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Going against the flow

Wells, cisterns and water in ancient Greece

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ABSTRACT

Despite the prevalent picture of the water supply in the ancient world as being dominated by fountains and aqueducts, the large number of excavated wells and cisterns show that these were the primary water sources for most individuals. Yet, little research has been done on their construction, function and use. This prompted the organization of the workshop *Going against the flow. Wells, cisterns and water in ancient Greece*, held at the Swedish Institute at Athens on 28–29 September 2017, and subsequent publication of the contributions in this volume. The ten papers presented here offer new evidence as well as a wide range of new perspectives on the use and function of wells and cisterns in ancient Greece. Considering the ubiquity of these installations in every type of setting during antiquity, from pan-Hellenic sanctuaries and civic centres to domestic workshops and remote farmhouses, it is hoped that the breadth of interest among the authors will allow other scholars to advance their own work further, illuminating new and exciting aspects of life in ancient Greece.

Keywords: wells, cisterns, water supply, ancient Greece, archaeology, climate, sanctuaries

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Cover illustration: section of typical ancient Greek cistern, by Patrik Klingborg
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MARTIN FINNÉ & INGA LABUHN

2. Hydro-climate in the Aegean from 700 BC to AD 300

Links between climate and freshwater availability

Abstract

Fresh water is and has always been a key resource for people and will continue to be so in the future. This paper provides general insights into the hydro-climate of the Aegean Sea and surrounding areas from 700 BC to AD 300 (2650 to 1650 years before present [BP], i.e. before AD 1950). The study is based on a review of available palaeoclimate evidence from the region. Collected data was standardized to enable a direct comparison between individual records and binned into 200-year time slices. Our data shows that from 700 BC to 350 BC the climate slowly went from drier to wetter. The period of wetter climate conditions persisted until around AD 50, when the wettest climate conditions in the period 700 BC to AD 300 occur. After AD 50 our data indicate that a transition into drier climate conditions was initiated and at around AD 450 dry conditions had developed in the Aegean. Information about past hydro-climatic conditions provides an idea of the natural input of fresh water in a highly complex system of natural and social mechanisms and components that control freshwater availability. The number of potential factors controlling freshwater availability calls for interdisciplinary approaches to investigate the potential effect of climate on freshwater availability further so that as many different factors and aspects as possible can be brought together. In this paper we discuss the utility of climate proxy data for comparisons with archaeological and historical information from the perspectives of geographic location, temporal range, dating precision, resolution of measurements, sensitivity of the proxy, the kind of climate and environmental information that can be derived from it, and whether it allows a quantification of climate variability.*

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Introduction

Fresh water is and has always been a key resource for people and will continue to be so in the future. Water is used by humans directly for drinking and washing and indirectly for watering plants and animals as well as in industrial processes. This chapter aims to provide a general insight into the hydro-climate of the period from 700 BC to AD 300 (2650 to 1650 years before present [BP] i.e. before AD 1950) based on the currently available palaeoclimate evidence from the Aegean and surrounding areas. The chapter will also be

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used to outline some of the inherent uncertainties and limitations of information about past climate variability, uncertainties that need to be kept in mind when discussing how hydro-climate data may be used to understand freshwater availability in ancient Greece.

In the Eastern Mediterranean region today, pressure on freshwater resources is high and expected to increase considering projected climate change and growing populations.[1] Therefore, understanding issues relating to fresh water in the region is of crucial interest, and studies of the past are necessary to put future scenarios into context. The Aegean region with its wealth of archaeological and historical data makes it a suitable area within which to investigate the potential impact of climate and climate change on human societies and lifeways. Climate and climate change have, on many occasions, been used to interpret and explain profound and rapid social transformations both on long (millennial to multi-centennial) and short (centennial to decadal) timescales.[2] In the Mediterranean area, links between climate and human societies often relate to hydrological variability, i.e. to fresh water. Freshwater availability is a key issue in many parts of the world, especially in those that have limited freshwater resources, such as arid or semi-arid regions, or where there are strong seasonal differences in precipitation and where groundwater resources may be unavailable or under pressure.[3] Hydro-climate and hydro-climatic change linked to changes in precipitation, evaporation rates and atmospheric circulation patterns provide a possible connection between freshwater availability and the climate system. In the longer term, freshwater availability and hydro-climate may also be connected through, for instance, water stored in glaciers and underground aquifers dating back to a more distant past.

Considering that many parts of the Eastern Mediterranean are semi-arid and experience a strong seasonal variation in precipitation, in combination with a pronounced seasonal evaporation, water resources are sensitive to hydro-climatic change, both in the past and in the present.[4] Water resources and freshwater availability, however, are also controlled by human activities (e.g. land use and water management) and physical properties of the land (e.g. soil types and geology).[5] Interdisciplinary approaches are well suited to deal with this complex network of interwoven factors relating to freshwater availability. Linking archaeological and historical evidence with information about the climate of the past and its variability and change, however, will always be a challenge given the complex causal relationships and the incomplete picture of the past provided by the evidence at hand. Before one embarks on such enterprises one should be aware of the fact that archaeological, historical and climatological evidence come with uncertainties, some of which may be shared and some of which are subject specific.[6]

The climate on Earth is constantly changing following cyclical variations in the amount and distribution of incoming energy from the sun and the complex interactions and feedback mechanisms between, for instance, the atmosphere, hydrosphere and land masses.[7] The resulting climate change occurs on different timescales from tens of thousands of years to millennial to centennial and decadal.[8] Widespread meteorological observations in the

[1] Lionello *et al.* 2012, xxxvii–xxxix; WWAP 2012; Collins *et al.* 2013, 1078–1080.

[2] Weiss *et al.* 1993; Berger & Guilaine 2009; Roberts *et al.* 2011b; Rosen & Rivera-Collazo 2012; Kaniewski *et al.* 2013; 2015.

[3] Döll 2009, 11; WWAP 2012.

[4] Lionello *et al.* 2006b, 15–16; García-Ruiz *et al.* 2011, 133–134.

[5] Jones 2013, 76.

[6] Izdebski *et al.* 2016, 19.

[7] Berger & Loutre 1991; Bond 2001; Ruddiman 2008.

