric dates of other proxy records could be compared until more similarly dated high-resolution archives become available. Intriguingly, the only hitherto published tree-ring chronology from the Asian monsoon region covering the period of interest was not indicative of the 4.2 ka event but instead showed a decrease in moisture availability between 4.0 and 3.5 ka (Yang et al., 2021). This would concur with Scroxton et al. (2023) who proposed a summer rainfall drying for 3.97-3.4 ka around the Indian Ocean basin, following winter-season droughts of the 4.2. ka event.

Late Quaternary context and global-scale forcing mechanisms

Moreover, there are proxy records indicating that the change lasted longer than few centuries suggesting that the event may not have been a sudden, isolated event but developing over a much longer period. With these regards, a “tripartite” climatic development has been inferred from Mediterranean proxy records between 4.3 and 3.8 ka (Magny et al., 2009) characterized a continuum of gradual aridification, severe drought, and return to wetter conditions (Glais et al., 2023). Additional results show that the drought in India may have lasted from 5 to 3 ka, with stronger drying between 4.8 and 3.5 ka (Roy et al., 2022; Scroxton et al., 2023; Behera and Chauhan, 2023). Recently, a gradual change to drier climate was reconstructed since 4.8 ka also in China (Niu et al., 2023), whereas in Ethiopia drying may have started around 5.2 ka (Lanckriet et al., 2017). Long-term change has also been inferred for pluvial conditions in Namibia since around 4.8 ka, with continuation until 2.5 ka (Sobol et al., 2022). Sensitivity of site conditions to different atmospheric patters such as ENSO variability and Inter-Tropical Convergence Zone (ITCZ) migrations has been suggested to explain the dating offsets in the Asian monsoon region (Dutt et al., 2021; Lin et al., 2022) and Africa (Lanckriet et al., 2017; Railsback et al., 2022).

On the other hand, as Cruz et al. (2021) pointed out, the long-term indications predating the event highlight possibility that climate system is moving toward regimes more sensitive to an abrupt change to occur around 4.2 ka. With these regards, North Atlantic forcings factors (Bond et al., 1997, 2001; Bianchi and McCave, 1999; Thornalley et al., 2009) appear the most commonly discussed factor attributed to the 4.2 ka event. This evidence represent sites not restricted to any particular region or proxy type (e.g. Sallun et al., 2012; Sun and Feng, 2013; Fubelli et al., 2013; López-Sáez et al., 2014; Walczak et al., 2015; Sarti et al., 2015; Tang et al., 2015; Blundell et al., 2018; Català et al., 2019; Tan et al., 2020). Actually, the ‘Bond 3 climate event’ and ‘Holocene event 3’ appear as occasionally used synonyms for the 4.2 ka event (Sun and Feng, 2013; Di Rita et al., 2018; Mighall et al., 2023). This forcing is commonly understood to drive a southward ITCZ shift at global scale (Broccoli et al., 2006; Yan and Liu, 2019), thus resulting in decreased rainfall over most of the Asian monsoon region (Zhang et al., 2020; Lin et al., 2022). Again, this would accord with the “cool poles, dry tropics” configuration during the 4.2 ka event (Mayewski et al., 2004). The monsoonal response to this forcing is accomplished within 110 years (Liu et al., 2018), which may partially explain the gradual long-term change in proxy records. Another reason could be that the Bond 3 event may have started to develop already around 4.6 ka (Figure 1c). It is essential to note that the North Atlantic forcing ties the 4.2 ka event to a series of similar events and climatic shifts through the Holocene with a cyclicity close to 1470 ± 500 years suggestively driven by solar forcing (Bond et al., 2001). Similar to the 4.2 ka event, the Bond 5 event at 8.2 ka (Alley and Ágústdóttir, 2005; Rohling and Pälike, 2005) and the Bond 1 event at 1.5 ka (Dark Ages Cold Period; Helama et al., 2017, 2021) contain shorter-term anomalies that punctuate a longer and less extreme period of gradually changing climate.

Also records related to ENSO (Figure 1d) and North Atlantic Oscillation (NAO) (Figure 1e) indicate small-scale perturbations between 4.2 and 4.0 ka. The NAO and the east Atlantic/west Russia (EAWR) patterns may have affected the climatic conditions around 4.2 ka, especially in the Mediterranean environments (e.g. Di Rita et al., 2018; Bini et al., 2019; Schirrmacher et al., 2019). However, the discussion remains superficial, not least due to deficit of NAO- and EAWR- related data. Increased ENSO variability has been recorded from around 4.4 ka towards the present (e.g. Du et al., 2021), with a complicated period of alternating El Niño/La Niña-like conditions at interdecadal time scales between 4.1 and 3.9 ka (Dang et al., 2020). These variations in ENSO have been related to intensification (Booth et al., 2005; Fisher et al., 2008; Li et al., 2018b) and/or temporal extension of the anomalous climatic conditions since 4.2 ka (Scroxton et al., 2023). According to Fisher et al. (2008), the timing of the 4.2 ka event seems to have "inaugurated" the modern ENSO world. Combined, an interplay of NAO and ENSO in modulating the Indian summer monsoon intensities over Holocene time scales has also been proposed (Banerji and Padmalal, 2022). Volcanic forcing is not discussed as an agent behind the 4.2 ka event, which is not surprising considering the quiescence of volcanism over this period. The volcanic forcing index (Kobashi et al., 2018) obtains near-zero values during the 4.2 ka event (Figure 1f) indicating virtually no influence from this factor.

Future directions

Climatic events discussed under the term ‘4.2 ka event’ represent various geographical regions and types of palaeoclimate information. The sites from Mediterranean to India and China are best replicated, whereas the sites outside this region, especially from high latitudes, remain poorly represented but their records are crucially needed for more detailed assessments of the event globally. Expressing the timing of the event simply as “4.2 ka” remain too simplistic and more detailed characterization of the findings is highly recommended to allow for palaeoclimatic and chronostratigraphic assessments of the event. Some weight should be assigned in developing the reconstructions of ENSO, NAO and EAWR variability and ITCZ migrations, to validate sensitivities of the growing proxy setup to relative roles of forcing factors, and to perform proxy–model comparisons. Probably the hardest barrier will be the development of well-dated high-resolution records to overcome the poor age constraints and to replicate the multiple proxy indications that seemingly took place during the event, as well as to disentangle the nucleus of the event (4.2-4.0 ka) from the more gradual, long-term climatic development. Such research seems to be just beginning. Well-dated high-resolution records will not only be needed in natural science but to improve integration in societal consequences to climate change.

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FIGURE CAPTIONS

Figure 1. Palaeoclimate records. Appearance of the 4.2 ka event in low-latitude and high-latitude sites of the Gulf of Oman (a) and the Mt Logan in Yukon (b) where the event is indicated by dolomite % wt. and $CaCO_3$ % wt. (Cullen et al., 2000) and $\delta^{18}O$ (Fisher et al., 2008) as proxies for aeolian activity and moisture, the stacked North Atlantic multi-core record of percentage of hematite-stained grains (% HSG) indicating the ice-rafted debris i.e., 'Bond events', juxtaposed with the ^{14}C production rate (pr, atoms/cm2/sec) indicating variations in solar activity, both (% HSG and ^{14}C PR) as analysed and presented in Bond et al. (2001), standardized to z-scores (Bond event 1, 3, and 5 are depicted) (c), a multi-proxy lake sediment record indicating the North Atlantic Oscillation based on lake sediments (NAO_{PCA3}) from southwestern Greenland available since 5.2 ka (Olsen et al., 2012) (d), a marine sediment record (lithic flux rate, %) off coastal Peru with El Niño–Southern Oscillation correspondence (Rein et al., 2005) (e), volcanic forcing index (VII) presented as 100-year non-overlapping means (Kobashi et al., 2017) (f), the $\delta^{18}O$ chronology from Mawmluh Cave speleothem (Berkelhammer et al., 2012) ratified as the Global Stratotype Section and Point for the lower boundary of the Meghalayan Age/Stage (Walker et al., 2018, 2019a, 2019b) (g), speleothem $\delta^{13}C$ chronology from in the Yangtze Valley, China, indicating two dry pulses (Zhang et al., 2023) (h), foraminifer $\delta^{18}O$ chronology from the Arabian Sea indicating two stages of weak Indian monsoon (Giesche et al., 2019) (i), $\delta^{18}O$ chronology of speleothem aragonite from north India shown with two dry anomalies (Giesche et al., 2023) (j), speleothem $\delta^{18}O$ chronology from Namibia indicated two-pulsed wet event depicted in low-resolution (thick line) (Sletten et al., 2013) and high-resolution data (thin line) as analysed and presented in Railsback et al. (2018) (k), and tree-ring $\delta^{13}C$ chronology (Helama et al., 2018) from northern Europe indicating two anomalies during which wet/overcast conditions prevailed (Helama and Oinonen, 2019) (l). Light and dark grey shading shown in right-hand plots indicate the timeframes between 4.4. and 3.8 ka and 4.2 and 4.0 ka, respectively. Gray