[8] Dansgaard *et al.* 1993; Bond 2001; Mayewski *et al.* 2004.

Mediterranean start in the early 19th century, but there are some considerably longer instrumental time series, e.g. from Italy.[9] There is also data to be gathered from sources like ships' logbooks and in some cases from ancient written sources.[10] To reach further back in time, beyond the observational records, palaeoclimatologists need to consult proxies from natural archives.

Natural archives like sediments, ice or trees can store information about the climate of the past; an indirect indicator of the climate recorded in an archive is referred to as a proxy.[11] Climatic and environmental parameters influence the formation processes of natural archives, and it is possible to gain insights into these processes through proxy measurements. Trees for example constitute a natural climate archive. Tree growth is partly determined by the climatic conditions, and these conditions are reflected in the width of tree rings. Measurements of tree ring width can therefore be used as a climate proxy.[12] A prerequisite for palaeoclimate studies is that an archive is datable, so that a chronology of the reconstructed climatic change can be established.[13]

Setting: modern climate of the Aegean and the Eastern Mediterranean

The geographical area in focus here is the Aegean Sea and the surrounding areas (refered to as the Aegean or the Aegean region). The Aegean Sea is located in between modern-day Greece and Turkey. To the west the mountainous Balkan peninsula constituting the present-day Greek Mainland is located, and to the east we find the western part of the Anatolian peninsula with its many headlands and bays. A great number of islands of different sizes and character, especially in the south and to the east, dot the Aegean Sea itself.

The present climate of the Aegean largely follows that of the wider Eastern Mediterranean region, which means that the climate is primarily characterized by hot dry summers and mild wet winters.[14] These characteristics are explained by seasonal changes in the large-scale atmospheric circulation patterns. During summer the Eastern Mediterranean is under the influence of the subtropical high-pressure system which creates dry conditions. As the subtropical high-pressure system shifts to the south during the northern hemisphere winter, westerly winds and low-pressure systems, cyclones, from the Atlantic can reach the Eastern Mediterranean to deliver their moisture. The vast majority (~80%) of precipitation falls during late autumn, winter and spring and is related to these low pressures of Atlantic origin, although local formation[15] and strengthening of low pressures occurs in the sea south of Genoa and near Cyprus.[16] During late spring, summer and early autumn, water loss through evaporation and transpiration from plants[17] is considerable. The climate can in many areas be considered to be semi-arid with a prolonged period of seasonal drought. In most of the Eastern Mediterranean and especially in the driest areas, precipitation amounts are particularly important for human activities.

However, the climate in the Eastern Mediterranean cannot be considered to be homogeneous and there is a complexity of local climates

9 Luterbacher *et al.* 2012, 91–92.
10 Luterbacher *et al.* 2012, 90, 96–98.
11 For an introduction to palaeoclimatology see e.g. Lowe & Walker 2015 or Ramstein *et al*. 2021.
12 For example, in dry regions where tree growth is limited by water availability, wet conditions would lead to the formation of wide tree rings, and dry conditions would lead to the formation of narrow rings.
13 For an introduction to dating of natural archives see e.g. Walker 2005.

14 Lionello *et al.* 2006b, 1; 2012, xxxix–xl.
15 So-called cyclogenesis.
16 Trigo *et al.* 1999, 1691; Lionello *et al.* 2006a, 331; Harding *et al.* 2009, 70.
17 Collectively known as evapotranspiration.

influenced by for example topography, dominant wind directions, moisture sources and the distance from the coast.[18] Topography plays an important role for local precipitation with mountain slopes facing towards the west receiving substantially more precipitation than slopes facing east.[19] When characterizing the climate in the Mediterranean, it can be useful to consider three different spatial scales: firstly, at the smallest scale, micro-ecologies and micro-climates, the local climate on an island or in a valley; secondly, the regional climate corresponding to larger areas such as the Aegean; and thirdly, the largest pan-Mediterranean scale. While the first was important in the past, as it is today, it is primarily at the regional scale that coherent trends of climate change can be identified, based on the available climate proxy data.

Past hydro-climate variability in the Aegean and the Eastern Mediterranean

Palaeoclimate data from the Eastern Mediterranean derive from a range of proxies retrieved from different natural archives. The most common archives are sediments from lakes or wetlands and speleothems. Marine sediment cores retrieved from the ocean floor in the open sea are also commonly analysed for numerous proxies. However, many marine records suffer from relatively poor temporal resolution because of the low sedimentation rates in many parts of the Mediterranean, and few marine cores present unambiguous hydro-climate proxies. In addition, there are also problems associated with the reservoir effect, which means that it is difficult to accurately date marine records, discussed below.[20] The most commonly utilized proxy to study hydro-climatic variability is the oxygen isotopic composition ($\delta^{18}O$) of carbonates. Naturally precipitating carbonates (e.g. speleothems in caves, carbonates in lake sediments and in shells of small animals) incorporate information about the surrounding environment as they form.[21] Pollen is also commonly analysed, since the vegetation is strongly dependent on water. However, in the context of the Eastern Mediterranean where human influence on the landscape has been significant since at least the Early Bronze Age, fossil pollen assemblages should primarily be treated as proxy for human activity and land-use changes.[22] It should be pointed out that they may (also) reflect climate-induced vegetation change.[23]

The available palaeoclimate data indicates that the modern inhomogeneous pattern of changes in precipitation also existed in the past in the Eastern Mediterranean. Reconstructions on a finer spatial scale than this large region are therefore necessary to investigate possible influences of hydro-climatic changes on human societies. The climate information in this chapter is based on data collected for two recent reviews of Mediterranean palaeoclimate records conducted by Labuhn *et al.*[24] and Finné *et al.*[25] The palaeoclimate records selected for these two studies present proxy data interpreted to reflect hydro-climatic change that have robust dating, relatively unambiguous proxy interpre-

[18] Trigo *et al.* 1999, 1685; 2002, 567–568; Lionello *et al.* 2006b, 4.

[19] E.g. Maheras & Anagnostopoulou 2003, 216.

[20] Siani *et al.* 2000; Reimer & McCormac 2002.

[21] This primarily occurs through the incorporation of different oxygen isotopes (^{16}O, ^{17}O and ^{18}O) coming from water molecules. The different oxygen isotopes in water can occur in different ratios which is controlled by e.g. precipitation amounts, temperature and atmospheric processes. Because the oxygen isotope composition in the precipitating carbonates is governed by the ratio of the isotopes in the water there is a link between the climate system and the $\delta^{18}O$ in e.g. a cave speleothem.

[22] Roberts *et al.* 2011b, 158; 2019, 933–935.

[23] Roberts *et al.* 2019, 934.

[24] Labuhn *et al.* 2018.

[25] Finné *et al.* 2019.

tation and a minimum mean sampling interval of 200 years.[26]

For the purpose of the present chapter, a total of eleven climate records from the previous reviews have been utilized, and carefully examined and treated numerically. The majority of these eleven palaeoclimate records comes from the Balkan peninsula, two records come from the northern part of the Aegean Sea and one record comes from south-west Turkey (*Fig. 1* and *Table 1*). Ten out of these eleven records belong to the Balkans region identified in Finné *et al.*[27] Finally, a record from Gölhisar Lake in south-west Turkey was added to this study, based on the similarities between this record and the ten records from the Balkans region during the 1st millennium AD.[28] There are more palaeoclimate records from the Aegean than included in this study.[29] The selection of records, for instance, omits temperature-related palaeoclimate records. The majority of these temperature records, however, derive from marine sediment cores[30] and therefore in many instances come with the limitations that relate to this type of record, see above.

Standardized z-scores[31] were calculated for each palaeoclimate record based on the mean and standard deviation. This creates a "common currency" that enables a direct comparison between individual records regardless of which climate proxy is involved, and regardless of the unit or the absolute values of the proxy measurement in each record. Further, the data was binned into 200-year time slices and average z-scores were calculated for each 200-year time slice (note that these numerically treated records do not reflect every detail of the original proxy data).[32] With this calculation of z-scores and the binning into 200-year time slices, it is possible to calculate a mean for the eleven individual records to create a regional mean (henceforth this mean is referred to as the "regional mean" for the Aegean). In addition, proxy data from the Peloponnese have been consulted to add further information about the climate conditions in the south-western part of the Aegean since the peninsula is relatively rich in palaeoclimate data, especially in comparison with much of the southern and eastern parts of the Aegean.

The calculated z-score is constructed in such a way that positive values, i.e. values above the mean, indicate wetter hydro-climate conditions whereas negative z-score values indicate drier conditions. Rather than presenting absolute values of change, e.g. mm of precipitation, intepretations of proxy data is commonly qualitative, e.g. wetter and drier, often relating to the mean of the proxy data series (for an extended discussion see below). For the z-score data, increasingly positive values indicate increasingly wetter conditions, and the more negative the values are, the drier hydro-climate conditions should have been. It should be noted, however, that the z-scores do not provide an absolute (quantative) measure of hydro-climate change. For example, a record showing negative z-score values during a given time period does not indicate that this time period was characterized

[26] For details regarding proxy type and dating method for each individual record please consult *Table 1*.

[27] Finné *et al.* 2019, 851.

[28] Labuhn *et al.* 2018, 80.

[29] See Finné *et al.* 2011, 3155–3157 for some additional records.

[30] Geraga *et al.* 2000; Rohling *et al.* 2002; Geraga *et al.* 2005; Kotthoff *et al.* 2008; Triantaphyllou *et al.* 2014.

[31] Standardized z-score, or standard score, represents the number of standard deviations by which a proxy value is above or below the mean of a time series. This means that proxy values above the mean have a positive z-score, and proxy values below the mean have a negative z-score. The z-score is calculated as:

$$z = \frac{(x-\mu)}{\sigma}$$

where:
x is the proxy value,
μ is the mean of all proxy values in the time series,
σ is the standard deviation of all proxy values in the time series.

[32] For details regarding the method consult Labuhn *et al.* 2018, 71.

by drought, but that hydro-climatic conditions were drier than on average at that location.

LONG-TERM HYDRO-CLIMATE CHANGE IN THE EASTERN MEDITERRANEAN —THE LAST 10,000 YEARS

In general, during the current warm period of the Holocene (from around 11,650 years before present, or 9,700 BC, to the present day), the hydro-climate in the Eastern Mediterranean can be described as being wetter in the early-mid Holocene followed by a drier mid-late Holocene.

The generally dry and cold conditions that prevailed in the Eastern Mediterranean during the last Ice Age were replaced by conditions that became warmer and moister at the start of the Holocene. However, it was not until around 6,550 BC that there was a coherent picture of a wetter climate in the Eastern Mediterranean region, although in the very easternmost part of the region proxy evidence clearly suggests that conditions were wetter at 8,050 BC.[33] The homogenous picture of a wetter climate in the Eastern Mediterranean prevailed until around 4,150 BC. From around 4,050 BC drier climate conditions developed throughout much of the Eastern Mediterranean, but the extent of this transition differed between areas of this vast region.[34] This inhomogeneous climate picture lasted until around 1,050 BC when the overall driest period is recorded throughout much of the Eastern Mediterranean. The possible impact of this dry period in relation to the end of the Late Bronze Age in the Eastern Mediterranean is a topic that has been discussed extensively.[35] Proxy data suggest that after around 1,050 BC some areas of the Eastern Mediterranean display shifts towards wetter conditions whereas some tend towards drier conditions.[36] The general climate picture outlined above is also one that is reflected in the regional mean of the palaeoclimate records selected for the present study (*Fig. 2*).

HYDRO-CLIMATE FROM 700 BC TO AD 300 IN THE AEGEAN

Following the dry period around 1,050 BC in the Aegean, the climate continued to vary, as can be seen in the selected climate records as well as the regional mean (*Fig. 2*). Not all eleven selected records have proxy data for the full period 700 BC to AD 300, but from 700 BC the regional mean clearly indicates that the climate moved from drier to wetter. Wetter climate conditions seem to have become more pronounced around 350 BC. The period of wetter climate conditions persists and at around AD 50 the wettest climate conditions in the period 700 BC to AD 300 occur. After AD 50 the regional mean indicates that a transition into drier climate conditions was initiated and at around AD 450 dry conditions have developed in the Aegean.