shading in left-hand plots indicate the timings of two isotopic excursions recorded within the 4.2 ka event. Horizontal axis: BP years (before AD 1950).

Figure 2. Characterization of the proxy setup. Number of published studies reviewed in this paper (a), and proportions of different geographical regions attributable to the 4.2 ka event (b) in the palaeoclimate literature, with corresponding proportions of reported climatic and environmental characteristics (c) and proxy types (d). Note that the number of proxy indications exceeds the number of studies: in the case of multiple indications per study, they were all included, with equal weight.

Figure 3. Geographical distribution of different climatic and environmental proxy indications during to the 4.2 ka event. The regions indicated by the pie charts are same as those given in Figure 2b. In the case of multiple indications per study, they were all included, with equal weight.

Figure 4. Temporal distribution of dating placements shown as (a) number of dates and as (b) bars covering a window with average and median starting and ending dates attributable to corresponding climatic and environmental events. The starting and ending years of the event used in these calculations were adopted as reported in the original papers. Horizontal axis: BP years (before AD 1950).

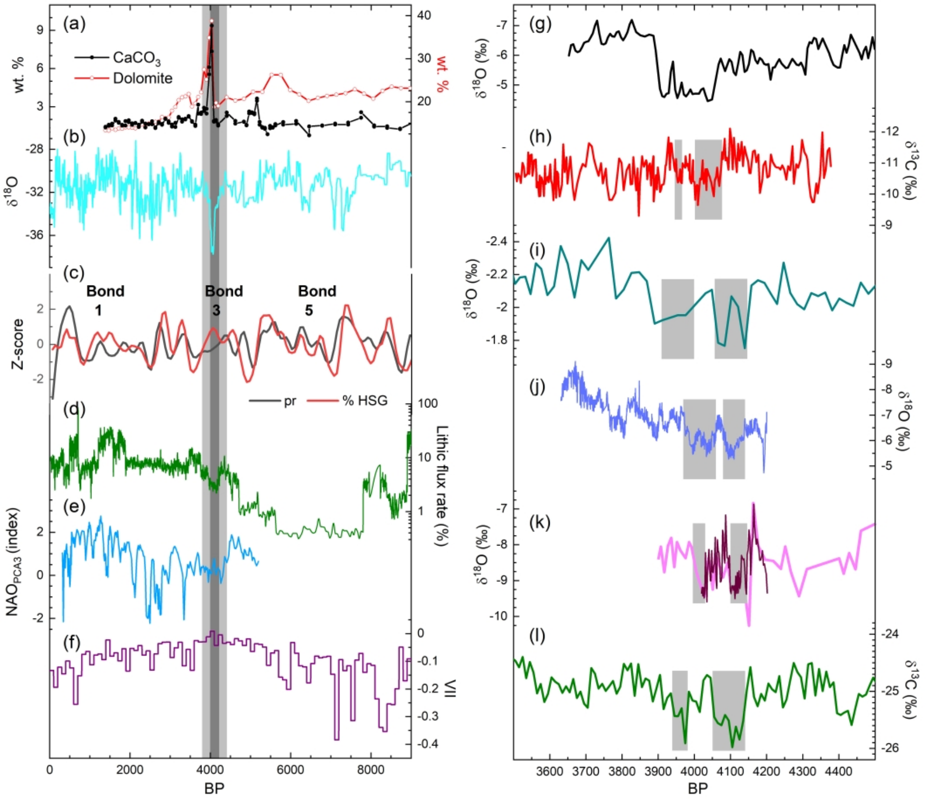

Figure 1.

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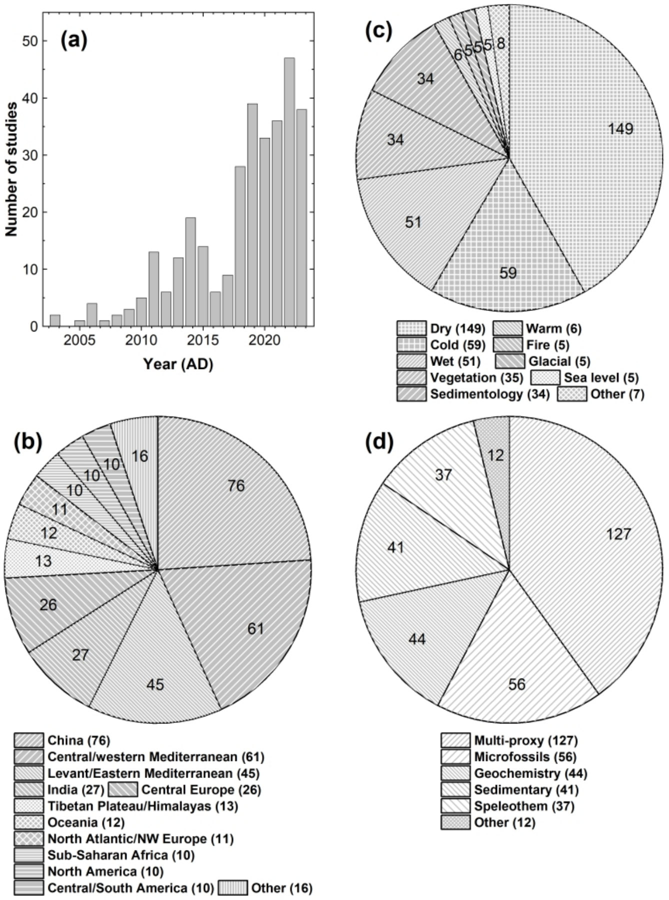

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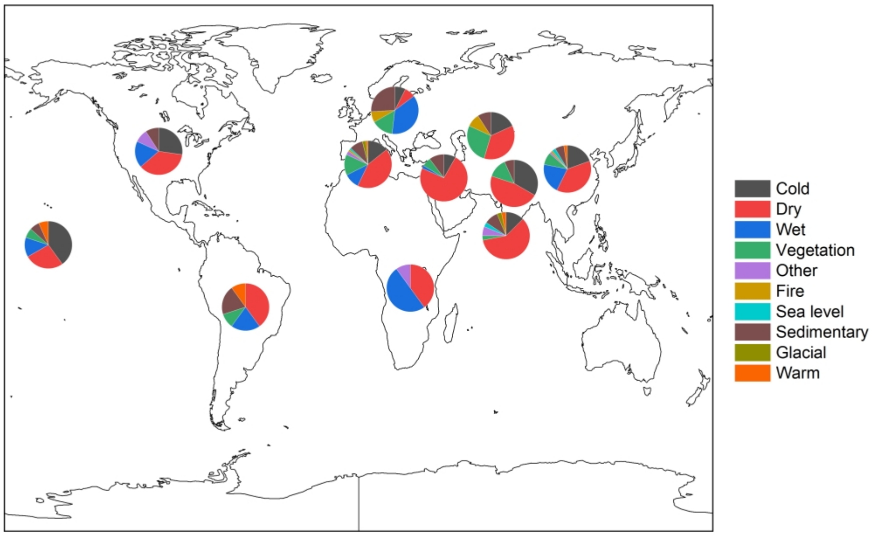

Figure 3.

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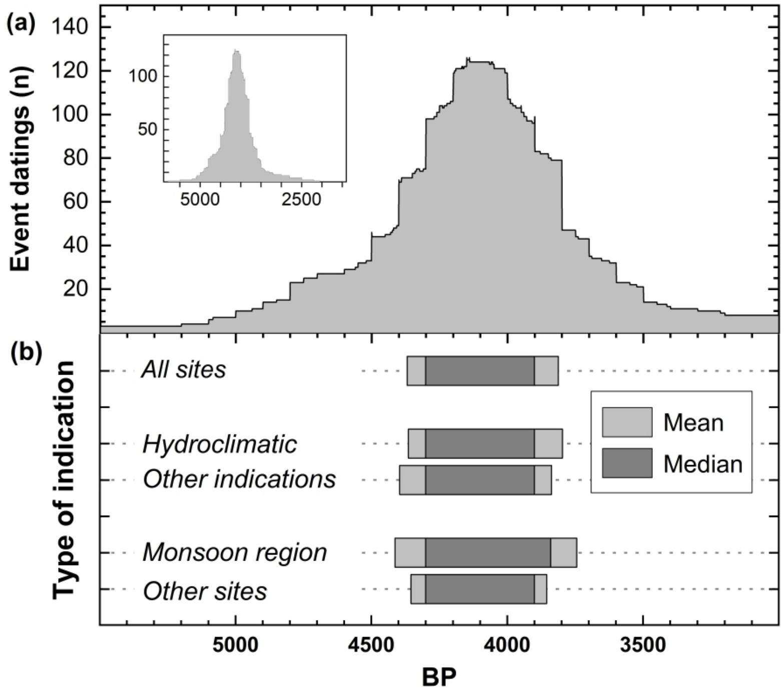

Figure 4.

305x229mm (600 x 600 DPI)

Supplementary Information

The 4.2 ka event: a review of palaeoclimate literature and directions for future research

Samuli Helama

Content:

Table S1. List of papers included in the literature review.

Author(s)	Year	Title
Alexandrowicz	2023	Application of malacological analysis to reconstruct climate fluctuations and human activity during the Middle and Late Holocene. Research in the valley of the …
Alinezhad et al.	2021	Lake Neor reveals how mountain vegetation responded to 7000 years of hydroclimate variability in northwestern Iran
Araus et al.	2014	Agronomic conditions and crop evolution in ancient Near East agriculture
Arnaud et al.	2012	Lake Bourget regional erosion patterns reconstruction reveals Holocene NW European Alps soil evolution and paleohydrology
Arz et al.	2006	A pronounced dry event recorded around 4.2 ka in brine sediments from the northern Red Sea
Avnaim-Katav et al.	2019	A multi-proxy shallow marine record for Mid-to-Late Holocene climate variability, Thera eruptions and cultural change in the Eastern Mediterranean
Azennoud et al.	2022	Climate controls on tufa deposition over the last 5000 years: A case study from Northwest Africa
Badino et al.	2018	8800 years of high-altitude vegetation and climate history at the Rutor Glacier forefield, Italian Alps. Evidence of middle Holocene timberline rise and glacier …
Bajo et al.	2017	Stalagmite carbon isotopes and dead carbon proportion (DCP) in a near-closed-system situation: An interplay between sulphuric and carbonic acid dissolution
Baldini et al.	2019	North Iberian temperature and rainfall seasonality over the Younger Dryas and Holocene
Basavaiah et al.	2015	Late Quaternary environmental and sea level changes from Kolleru Lake, SE India: Inferences from mineral magnetic, geochemical and textural analyses
Benson et al.	2021	A speleothem record from Portugal reveals phases of increased winter precipitation in western Iberia during the Holocene
Berger et al.	2012	Rivers of the Hadramawt watershed (Yemen) during the Holocene: Clues of late functioning
Berger et al.	2013	The dynamics of mangrove ecosystems, changes in sea level and the strategies of Neolithic settlements along the coast of Oman (6000–3000 cal. BC)
Berkelhammer et al.	2012	An abrupt shift in the Indian monsoon 4000 years ago
Bernal-Wormull et al.	2023	New insights into the climate of northern Iberia during the Younger Dryas and Holocene: The Mendukilo multi-speleothem record
Beuzen-Waller et al.	2019	Geoarchaeological investigation of the Quriyat coastal plain (Oman)

Bliedtner et al.	2022	Holocene temperature variations in semi-arid central Mongolia—a chronological and sedimentological perspective from a 7400-year lake sediment record …
Booth et al.	2005	A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages
Borrelli et al.	2014	Geoarchaeological and historical implications of late Holocene landscape development in the Carseolani Mountains, central Apennines, Italy
Branch	2013	Early–Middle Holocene vegetation history, climate change and human activities at Lago Riane (Ligurian Apennines, NW Italy)
Brice et al.	2023	Millennial-scale oscillations and an environmental regime shift around the Middle to Late Holocene transition in the North Atlantic region based on a multiproxy record …
Brisset et al.	2013	Non-reversible geosystem destabilisation at 4200 cal. BP: Sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean alpine …
Brisset et al.	2020	Socio-ecological contingencies with climate changes over the prehistory in the Mediterranean Iberia
Burdanowitz et al.	2021	Signals of Holocene climate transition amplified by anthropogenic land-use changes in the westerly–Indian monsoon realm
Carolin et al.	2019	Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change
Cartier et al.	2015	5000 years of lacustrine ecosystem changes from Lake Petit (Southern Alps, 2200 m asl): Regime shift and resilience of algal communities
Cartier et al.	2019	Diatom-oxygen isotope record from high-altitude Lake Petit (2200 m asl) in the Mediterranean Alps: shedding light on<? xmltex\break?> a climatic pulse at 4.2 …
Català et al.	2019	Holocene hydrography evolution in the Alboran Sea:<? xmltex\break?> a multi-record and multi-proxy comparison
Chen & Wang	2012	Middle-Late Holocene vegetation history and environment changes revealed by pollen analysis of a core at Qingdao of Shandong Province, East China
Chen et al.	2018	Radiocarbon dating and stable carbon isotopic analyses of Neolithic and Bronze Age staple crops in the lower Yellow River area and their paleodietary implications
Chen et al.	2021	Paleoclimate changes over the past 13,000 years recorded by Chibuzhang Co sediments in the source region of the Yangtze River, China
Chen et al.	2022	Westerlies effect in Holocene paleoclimate records from the central Qinghai-Tibet Plateau
Chen et al.	2023	Holocene vegetation and climate reconstructions from pollen records in the Mu Us Sandy Land, China