The regional mean is a useful way to investigate climate at a regional scale. However, it is clear from *Fig. 2* that the individual records may not always be in harmony with the regional mean. The coherence of the regional mean is visualized in *Fig. 2* by the grey shading which represents one standard deviation from the mean value. Throughout the study period the standard deviation is increasing, i.e. the grey area becomes wider, until it peaks around AD 250 (*Fig. 2*). This may reflect regional difference, but many of the apparent incoherencies in changes in the hydro-climate are more likely a result of uncertainties in the individual chronologies, which influence whether detected changes appear synchronous or not. Another factor that may influence the increasing

33 Finné *et al.* 2019, 854–855.
34 Finné *et al.* 2011, 3160, 3167; 2019, 859.
35 See e.g. Drake 2012; Cline 2014; Kaniewski *et al.* 2015; Knapp & Manning 2016; Finné *et al.* 2017.
36 Finné *et al.* 2019, 854.

standard deviation is the growing human pressure in the period[37] that could, for instance, affect water levels in lakes, and the composition and influx of sediments to lakes and wetlands on a local basis, that in turn will affect proxy recordings. In addition, the meaning of individual proxy records (e.g. reflecting run-off or precipitation), as well as the season they represent, is generalized in the analysis as average "hydro-climate conditions". This means, for instance, that if the main climate variable, or season, represented by a certain proxy has changed over time,[38] this will not be represented in our study and thus add uncertainty.

The regional climate picture for the Aegean is well reflected also in proxy records from the Peloponnese peninsula that were not included in the numerical treatment due to ambiguities in interpretations and chronologies. Palaeoclimate records from Alepotrypa and Kapsia caves and from the Agios Floros wetland and the Asea Valley clearly indicate that climate conditions went from drier to wetter around 600 BC.[39] A brief period of dry conditions around AD 50 is evident in the two cave records, followed by a return to wetter conditions before a transition into drier conditions is initiated. Around AD 300–350 dry conditions seem to dominate over the Peloponnese peninsula.[40]

Methodological aspects and limitations of palaeoclimate data

The utility of a climate proxy record for comparison with archaeological and historical information depends on a range of factors including geographic location, temporal range, dating precision, resolution of measurements, sensitivity of the proxy, the kind of climate and environmental information that can be derived from the proxy, and whether it allows a quantification of climate variability.

DATING CONTROL AND TEMPORAL RESOLUTION

Palaeoclimate information relies on dating of the natural archive to place the reconstructed climatic change along the timeline of history. Any comparisons between palaeoclimate information and archaeological and historical data are speculative without a precise chronology of the climate proxy data, as well as of the archaeological and historical data. Dating of natural archives can be undertaken using a range of different methods.[41] The three most common ones are radiocarbon dating, Uranium-Thorium dating[42] (also referred to as Uranium series dating) and dendrochronology. The first two methods are based on the measurements of radioactive isotopes and their decay products to estimate the age of a sample, and are consequently often referred to as radiometric methods. In both cases, individual samples from different levels in the natural archive are collected and analysed and thus no continuous chronology is obtained. Since samples for proxy measurements are sampled more densely, i.e. at higher resolution, an interpolation between the dated levels is required to create an age-depth model that assigns an age to each proxy data point.[43] Dendrochronology on the other hand does not have anything to do with radioactive decay; this method relies on counting of annual tree rings.

[37] Roberts *et al.* 2019, 925–926.
[38] As in the case of Lake Sidi Ali in Morocco, see Zielhofer *et al.* 2017, 45.
[39] Finné *et al.* 2014; Unkel *et al.* 2014; Boyd 2015; Katrantsiotis *et al.* 2016; for a review see Weiberg *et al.* 2016, 47, 50.
[40] Weiberg *et al.* 2016, 50–51.
[41] Walker 2005.
[42] For an introduction to radiocarbon dating and Uranium-Thorium dating see e.g. Richards & Dorale 2003; Hua 2009.
[43] For an introduction to age-depth modelling see e.g. Blaauw & Christen 2011; Scholz & Hoffmann 2011.

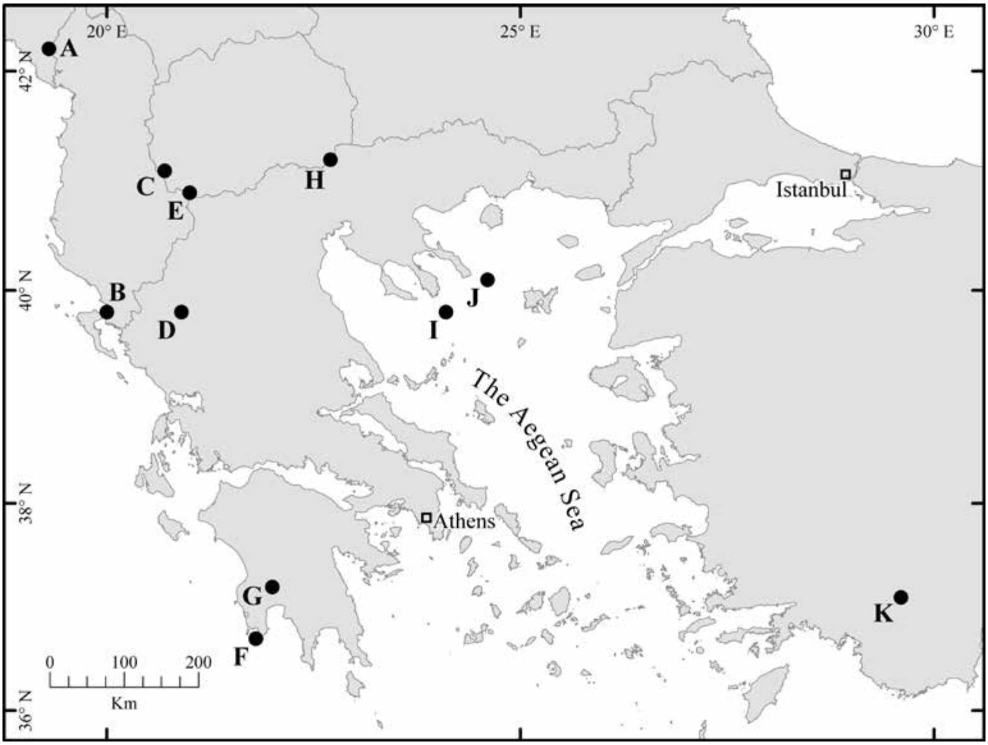

Fig. 1. Map of the Aegean and the surrounding areas together with the location of the selected climate proxy records used in this chapter (A–K). ID letters correspond to Table 1. *Illustration: Martin Finné.*

Table 1. List of climate proxy records selected for this study, sorted by location from west (A) to east (K), together with basic metadata and reference information. ID letters are linked to Figs. 1 *and* 2. *Latitude and longitude are in decimal degrees. All ^{14}C are accelerator mass spectrometer (AMS) dating.*

ID	Site name	Latitude	Longitude	Main proxy	Dating technique	Reference
A	Lake Shkodra	42.2	19.3	$\delta^{18}O_{carbonate}$	^{14}C, tephra	Zanchetta *et al*. 2012
B	Lake Butrint	39.8	20.0	Sr/Ca	^{14}C	Morellón *et al*. 2016
C	Lake Ohrid	41.1	20.7	$\delta^{18}O_{carbonate}$	^{14}C, tephra	Lacey *et al*. 2015
D	Lake Ioannina	39.8	20.9	$\delta^{18}O_{carbonate}$	^{14}C	Frogley *et al*. 2001
E	Lake Prespa	40.9	21.0	$\delta^{18}O_{carbonate}$	^{14}C, tephra	Leng *et al*. 2010
F	Mavri Trypa Cave	36.7	21.8	$\delta^{18}O$	U-Th	Finné *et al*. 2017
G	Agios Floros	37.2	22.0	$\delta D_{n\text{-}alkanes}$	^{14}C	Norström *et al*. 2018
H	Lake Dojran	41.2	22.7	K	^{14}C	Francke *et al*. 2013
I	Aegean Sea, SL148	39.8	24.1	$\delta^{13}C_{\textit{Uvigerina med.}}$	^{14}C	Kuhnt *et al*. 2008
J	N Aegean Sea, M2	40.1	24.6	$\delta^{13}C_{org.}$	^{210}Pb, ^{14}C	Gogou *et al*. 2016
K	Gölhisar (lake)	37.1	29.6	$\delta^{18}O_{carbonate}$	^{14}C, tephra	Eastwood *et al*. 2007

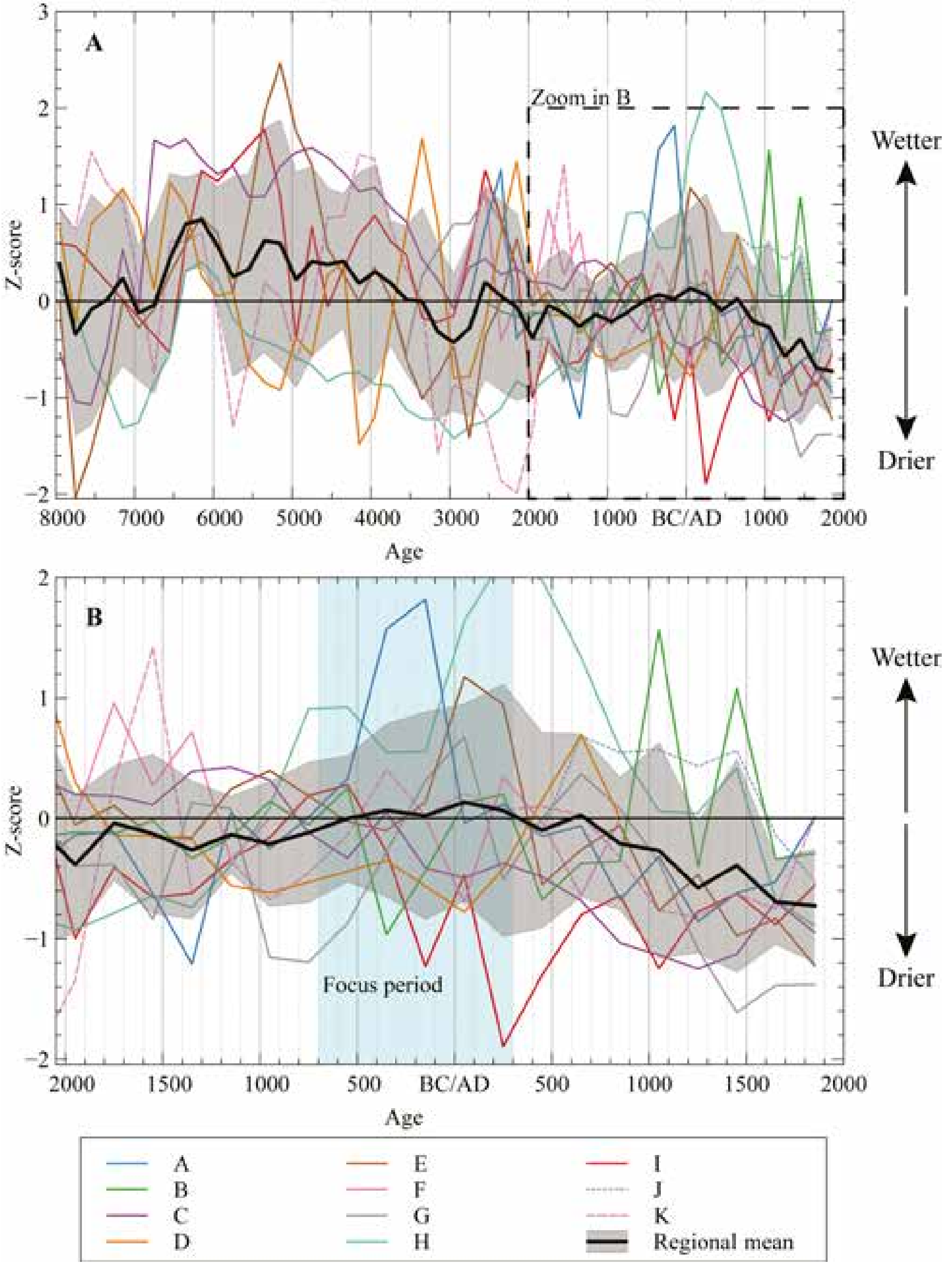

Fig. 2. Individual z-score records from the selected sites (A–K) and the calculated regional mean representing the regional climate picture for the Aegean. Grey shading represents one standard deviation from the regional mean. Positive z-score values represent wetter climate conditions and negative z-score values represent drier climate conditions. In A the full Holocene sequence is shown and in B the last 4,000 years for better definition of the focus period of 700 BC to AD 300. ID letters correspond to Table 1. *Illustration: Martin Finné.*