Cheng et al.	2023	Mid-to late Holocene vegetation response to relative sea-level fluctuations recorded by multi-proxy evidence in the Subei Plain, eastern China
Constantine et al.	2019	Mid-to late Holocene cooling events in the Korean Peninsula and their possible impact on ancient societies
Costas et al.	2014	Climate-driven episodes of dune mobilization and barrier growth along the central coast of Portugal
Courtin et al.	2021	Vegetation changes in southeastern Siberia during the Late Pleistocene and the Holocene
Coussin et al.	2023	Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: Climate variability at orbital to centennial timescales
Cruz et al.	2019	Mid–late Holocene event registered in organo-siliciclastic sediments of Lagoa Salgada carbonate system, southeast Brazil
Czerwiński et al.	2020	Late Holocene transformations of lower montane forest in the Beskid Wyspowy Mountains (Western Carpathians, Central Europe): a case study from Mount Mogielica
Dabhi et al.	2022	Mid-late Holocene climatic reconstruction from coastal dunes of the western Kachchh, India
Dang et al.	2020	El Niño/Southern Oscillation during the 4.2 ka event recorded by growth rates of corals from the North South China Sea
Das et al.	2022	Evidence for seawater retreat with advent of Meghalayan era (~ 4200 a BP) in a coastal Harappan settlement
Dash et al.	2022	An environmental magnetic record of Holocene climatic variability from the Chilika Lagoon, Southern Mahanadi Delta, east coast of India
De Falco et al.	2022	Evolution of a single incised valley related to inherited geology, sea level rise and climate changes during the Holocene (Tirso river, Sardinia, western …
Dean et al.	2015	Eastern Mediterranean hydroclimate over the late glacial and Holocene, reconstructed from the sediments of Nar lake, central Turkey, using stable isotopes and …
Delibes de Castro et al.	2015	The archaeological and palynological record of the Northern Plateau of Spain during the second half of the 3rd millennium Bc
Di Lorenzo et al.	2021	Human impact and landscape changes between 3000 and 1000 BC on the Tropea Promontory (Calabria, Italy)
Di Lorenzo et al.	2023	A high-resolution record of landscape changes and land use over the last 5000 years in western Calabria (S. Eufemia Gulf, southern Tyrrhenian Sea, Italy)
Di Rita & Magri	2019	The 4.2 ka event in the vegetation record of the<?xmltex\break?> central Mediterranean
Di Rita et al.	2018	Late Holocene environmental dynamics, vegetation history, human impact, and climate change in the ancient Literna Palus (Lago Patria; Campania, Italy)

Di Rita et al.	2018	Late Holocene forest dynamics in the Gulf of Gaeta (central Mediterranean) in relation to NAO variability and human impact
Di Rita et al.	2018	Late Holocene forest dynamics in the Gulf of Gaeta (central Mediterranean) in relation to NAO variability and human impact
Di Rita et al.	2022	Sign-switching ecological changes in the Mediterranean Basin at 4.2 ka BP
Dobrowolski et al.	2017	Origin and Neoholocene evolution of spring-fed fens in Wardzyń, Łódź Upland, Central Poland
Drysdale et al.	2006	Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone
Duan et al.	2023	Karst-ecological changes during the middle and late Holocene in Southwest China revealed by δ18O and δ13C records in a stalagmite
Dupont et al.	2022	Episodic deposition of stalagmites in the northeastern Democratic Republic of the Congo suggests Equatorial Humid Periods during insolation maxima
Dutt et al.	2018	A long arid interlude in the Indian summer monsoon during~ 4,350 to 3,450 cal. yr BP contemporaneous to displacement of the Indus valley civilization
Egli et al.	2020	Landscape evolution, post-LGM surface denudation and soil weathering processes from Dickinson Park mire, Wind River Range, Wyoming (USA)
Erästö & Homström	2006	Selection of prior distributions and multiscale analysis in Bayesian temperature reconstructions based on fossil assemblages
Field et al.	2018	Coherent patterns of environmental change at multiple organic spring sites in northwest Australia: Evidence of Indonesian-Australian summer monsoon variability over …
Finkelstein & Langgut	2014	Dry climate in the Middle Bronze I and its impact on settlement patterns in the Levant and beyond: new pollen evidence
Fisher et al.	2008	The Mt Logan Holocene—late Wisconsinan isotope record: tropical Pacific—Yukon connections
Flohn et al.	2011	Carbon stable isotope analysis of cereal remains as a way to reconstruct water availability: preliminary results
Florescu et al.	2019	Holocene rapid climate changes and ice-rafting debris events reflected in high-resolution European charcoal records
Fubelli et al.	2013	Holocene aggradation/erosion of a tufa dam at Triponzo (Central Italy)
Galaz-Samaniego et al.	2023	Lateglacial and Holocene palaeoenvironments at Sierra La Madera, northwestern Mexico: Sharp signals of Younger Dryas and North American monsoon
Gałka et al.	2016	A 9000 year record of cyclic vegetation changes identified in a montane peatland deposit located in the Eastern Carpathians (Central-Eastern Europe): Autogenic …

Gallach et al.	2020	Climatic and structural controls on Late-glacial and Holocene rockfall occurrence in high-elevated rock walls of the Mont Blanc massif (Western Alps)
Gao et al.	2023	Phytolith evidence for changes in the vegetation diversity and cover of a grassland ecosystem in Northeast China since the mid-Holocene
García et al.	2022	Paleoenvironmental changes of the last 16,000 years based on diatom and geochemical stratigraphies from the varved sediment of Holzmaar (West-Eifel Volcanic …
García-Morato et al.	2023	Solving a 'puzzle'. The global 4.2 ka Bond Event at El Mirador cave (Sierra de Atapuerca, Burgos, Spain) and the importance of small mammal taphonomy to the …
Gautam et al.	2021	Indian monsoon variability during the last 46 kyr: isotopic records of planktic foraminifera from southwestern Bay of Bengal
Geirsdóttir et al.	2019	The onset of neoglaciation in Iceland and the 4.2 ka event
Ghosh et al.	2023	Last 10 millennial history of Indian summer monsoon in the Bengal region–a multi-proxy reconstruction from a lacustrine archive
Giesche et al.	2019	Indian winter and summer monsoon strength over the 4.2 ka BP event in foraminifer isotope records from<? xmltex\break?> the Indus River delta in the …
Giesche et al.	2023	Recurring summer and winter droughts from 4.2-3.97 thousand years ago in north India
Giraudi et al.	2011	The Holocene climatic evolution of Mediterranean Italy: A review of the continental geological data
Glais et al.	2023	Rapid climate changes and human dynamics during the holocene in the eastern mediterranean (Lower Strymon Valley, northern Greece)
Goudeau et al.	2014	The Glacial–Interglacial transition and Holocene environmental changes in sediments from the Gulf of Taranto, central Mediterranean
Gouriveau et al.	2020	Holocene vegetation history in the Northern Vosges Mountains (NE France): Palynological, geochemical and sedimentological data
Gouriveau et al.	2021	From the Neolithic to the present day: The impact of human presence on floristic diversity in the sandstone Northern Vosges (France) Du Néolithique à nos …
Grachev et al.	2021	The Holocene paleoenvironmental history of Western Caucasus (Russia) reconstructed by multi-proxy analysis of the continuous sediment sequence from Lake …
Gutiérrez et al.	2013	Late Holocene evolution of playa lakes in the central Ebro depression based on geophysical surveys and morpho-stratigraphic analysis of lacustrine terraces
Haenssler et al.	2014	Driving mechanisms of Holocene lagoon development and barrier accretion in Northern Elis, Peloponnese, inferred from the sedimentary record of the Kotychi …
Halfen et al.	2010	Holocene stratigraphy and chronology of the Casper dune field, Casper, Wyoming, USA

Hammarlund et al.	2003	Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden
Harning et al.	2021	Response of biological productivity to North Atlantic marine front migration during the Holocene
Hazell et al.	2022	Response of the Akrotiri Marsh, island of Cyprus, to Bronze Age climate change
He et al.	2021	Multi-proxy evidence of environmental change related to collapse of the Liangzhu Culture in the Yangtze Delta, China
Helama & Oinonen	2019	Exact dating of the Meghalayan lower boundary based on high-latitude tree-ring isotope chronology
Hillman et al.	2021	A 17,000-year multi-proxy study of the Indian Summer Monsoon from Lake Dian, Yunnan, China
Hong et al.	2009	Temperature evolution from the δ18O record of Hani peat, Northeast China, in the last 14000 years
Hong et al.	2018	The respective characteristics of millennial-scale changes of the India summer monsoon in the Holocene and the Last Glacial
Hou et al.	2022	Enhanced aridity in the source region of the Yangtze River since 5.8 ka revealed by the sediments of Saiyong Co
Hu et al.	2014	Holocene shifts in riverine fine-grained sediment supply to the East China Sea Distal Mud in response to climate change
Huang et al.	2010	Extraordinary floods of 4100– 4000 a BP recorded at the Late Neolithic ruins in the Jinghe River gorges, Middle Reach of the Yellow River, China
Huang et al.	2011	Extraordinary floods related to the climatic event at 4200 a BP on the Qishuihe River, middle reaches of the Yellow River, China
Huang et al.	2013	Humification degree of peat and its implications for Holocene climate change in Hani peatland, Northeast China
Huang et al.	2023	An environmental crisis and its cultural impact in eastern China around 6000 years ago
Innes et al.	2014	Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at …
Isola et al.	2019	The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apuan Alps, central Italy)
Jalali & Sicre	2019	The 4.2 ka event in the Euro-Mediterranean region—a study from the MISTRALS/PALEOMEX program
Jalali et al.	2019	Influence of the North Atlantic subpolar gyre circulation on the 4.2 ka BP event
Jiménez-Moreno et al.	2020	The Holocene Cedrus pollen record from Sierra Nevada (S Spain), a proxy for climate change in N Africa