Dendrochronology is the most exact of all dating methods, because a precise year can be identified for each tree ring and verified between multiple trees through the so-called cross-dating.[44] Annual lamination can sometimes be identified in other types of natural archives, for example speleothems and lake sediments.[45] In these instances, a similar layer-counting approach can be applied, without verification through cross-dating, however, due to a lack of multiple samples.

All dating is subject to uncertainties. For example, uncertainties for ages retrieved through radiocarbon dating relate to analytical errors associated with the measurement, and the uncertainties involved in the calibration to calendar years using a calibration curve.[46] Additionally, the uncertainties of radiocarbon dating can be further increased by reservoir effects, such as the so-called "hard water effect" and the "marine reservoir effect".[47] The hard water effect occurs in areas with limestone bedrock when old, inert carbon from the carbonate rock dissolves in the water, and is subsequently incorporated into living organisms and then ultimately into the sediments. The marine reservoir effect occurs in the world's oceans and is linked to the slow uptake and mixing of atmospheric carbon (including ^{14}C). Both effects can cause radiocarbon ages to appear older than they actually are and need to be corrected for. Uranium-Thorium dating has two major advantages over radiocarbon dating: it is not affected by hard water and reservoir effects and it does not require any calibration to yield calendar ages. On the other hand, it is important that the dated sample is sufficiently rich in Uranium and is clean in that sense that all Thorium measured derives from Uranium decay and that open-system conditions have not occurred since deposition.[48]

A precise dating of a climate proxy record will provide us with the knowledge of what time period this data series represents. Another aspect intimately connected to the issue of dating control is the temporal resolution of a climate record. The temporal resolution depends on the growth/deposition rate of the natural archive and the sampling interval of the proxy, but it also relates to the dating of the archive since it often needs to be computed from the retrieved ages. The temporal resolution is key to understanding duration and pace of change and is a measure of a record's capability to provide information about climate change on timescales relevant to human perception. It may be translated into the human realm by thinking of *how* someone, or a community, perceived a changing situation.[49] Dating uncertainties thus have a direct impact on our ability to know *when* something occurred, and they also have an effect on our understanding of *how* change was perceived.[50] These are key factors when relating palaeoclimate data to human perspec-

44 Cook & Kairiukstis 2013, 43–44. Cross-dating denotes the visual and statistical matching of characteristic ring width patterns between different trees. If the time spans covered by two tree samples overlap, they can potentially be cross-dated. With large numbers of trees, this cross-check ensures an accurate dating, and also enables the construction of tree ring chronologies far back in time.

45 Baker *et al.* 2008; Zolitschka *et al.* 2015.

46 Reimer *et al.* 2013. Because the concentration of ^{14}C in the atmosphere varies over time the measured ^{14}C concentration in a sample cannot directly be translated into an age expressed in calendar years. To find the calendar year one needs to find a sample of a known age with the same ^{14}C proportion as in the measured sample. This is done by comparing the measurement results with a so-called calibration curve providing the known ages and ^{14}C proportions. Because the ^{14}C measurements of both the measured sample and the one of known age have limited precisions a range of calendar years is possible thus increasing the age uncertainty in the calibrated age.

47 Reimer & McCormac 2002, 159; Walker 2005, 26, 29.

48 Hellstrom 2006, 289; Scholz & Hoffmann 2008, 53, 67.

49 Finné & Weiberg 2018, 271.

50 Finné & Weiberg 2018, 271.

tives derived from archaeological/historical datasets.[51]

Substantial progress has been made in recent years regarding the dating precision and temporal resolution of palaeoclimate and palaeoenvironmental records.[52] Chronological uncertainties still often span at least two human generations, however, and the temporal resolution is still commonly counted in decades. Tree ring records could potentially improve the situation of chronological control but to date no record extends further back than AD 1089 in the Aegean.[53] In the case of the Peloponnese it is unlikely that it will be possible to reach further back than *c*. 400 years due to the lack of old trees.[54]

HOW REPRESENTATIVE ARE LOCAL CLIMATE RECORDS FOR LARGER REGIONS?

If local palaeoclimate information of sufficient resolution and quality is not available it may be tempting to resort to a well-known climate record which may be located further away.[55] This use of palaeoclimate information may, however, be problematic. Precipitation variability and change, for example, occurs on different spatial scales from regional to local. Differences in precipitation can even be seen at the micro level, such as between adjacent valleys.[56] In the Eastern Mediterranean, heterogenous spatial patterns in precipitation are observed in modern precipitation,[57] as well as in proxy-based climate reconstructions and in climate modelling experiments.[58] The spatial coherence of climate variability can be tested using instrumental measurements and pseudo-proxy experiments with climate models.[59] It should, however, always be kept in mind that even if the present climate at a distant location appears to be representative for a given study site, this may not have been the case in the past.

CALIBRATING PROXIES TO OBTAIN INFORMATION ABOUT CLIMATE

The identification of relationships between a proxy and different climate variables is known as calibration. The interpretation of proxy data is often qualitative, i.e. wetter–drier or warmer–colder. Quantitative interpretations—finding an absolute scale of change in millimetres or degrees centigrade—remain a challenge because they require that the proxy values can be transferred to the climatological and/or meteorological variables that they are interpreted to represent. To do so, a detailed understanding of how climate influences the physical, chemical and biological processes behind the formation of the natural archive are needed. With high-enough dating precision and resolution, proxy measurements can be directly compared with instrumental meteorological data, as it is commonly done in tree ring studies.