Jin et al.	2019	Chronology of coastal aeolian deposition and its paleoenvironmental implications on the Liuao Peninsula of South China
Jones et al.	2018	A multi-proxy approach to understanding complex responses of salt-lake catchments to climate variability and human pressure: A Late Quaternary case study from ...
Joshi et al.	2021	Hydro-climatic variability during last five thousand years and its impact on human colonization and cultural transition in Ladakh sector, India
Kaal et al.	2011	Long-term deforestation in NW Spain: linking the Holocene fire history to vegetation change and human activities
Kabot-Bahr et al.	2021	A tale of shifting relations: East Asian summer and winter monsoon variability during the Holocene
Kajita et al.	2018	Extraordinary cold episodes during the mid-Holocene in the Yangtze delta: Interruption of the earliest rice cultivating civilization
Kajita et al.	2020	High time-resolution alkenone paleotemperature variations in Tokyo Bay during the Meghalayan: Implications for cold climates and social unrest in Japan
Kajita et al.	2023	Climatic change around the 4.2 ka event in coastal areas of the East China Sea and its potential influence on prehistoric Japanese people
Kaniewski et al.	2018	Holocene evolution of Portus Pisanus, the lost harbour of Pisa
Kaniewski et al.	2018	Croatia's mid-Late Holocene (5200-3200 BP) coastal vegetation shaped by human societies
Karachurina et al.	2023	Terrestrial vegetation and lake aquatic community diversity under climate change during the mid–late Holocene in the Altai Mountains
Karpińska-Kołaczek et al.	2018	The impact of climate changes during the last 6000 years on a small peatland in North-Eastern Poland: A multi-proxy study
Kathayat et al.	2017	The Indian monsoon variability and civilization changes in the Indian subcontinent
Kathayat et al.	2018	Evaluating the timing and structure of the 4.2 ka event in the Indian summer monsoon domain from an annually resolved speleothem record from Northeast ...
Kato et al.	2021	Influences of temperature and the meteoric water δ18O value on a stalagmite record in the last deglacial to middle Holocene period from southwestern Japan
Kawahata	2019	Climatic reconstruction at the Sannai-Maruyama site between Bond events 4 and 3—implication for the collapse of the society at 4.2 ka event
Khalidi et al.	2020	9000 years of human lakeside adaptation in the Ethiopian Afar: Fisher-foragers and the first pastoralists in the Lake Abhe basin during the African Humid Period
Kobe et al.	2022	Lateglacial–Holocene environments and human occupation in the Upper Lena region of Eastern Siberia derived from sedimentary and zooarchaeological ...

Koizumi & Yamamoto	2011	Oceanographic variations over the last 150,000 yr in the Japan Sea and synchronous Holocene with the Northern Hemisphere
Kołaczek et al.	2020	Towards the understanding the impact of fire on the lower montane forest in the Polish Western Carpathians during the Holocene
Kotlia & Joshi	2013	Late Holocene climatic changes in garhwal Himalaya
Kotlia et al.	2010	Late Quaternary climatic changes in the eastern Kumaun Himalaya, India, as deduced from multi-proxy studies
Kumar et al.	2021	Holocene paleoenvironmental changes in the marginal marine basin of Great Rann of Kachchh, western India: Insights from sedimentological and mineral magnetic …
Kuzucuoğlu et al.	2011	Mid-to late-Holocene climate change in central Turkey: The Tecer Lake record
Lacey et al.	2015	A high-resolution Late Glacial to Holocene record of environmental change in the Mediterranean from Lake Ohrid (Macedonia/Albania)
Lanckriet et al.	2017	Late Quaternary changes in climate and land cover in the Northern Horn of Africa and adjacent areas
Le Houedec et al.	2020	Suborbital hydrological variability inferred from coupled benthic and planktic foraminiferal-based proxies in the southeastern Mediterranean during the last 19 ka
Lefebvre et al.	2021	Development and degradation of a submontane forest in the Beskid Wyspowy Mountains (Polish Western Carpathians) during the Holocene
Leipe et al.	2018	Vegetation change and human impacts on Rebun Island (Northwest Pacific) over the last 6000 years
Leng et al.	2019	Response of prehistoric human activity to environmental changes since 7,000 cal yr BP in Nenjiang River Basin, northeast China
LeRoy & Giralt	2021	Humid and cold periods in the last 5600 years in Arid Central Asia revealed by palynology of Picea schrenkiana from Issyk-Kul
Li et al.	2013	Relationship between environmental change and human activities in the period of the Shijiahe culture, Tanjialing site, Jianghan Plain, China
Li et al.	2014	Environmental humidity changes inferred from multi-indicators in the Jianghan Plain, Central China during the last 12,700 years
Li et al.	2018	A high-resolution pollen record from East China reveals large climate variability near the Northgrippian-Meghalayan boundary (around 4200 years ago) exerted …
Li et al.	2018	Holocene surface hydroclimate changes in the Indo-Pacific warm pool
Li et al.	2020	Diatom evidence for mid-Holocene peatland water-table variations and their possible link to solar forcing
Li et al.	2021	Holocene Lake Evolution and Glacial Fluctuations Indicated by Carbonate Minerals and Their Isotopic Compositions in the Sediments of a Glacial Melt …

Li et al.	2021	Abrupt climatic shift at~ 4000 cal. yr BP and late Holocene climatic instability in arid Central Asia: Evidence from Lop Nur saline lake in Xinjiang, China
Li et al.	2022	Phytolith and simulation evidence for precipitation-modulated vegetation dynamics along the East Asian monsoon margin
Li et al.	2023	Precipitation variations since the Last Deglacial reconstructed from pollen records in the Central Plains of China
Li et al.	2023	Climatic and hydrological variations on the southwestern Tibetan Plateau during the last 30,000 years inferred from a sediment core of Lake Zabuye
Liefert & Shuman	2022	Expression of the "4.2 ka event" in the southern Rocky Mountains, USA
Lin et al.	2022	Spatially diverse hydroclimatic response to the 4.2 ka event in the Asian monsoon region
Liu et al.	2015	Late Pleistocene and Holocene palaeoflood events recorded by slackwater deposits in the upper Hanjiang River valley, China
Liu et al.	2017	A 4000-yr multi-proxy record of Holocene hydrology and vegetation from a peatland in the Sanjiang Plain, Northeast China
Liu et al.	2022	Vegetation and environmental changes since the Last Glacial Maximum inferred from a lake core from Saiyong Co, central Tibetan Plateau
Loisel & Bunsen	2020	Abrupt fen-bog transition across southern patagonia: Timing, causes, and impacts on carbon sequestration
Lončar et al.	2017	Early and mid-Holocene environmental conditions in the eastern Adriatic recorded in speleothems from Mala špilja Cave and Velika špilja cave (Mljet island …
Lončar et al.	2019	Holocene climatic conditions in the eastern Adriatic recorded in stalagmites from Strašna peć Cave (Croatia)
Longman et al.	2021	Carbon accumulation rates of Holocene peatlands in central–eastern Europe document the driving role of human impact over the past 4000 years
López-Sáez et al.	2014	Vegetation history, climate and human impact in the Spanish Central System over the last 9000 years
Lu et al.	2019	Variability of East Asian summer monsoon precipitation during the Holocene and possible forcing mechanisms
Luelmo-Lautenschlaeger et al.	2023	Long-term vegetation history of a relict birch forest (Betula pubescens subsp. celtiberica (Rothm. & Vasc.) Rivas Mart.) in the Toledo Mountains (central Iberia) …
Ma et al.	2023	Links between geochemical weathering on the NE Tibetan Plateau and global climate change since the Last Deglacial
MacDonald et al.	2016	Prolonged California aridity linked to climate warming and Pacific sea surface temperature
Magny et al.	2009	Possible complexity of the climatic event around 4300—3800 cal. BP in the central and western Mediterranean

Magny et al.	2011	Orbital imprint on Holocene palaeohydrological variations in west-central Europe as reflected by lake-level changes at Cerin (Jura Mountains, eastern France)
Majumder et al.	2022	Late Quaternary variations in the Oxygen Minimum Zone linked to monsoon shifts as seen in the sediment of the outer continental shelf of the eastern Arabian Sea
Maleki et al.	2023	A loess-paleosol record of climate and vegetation change during the past 27,000 years from South-East of the Caspian Sea, Iran
Margaritelli et al.	2022	Globorotalia truncatulinoides in the Mediterranean Basin during the Middle–Late Holocene: Bio-Chronological and Oceanographic Indicator
Marks et al.	2018	Holocene lake sediments from the Faiyum Oasis in Egypt: a record of environmental and climate change
Marks et al.	2022	High-resolution insight into the Holocene environmental history of the Burullus Lagoon in northern Nile delta, Egypt
Masi et al.	2013	Stable isotope analysis of archaeological oak charcoal from eastern Anatolia as a marker of mid-Holocene climate change
Mazei et al.	2023	Multi-Proxy Paleoecological Reconstruction of Peatland Initiation, Development and Restoration in an Urban Area (Moscow, Russia)
Mazurkevich et al.	2020	Natural and anthropogenic impact on the formation of archaeological layers in a lake shore area: case study from the Serteya II site, Western Russia
McCave & Andrews	2019	Distinguishing current effects in sediments delivered to the ocean by ice. II. Glacial to Holocene changes in high latitude North Atlantic upper ocean flows
Meco et al.	2018	Mid and Late Holocene sea level variations in the Canary Islands
Mehrotra et al.	2022	Middle to Late Holocene climate, vegetation and sea-level changes in NW Tripura, northeast India, based on palynological and mineral magnetic evidence
Mehrotra et al.	2019	Resonance of the '4.2 ka event'and terminations of global civilizations during the Holocene, in the palaeoclimate records around PT Tso Lake, Eastern Himalaya
Mercuri et al. 2019	2019	Middle-to late-Holocene fire history and the impact on Mediterranean pine and oak forests according to the core RF93-30, central Adriatic Sea
Metcalfe et al.	2022	Response of a low elevation carbonate lake in the Yucatan Peninsula (Mexico) to climatic and human forcings
Mighall et al.	2023	Climate Change, Fire and Human Activity Drive Vegetation Change during the Last Eight Millennia in the Xistral Mountains of NW Iberia
Mischke & Zhang	2010	Holocene cold events on the Tibetan Plateau
Misra et al.	2019	Holocene climate records from lake sediments in India: Assessment of coherence across climate zones

Mologni et al.	2020	Frequency of exceptional Nile flood events as an indicator of Holocene hydro-climatic changes in the Ethiopian Highlands
Morris et al.	2015	Untangling climate signals from autogenic changes in long-term peatland development
Mroczkowska et al.	2021	Middle Holocene Climate Oscillations Recorded in the Western Dvina Lakeland
Mügler et al.	2010	A multi-proxy approach to reconstruct hydrological changes and Holocene climate development of Nam Co, Central Tibet
Nakamura et al.	2016	Weak monsoon event at 4.2 ka recorded in sediment from Lake Rara, Himalayas
Navarro-Hervás et al.	2014	Evaporite evidence of a mid-Holocene (c. 4550–4400 cal. yr BP) aridity crisis in southwestern Europe and palaeoenvironmental consequences
Ni et al.	2022	Holocene climate evolution: information from the Lacustrine–Fluvial sediment in North China
Niederman et al.	2021	Hydroclimate change in the Garhwal Himalaya, India at 4200 yr BP coincident with the contraction of the Indus civilization
Niu et al.	2023	Middle to late Holocene plant cover variation in relation to climate, fire, and human activity in the Songnen grasslands of northeastern China
Nottebaum et al.	2022	Late Quaternary landscape evolution and paleoenvironmental implications from multiple geomorphic dryland systems, Orog Nuur Basin, Mongolia
Ocakoğlu et al.	2019	Human-climate interactions since the neolithic period in Central Anatolia: Novel multi-proxy data from the Kureyşler area, Kütahya, Turkey
Ocakoğlu et al.	2022	Lake level changes and paleo-precipitation estimations based on colluvial stratigraphy of Holocene sediments in West Anatolia (Simav Graben)
Ohlendorf et al.	2014	Late Holocene hydrology inferred from lacustrine sediments of Laguna Cháltel (southeastern Argentina)
Park et al.	2019	Abrupt Holocene climate shifts in coastal East Asia, including the 8.2 ka, 4.2 ka, and 2.8 ka BP events, and societal responses on the Korean peninsula
Park et al.	2021	Holocene hydroclimate reconstruction based on pollen, XRF, and grain-size analyses and its implications for past societies of the Korean Peninsula
Parker & Goudie	2008	Geomorphological and palaeoenvironmental investigations in the southeastern Arabian Gulf region and the implication for the archaeology of the region
Pędziszewska et al.	2015	Holocene environmental changes reflected by pollen, diatoms, and geochemistry of annually laminated sediments of Lake Suminko in the Kashubian Lake District (N …
Peng et al.	2021	Abrupt climate variability since the last deglaciation based on a high-resolution peat dust deposition record from southwest China

Peyron et al.	2011	Holocene seasonality changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece)
Peyron et al.	2013	Contrasting patterns of climatic changes during the Holocene across the Italian Peninsula reconstructed from pollen data
Phartiyal et al.	2020	Late-Holocene climatic record from a glacial lake in Ladakh range, Trans-Himalaya, India
Piccarreta et al.	2011	Holocene geomorphic activity related to climatic change and human impact in Basilicata, Southern Italy
Pleskot et al.	2020	Searching for the 4.2 ka climate event at Lake Spore, Poland
Pontevedra-Pombal et al.	2019	10,000 years of climate control over carbon accumulation in an Iberian bog (southwestern Europe)
Prasad et al.	2014	Prolonged monsoon droughts and links to Indo-Pacific warm pool: A Holocene record from Lonar Lake, central India
Psomiadis et al.	2018	Speleothem record of climatic changes in the northern Aegean region (Greece) from the Bronze Age to the collapse of the Roman Empire
Pustovoytov et al.	2007	Evidence for Holocene environmental changes in the northern Fertile Crescent provided by pedogenic carbonate coatings
Railsback et al.	2011	Petrographic and isotopic evidence for Holocene long-term climate change and shorter-term environmental shifts from a stalagmite from the Serra do Courel of ...
Railsback et al.	2018	The timing, two-pulsed nature, and variable climatic expression of the 4.2 ka event: A review and new high-resolution stalagmite data from Namibia
Railsback et al.	2022	Additional multi-proxy stalagmite evidence from northeast Namibia supports recent models of wetter conditions during the 4.2 ka Event in the Southern Hemisphere
Regattieri et al.	2014	Lateglacial to holocene trace element record (Ba, Mg, Sr) from corchia cave (Apuan Alps, central Italy): paleoenvironmental implications
Ren et al.	2022	Effects of human activities on mountain forest in northern China during the middle Holocene
Revelles et al.	2022	Site formation processes, human activities and palaeoenvironmental reconstructions from archaeobotanical records in cave and rock-shelter sites in NE Iberia
Revelles et al.	2019	Coastal landscape evolution of Corsica island (W. Mediterranean): palaeoenvironments, vegetation history and human impacts since the early Neolithic period
Riehl et al.	2009	Local Holocene environmental indicators in Upper Mesopotamia: Pedogenic carbonate record vs. archaeobotanical data and archaeoclimatological models