To date, there are only a few studies that present a quantitative calibration of proxies, e.g. oxygen isotope ratios, from speleothems in the Eastern Mediterranean, highlighting the many difficulties involved in this work. In examples from Israel (Soreq Cave) and Turkey (Akçakale Cave), high-resolution analysis of oxygen isotope ratios in speleothems formed during a known period of time in the recent past, in combination with monitoring of local meteorological and hydrological conditions, have allowed the calibration of this proxy against precipitation amounts based on the establishment of the mathematical relationship

51 Knapp & Manning 2016.
52 Finné & Weiberg 2018, 275–276.
53 Griggs *et al.* 2007, 1087.
54 Finné & Weiberg 2018, 277.
55 E.g. Fuchs 2007, 352–353.
56 Voudouris *et al.* 2007, 3.
57 Xoplaki *et al.* 2004, 65.
58 Brayshaw *et al.* 2011, 28; Finné *et al.* 2011, 3166–3168; Roberts *et al.* 2011a, 9–10; Finné *et al.* 2019, 859.
59 Smerdon 2012, and references therein.

between the two.[60] The present-day relationship between climate and proxy is then extrapolated beyond the period of instrumental measurements assuming that it has remained constant over time, although this is not always the case. Any reconstructions of precipitation amounts based on the calibration will inherently contain uncertainties and should include a measure of this uncertainty that expresses how likely it is that reconstructed values fall in a certain range.

Another factor that is related to calibration is the extent to which a proxy is climate dependent, denoted as proxy sensitivity. Although no major shift in Earth's climate has occurred since the last transition from glacial to interglacial conditions, the Holocene climate has never been stable. These subtler changes may have had significant influences on human societies if thresholds were crossed. For example, even a minor decrease in precipitation can have severe consequences for an agricultural system if the water demand of main crops is no longer met. To study climate variability in the context of the ancient Greek world requires sensitive proxies that respond to the subtler changes we expect to have occurred, and allow the climate signal to be distinguished from the "noise" inherent in each proxy record: that is, the random variability in the proxy record which is not linked to climatic influence.

Discussion and conclusions

The data and method selection have important implications for linking hydro-climate data with archaeological and historical data. In the following discussion the aspects of temporal resolution and spatial representativeness for hydro-climate data will be discussed in relation to archaeological and historical data. Thereafter we will outline some thoughts around the role of hydro-climate for ancient Greek societies, and for freshwater availability of these societies as well as the importance of interdisciplinary approaches to studies of freshwater availability in the past.

The strength of the selected records is that they comprise a well-dated set of records from different areas of the Aegean that rely on proxies that are relatively unambiguous in their interpretations. Considering the spatial distribution of the selected palaeoclimate records it is clear that much of the southern Aegean Sea itself and the coastal areas surrounding the sea are devoid of data (*Fig. 1*). However, the usefulness of these sites to investigate the climate in the Aegean is indicated by the similar behaviour of the included proxy records and that both Labuhn *et al.*[61] and Finné *et al.*[62] identified regional coherence in hydro-climate across this region.

At this point we assume therefore that the regional mean reflects regionally coherent centennial-scale hydro-climate trends that would have affected the Aegean in the past. The local expression of these, i.e. what the local effects on climate were of these regional trends, however, is something that needs to be studied further using individual proxy records from a number of sites in different settings throughout the Aegean.

The temporal resolution of the selected palaeoclimate records and the numerical treatment allow centennial-scale inferences of hydro-climatic variability. This means that decadal-scale variability and event-like shifts in the hydro-climate cannot be resolved and that detailed comparisons with archaeological and historical data must not be carried out. With centennial-scale hydro-climate information, comparisons are restricted towards more long-

[60] Bar-Matthews & Ayalon 2004, 370, 381; Jex *et al.* 2010, 214–216.

[61] Labuhn *et al.* 2018, 79–80.

[62] Finné *et al.* 2019, 854–855.

term societal processes rather than rapid shifts occurring with a single person's lifetime or during a generation or two.

HYDRO-CLIMATE CLIMATE VARIABILITY AND FRESHWATER AVAILABILITY IN ANCIENT GREECE

It is possible to study archaeological and historical issues without considering hydro-climate and hydro-climatic change. Even issues that relate to freshwater availability in the ancient past can be studied without giving hydro-climate any explanatory value.[63] However, adding information about hydro-climate to evidence from archaeology and history can add great value to our understanding of economico-political fluctuations within ancient societies and to determine the variable degree of vulnerability within them. Discussions around these topics have often focused on short-term turns of events, primarily to periods when there are suggestions of chronological coincidences between climate anomalies ("events") and relatively high-paced societal transformation.[64] Until now, evaluation of more long-term processes, whether centennial or millennial, has been less common but is important to highlight the full span of climate change across time.[65] The wider temporal scope will require higher degrees of generalization,[66] but means on the other hand that it is possible to explore how periods of wetter as well as drier conditions could have had a decisive effect on the livelihoods of ancient societies.

In many instances in the Aegean region, and in the Mediterranean, agricultural activities have provided a possible and rather direct link between human societies and hydro-climatic change that has been investigated in order to understand how climate change may have impacted societies.[67] During the course of history, dry farming, i.e. farming relying on rainwater, has dominated in the Eastern Mediterranean, something that has caused the agricultural system potentially to be exposed to drought or reduced precipitation. In relation to agricultural practices, water management and conservation were important in the past and remain important for present-day Mediterranean societies.[68]

Freshwater availability and the freshwater supply systems for use primarily beyond the agricultural economy, on the other hand, seem more seldomly investigated in relation to hydro-climate and hydro-climatic change in the Aegean. There has been an increased interest in questions related to water management and sustainability in ancient societies during the last decades, driven by the increasing awareness of the challenges to modern societies in the face of climate change and population growth.[69] The potential for linking the freshwater availability of the ancient Aegean world to hydro-climate change—to drier and wetter conditions—remains largely untapped. It is a prospect that should be investigated more closely using multiple lines of inquiry. Key to such endeavours is providing a more detailed picture of the hydro-climate in the Aegean based on chronologically precise and high-resolution proxy data, as well as high-quality archaeological and historical data.