Riehl et al.	2014	Drought stress variability in ancient Near Eastern agricultural systems evidenced by δ13C in barley grain
Rivera-Araya et al.	2023	A 33,000-year paleohydrological record from Sanamere Lagoon, north-eastern tropical savannas of Australia
Robles et al.	2022	Impact of climate changes on vegetation and human societies during the Holocene in the South Caucasus (Vanevan, Armenia): A multiproxy approach including …
Rodriguez-Ruano et al.	2023	Assigning causality to events in the Holocene record of coral reefs
Roy et al.	2022	Reconstruction of the late Holocene climate variability from the summer monsoon dominated Bhagirathi valley, western Himalaya
Ruan et al.	2016	Evidence of a prolonged drought ca. 4200 yr BP correlated with prehistoric settlement abandonment from the Gueldaman GLD1 Cave, Northern Algeria
Sallun et al.	2012	Geochemical evidence of the 8.2 ka event and other Holocene environmental changes recorded in paleolagoon sediments, southeastern Brazil
Saravanan et al.	2019	Late Holocene long arid phase in the Indian subcontinent as seen in shallow sediments of the eastern Arabian Sea
Sarti et al.	2015	Climatic signature of two mid–late Holocene fluvial incisions formed under sea-level highstand conditions (Pisa coastal plain, NW Tuscany, Italy)
Schiller et al.	2022	Holocene geo-ecological evolution of Lower Geyser Basin, Yellowstone National Park (USA)
Schirrmacher et al.	2020	Fossil leaf wax hydrogen isotopes reveal variability of Atlantic and Mediterranean climate forcing on the southeast Iberian Peninsula between 6000 to 3000 …
Schirrmacher et al.	2020	Spatial patterns of temperature, precipitation, and settlement dynamics on the Iberian Peninsula during the Chalcolithic and the Bronze Age
Schirrmacher et l.	2019	Multi-decadal atmospheric and marine climate variability in southern Iberia during the mid-to late-Holocene
Schmidt et al.	2011	Holocene settlement shifts and palaeoenvironments on the Central Iranian Plateau: investigating linked systems
Schroeter et al.	2020	How to deal with multi-proxy data for paleoenvironmental reconstructions: Applications to a Holocene lake sediment record from the Tian Shan, Central Asia
Scroxton et al.	2022	Tropical Indian Ocean basin hydroclimate at the Mid-to Late-Holocene transition and the double drying hypothesis
Scroxton et al. 2023	2023	Hydroclimate variability in the Madagascar and Southeast African summer monsoons at the Mid-to Late-Holocene transition
Seguin et al.	2020	Reconstruction of palaeoenvironmental variability based on an inter-comparison of four lacustrine archives on the Peloponnese (Greece) for the last 5000 …

Sengupta et al.	2020	Did the Harappan settlement of Dholavira (India) collapse during the onset of Meghalayan stage drought?
Şenkul et al.	2022	High-resolution geochemical (µXRF) and palynological analyses for climatic and environmental changes in lake sediments from Sultansazlığı Marsh (Central Anatolia …
Shah et al.	2022	Holocene climate events and associated land use changes in the eastern coast of India: Inferences from the Chilika Lagoon
Shao et al.	2006	Long-term trend and abrupt events of the Holocene Asian monsoon inferred from a stalagmite δ18O record from Shennongjia in Central China
Sharifi et al.	2015	Abrupt climate variability since the last deglaciation based on a high-resolution, multi-proxy peat record from NW Iran: The hand that rocked the Cradle of Civilization?
Shu et al.	2023	Southward migration of the monsoonal rainbelt hinders paleosol development and preservation in north-central China dunefield after the Middle-Late Holocene …
Shuchun et al.	2022	Moisture conditions during the Younger Dryas and 4.2 ka event as revealed from a subalpine peat record in the Luoxiao Mountains, southern China
Shukla et al.	2018	Late Quaternary glaciation history of monsoon-dominated Dingad basin, central Himalaya, India
Shuman & Burrell	2017	Centennial to millennial hydroclimatic fluctuations in the humid northeast United States during the Holocene
Silva et al.	2020	Pleistocene to Holocene phases of sedimentation and soil formation in the semiarid SE Spain (Eastern Betic Cordillera).
Singh et al.	2022	Paleomonsoonal shifts during~ 13700 to 3100 yr BP in the central Ganga Basin, India with a severe arid phase at~ 4.2 ka
Sjöström et al.	2022	Late Holocene peat paleodust deposition in south-western Sweden-exploring geochemical properties, local mineral sources and regional aeolian activity
Sletten et al.	2013	A petrographic and geochemical record of climate change over the last 4600 years from a northern Namibia stalagmite, with evidence of abruptly wetter climate at the …
Sobol et al.	2022	Characterizing the Meghalayan Stage in southern Africa: A multiproxy record of paleoenvironmental change at the southern margin of the Kalahari
Speciale et al.	2020	The case study of Case Bastione: First analyses of 3rd millennium cal BC paleoenvironmental and subsistence systems in central Sicily
St. Amand et al.	2020	Leveraging legacy archaeological collections as proxies for climate and environmental research
Stankevica et al.	2015	Reconstruction of the Holocene palaeoenvironmental conditions accordingly to the multiproxy sedimentary records from Lake Pilvelis, Latvia

Staubwasser et al.	2003	Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability
Stefanini et al.	2018	Appraising the cohesion of palaeoenvironmental reconstructions in north-west Spain since the mid-Holocene from a high temporal resolution multi-proxy peat record
Stobbe & Gumnior	2021	Palaeoecology as a Tool for the Future Management of Forest Ecosystems in Hesse (Central Germany): Beech (Fagus sylvatica L.) versus Lime (Tilia cordata Mill.)
Sun & Feng	2013	Holocene climatic reconstructions from the fossil pollen record at Qigai Nuur in the southern Mongolian Plateau
Sun et al.	2019	The coupled evolution of mid-to late Holocene temperature and moisture in the southeast Qaidam Basin
Surić et al.	2021	Holocene hydroclimate changes in continental Croatia recorded in speleothem δ13C and δ18O from Nova Grgosova Cave
Susini et al.	2023	Holocene palaeoenvironmental and human settlement evolution in the southern margin of the Salpi lagoon, Tavoliere coastal plain (Apulia, Southern Italy)
Takata et a.	2022	Benthic foraminifera in the Nakdong River Delta (southeast Korea) and their response to middle Holocene climatic change in the coastal environment of the East …
Tan et al.	2018	Centennial-to decadal-scale monsoon precipitation variations in the upper Hanjiang River region, China over the past 6650 years
Tan et al.	2020	Holocene monsoon change and abrupt events on the western Chinese Loess Plateau as revealed by accurately dated stalagmites
Tan et al.	2023	Levoglucosan and its isomers in terrestrial sediment as a molecular markers provide direct evidence for the low-temperature fire during the mid-Holocene in the …
Tang et al.	2015	High-resolution magnetic and palynological records of the last deglaciation and Holocene from Lake Xiarinur in the Hunshandake Sandy Land, Inner Mongolia
Thatcher et al.	2020	Hydroclimate variability from western Iberia (Portugal) during the Holocene: Insights from a composite stalagmite isotope record
Tian et al.	2020	Holocene vegetation and climate changes in the Huangqihai Lake region, Inner Mongolia
Tichá et al.	2023	Climate-related soil saturation and peatland development may have conditioned surface water brownification at a central European lake for millennia
Tlapáková et al.	2021	Holocene fluvial terraces reveal landscape changes in the headwater streams of the Moravskoslezské Beskydy Mountains, Czechia
Tsyganov et al.	2021	Key periods of peatland development and environmental changes in the middle taiga zone of Western Siberia during the Holocene