One apparent problem with the regional scale of the hydro-climate data presented here is the comparability with the often local evidence for infrastructure relating to the supply of fresh water, e.g. wells, cisterns and aqueducts, and to

63 Glaser 1983; Crouch 1993; contributions in Aristodemou & Tassios 2018.

64 Weiss *et al.* 1993; Drake 2012; Kaniewski *et al.* 2015; Finné *et al.* 2017.

65 Rosen & Rivera-Collazo 2012; Marston 2015; Lawrence *et al.* 2016; Weiberg *et al.* 2016; Allcock 2017; Weiberg & Finné 2018.

66 Lane 2015, 4.

67 Marston 2015, 201–202.

68 Halstead 1989, 72–73; Staubwasser & Weiss 2006, 372–374.

69 Antoniou *et al.* 2006; Mays 2010; Antoniou *et al.* 2014; Klingborg & Finné 2018.

freshwater consumption. To alleviate this problem a next step would be to revisit the most highly resolved palaeoclimate records from the Aegean region, i.e. the original proxy data, rather than the numerically treated data used here, to further investigate any potential links between freshwater availability and hydro-climatic change. Furthermore, any societal impact of changes in the hydro-climate will depend on the amplitude of change (how much did it change) and the rate or pace of change (how quickly did it change), but it will also be closely related to the society's level of technology and complexity and its resilience.[70] These issues are related to the importance of stability in hydro-climate which is something that recently has gained attention in research on human-environmental dynamics.[71] More stable hydro-climate conditions will create a more predictable environment for human activities, whether the climate was wetter or drier. Stable climate conditions, as opposed to more volatile conditions, can have a positive effect on adapting social and economic systems to the situation.[72] In a freshwater availability perspective, the effects of hydro-climatic stability, and thus predictability, were investigated with a focus on rainwater harvesting using cisterns in ancient Greece.[73] In that paper the authors highlight the role of active human participation for freshwater availability in the context of short-term variability in hydro-climate conditions. The susceptibility to short-term and/or long-term change in hydro-climate also depends on how fresh water is supplied, whether the main source is rainwater collected in cisterns, water from rivers or lakes, water from an aqueduct, or water from a karstic spring. During short-term (yearly to decadal) periods of drier hydro-climatic conditions there was probably less water to be collected in cisterns using rainwater-harvesting techniques,[74] and water levels in open water bodies such as rivers and lakes may have dropped, unless they were fed by water from karstic aquifers or glaciers. However, short-term periods of drier conditions may have been buffered by spring water originating from karstic aquifers. Recent modelling results have shown that the infiltration capacities of areas with karstic bedrock, i.e. many areas of the Aegean, prohibit surface run-off and reduce evapotranspiration when hydro-climatic conditions are wetter and allow for a non-negligible recharge also during dry conditions.[75] This suggests that areas with karstic bedrock may be more resilient to changes in hydro-climate in terms of both drought and flooding. However, in the long term (decadal to centennial), hydro-climatic change may be linked to the amount of water entering karstic aquifers and groundwater, ultimately affecting how much fresh water can be supplied by karstic springs, and wells tapping into the groundwater. Consequently, it may be suggested that a shift to drier climate conditions did not have an immediate, short-term, effect on water supply in domestic, urban and industrial contexts, in contrast to the effect it would have had on dry farming, which likely was more direct.

The palaeoclimate data can currently provide us with information about the nature of the natural input of fresh water, whether it was higher or lower during certain periods of the past. It is not until quantitative proxies have been developed further that we can get ideas of the amount of fresh water that was put into the natural system and therefore potentially available as fresh water for human consumption. What the hydro-climate data will not ever be able to tell us is how much of this available fresh water was extracted for human use, or how it was extracted, and the palaeoclimate data will

70 For a local example see Weiberg & Finné 2018.
71 Kennett & Marwan 2015, 8; Akers *et al.* 2016, 285–286.
72 Weiberg & Finné 2018, 13.
73 Klingborg & Finné 2018.
74 Klingborg & Finné 2018, 128–129.
75 Hartmann *et al.* 2015, 1741.

not tell us anything about how much fresh water was actually consumed or how it was consumed. Thus, we cannot know if the potentially available fresh water was ample or scarce from a human perspective, or if certain smaller changes in available amounts were more significant than apparently larger ones because it meant thresholds were crossed leading to negative or positive ripple effects. Such key aspects for considering ancient freshwater availability need to be approached by interdisciplinary work.

In this chapter we have provided an insight into the hydro-climate of the period from 700 BC to AD 300. This data provides the environmental backdrop against which it will be possible to start discussing the potential effects that the hydro-climate may have had on freshwater availability. From the data presented in this chapter it is clear that the hydro-climate in the period went from drier to wetter, to remain wetter for most of the period until it became drier again towards the end. Proxy information about the hydro-climate conditions will merely provide an idea of the natural input of fresh water in a highly complex system of natural and social mechanisms and components. Freshwater availability is controlled by bedrock properties, vegetation as well as human decisions, technologies, economic and political factors in combination with climate both in the long and the short term.[76] To investigate the potential effect of climate on freshwater availability further, interdisciplinary studies are necessary so that as many different factors and aspects as possible can be brought together.

What is hopefully clear from the foregoing is that trying to understand and reconstruct climate change is difficult and affected by uncertainties relating both to measurements and interpretations. These uncertainties need to be kept in mind when working directly with, or applying palaeoclimate data to, for example, archaeological contexts. Although belonging to different academic disciplines and with different scientific discourses, there are strong similarities between archaeological and historical research and the palaeoenvironmental sciences (including palaeoclimatology) because they all deal with the past based on the study of different archives.[77] Izdebski *et al.* state that this lack of "direct contact with the studied phenomenon has a strong influence on the methodologies of these disciplines as they all require the search for traces of the past in the present."[78]

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[76] Jones 2013, 77–78.

[77] Izdebski *et al.* 2016, 8.
[78] Izdebski *et al.* 2016, 8.

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