Utida et al.	2020	Climate changes in Northeastern Brazil from deglacial to Meghalayan periods and related environmental impacts
Van der Meeren et al.	2022	Anthropogenic Influences on Soil Erosion since the Late Holocene and Contrasting Regional Sustainability in China
Vignola et al.	2018	δ13C values in archaeological 14C-AMS dated charcoals: Assessing mid-Holocene climate fluctuations and human response from a high-resolution isotope record …
Vignola et al.	2022	Mid-late Holocene vegetation history of the Argive Plain (Peloponnese, Greece) as inferred from a pollen record from ancient Lake Lerna
Walczak et al.	2015	Reconstructing high-resolution climate using CT scanning of unsectioned stalagmites: A case study identifying the mid-Holocene onset of the Mediterranean climate in …
Wang	2021	Mid-Late Holocene Stalagmite δ18O and δ13C Records in Naduo Cave, Guizhou Province, China
Wang et al.	2016	The abrupt climate change near 4,400 yr BP on the cultural transition in Yuchisi, China and its global linkage
Wang et al.	2019	The African Humid Period, rapid climate change events, the timing of human colonization, and megafaunal extinctions in Madagascar during the Holocene: Evidence …
Wang et al.	2022	Spatial and temporal characteristics of the precipitation response to the 4.2 ka event in the Asian summer monsoon region
Wang et al.	2022	Hydroclimatic changes in south-central China during the 4.2 ka event and their potential impacts on the development of Neolithic culture
Wang et al.	2022	Abrupt Drying on the Southeast Coast of China during the Mid-to-late Holocene Transition
Wang et al.	2022	A high-resolution stalagmite record from Luoshui Cave, Central China over the past 23.5 kyr
Wang et al.	2023	Rapid environmental changes in the Lake Qinghai basin during the late Holocene
Watanabe et al.	2019	Oman corals suggest that a stronger winter shamal season caused the Akkadian Empire (Mesopotamia) collapse
Wieckowska-Lüth et al.	2021	The palaeoenvironment and settlement history of a lakeshore setting: An interdisciplinary study from the multi-layered archaeological site of Serteya II, Western Russia
Wogay et al.	2021	Environmental magnetism study during the Mid-Late Holocene transition and its cultural implications in Mesoamerica
Wu et al.	2017	Mid-Holocene palaeoflood events recorded at the Zhongqiao Neolithic cultural site in the Jianghan Plain, middle Yangtze River Valley, China
Xiao et al.	2018	The 4.2 ka BP event: multi-proxy records from a closed lake in the northern margin of the East Asian summer monsoon

Xiao et al.	2019	The 4.2 ka event and its resulting cultural interruption in the Daihai Lake basin at the East Asian summer monsoon margin
Xie et al.	2021	Changes in the hydrodynamic intensity of Bosten Lake and its impact on early human settlement in the northeastern Tarim Basin, Arid Central Asia
Yan & Wünnemann	2014	Late Quaternary water depth changes in Hala Lake, northeastern Tibetan Plateau, derived from ostracod assemblages and sediment properties in multiple sediment …
Yang et al.	2015	Groundwater sapping as the cause of irreversible desertification of Hunshandake Sandy Lands, Inner Mongolia, northern China
Yang et al.	2019	Total photosynthetic biomass record between 9400 and 2200 BP and its link to temperature changes at a High Arctic site near Ny-Ålesund, Svalbard
Yang et al.	2020	A stalagmite δ18O record from Jinfo Cave, southern China reveals early-mid holocene variations in the East Asian Summer Monsoon
Yang et al.	2023	Genomic investigation of the Chinese alligator reveals wild-extinct genetic diversity and genomic consequences of their continuous decline
Yang et al.	2023	Mid-to Late Holocene geomorphodynamics in a long-term settled mountain catchment in the Pergamon micro-region, western Turkey
Ye et al.	2022	Palynology-based reconstruction of Holocene environmental history in the northern Yangtze Delta, China
Ülgen et al.	2012	Climatic and environmental evolution of Lake Iznik (NW Turkey) over the last~ 4700 years
Yu et al.	2020	Extreme flooding of the lower Yellow River near the Northgrippian-Meghalayan boundary: Evidence from the Shilipu archaeological site in southwestern Shandong …
Zanchetta et al.	2011	Tephrostratigraphy, chronology and climatic events of the Mediterranean basin during the Holocene: an overview
Zanchetta et al.	2016	The so-called “4.2 event” in the central Mediterranean and its climatic teleconnections
Zanchetta et al.	2019	Tephrostratigraphy of paleoclimatic archives in central Mediterranean during the Bronze Age
Zanon et al.	2019	Palaeoenvironmental dynamics at the southern Alpine foothills between the Neolithic and the Bronze Age onset. A multi-proxy study from Bande di Cavriana (Mantua …
Zdanowicz et al.	2014	Ice cores from the St-Elias Mountains, Yukon Territory, Canada: Their significance for the Holocene climate history, volcanism and air pollution trends in the Northwest …

Zerathe et al.	2014	Mid-Holocene cluster of large-scale landslides revealed in the Southwestern Alps by 36Cl dating. Insight on an Alpine-scale landslide activity
Zhang et al.	2018	Hydroclimatic variations in southeastern China during the 4.2 ka event reflected by stalagmite records
Zhang et al.	2020	Contrasting impacts of the 8.2-and 4.2-ka abrupt climatic events on the regional vegetation of the Hulun Lake region in north-eastern China
Zhang et al.	2020	Holocene moisture variations in the Arid Central Asia: new evidence from the southern Altai Mountains of China
Zhang et al.	2021	Collapse of the Liangzhu and other Neolithic cultures in the lower Yangtze region in response to climate change
Zhang et al.	2022	Anthropogenic Influences on Soil Erosion since the Late Holocene and Contrasting Regional Sustainability in China
Zhang et al.	2023	Hydroclimatic variation over central China during the 4.2 ka event and its implications for cultural transformation
Zhang et al.	2023	Lake level evidence for a mid-Holocene East Asian summer monsoon maximum and the impact of an abrupt late-Holocene drought event on prehistoric cultures in …
Zhang et al.	2023	High-resolution records of sea surface temperature and salinity in the East China Sea over the past 14.2 kyr: Implication from alkenone and its hydrogen isotopes
Zhao et al.	2018	A multi-proxy late Holocene climate record from aeolian deposits of the Horqin sandy land, northeast China and its societal implications
Zhu et al.	2017	Late Neolithic phytolith and charcoal records of human activities and vegetation change in Shijiahe culture, Tanjialing site, China
Zhuang & Kidder	2014	Archaeology of the Anthropocene in the Yellow River region, China, 8000–2000 cal. BP
Zielhofer et al.	2019	Western Mediterranean hydro-climatic consequences of Holocene ice-rafted debris (Bond) events
Zolitschka et al.	2021	Environmental variability at the margin of the South American monsoon system recorded by a high-resolution sediment record from Lagoa Dourada (South Brazil)
Zong et al.	2011	Mid-Holocene coastal hydrology and salinity changes in the east Taihu area of the lower Yangtze wetlands, China

Table S2. List of synonyms for the 4.2 ka event used in the literature.

4.2 ka event
4.2 ka BP event
4.2 ka calBP event
4.2-kiloyear event
4.2-kiloyear BP event
2200 BC event
2200 BCE event
4200 BP event
4200 cal BP event
4200 calBP event
4.2 kyr event
4.2 kyr BP event
4.2 kyr cal BP event
4.2 kya event