



## The 4.2 ka BP Event in the Mediterranean region: an overview

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**Abstract.** The Mediterranean region and the Levant have returned some of the clearest evidence of a climatically dry period occurring around 4200 years ago. However, some regional evidence is controversial and contradictory, and issues remain regarding timing, progression, and regional articulation of this event. In this paper, we review the evidence from selected proxies (sea-surface temperature, precipitation, and temperature reconstructed from pollen,  $\delta^{18}\text{O}$  on speleothems, and  $\delta^{18}\text{O}$  on lacustrine carbonate) over the Mediterranean Basin to infer possible regional climate patterns during the interval between 4.3 and 3.8 ka. The values and limitations of these proxies are discussed, and their potential for furnishing information on seasonality is also ex-

plored. Despite the chronological uncertainties, which are the main limitations for disentangling details of the climatic conditions, the data suggest that winter over the Mediterranean involved drier conditions, in addition to already dry summers. However, some exceptions to this prevail – where wetter conditions seem to have persisted – suggesting regional heterogeneity in climate patterns. Temperature data, even if sparse, also suggest a cooling anomaly, even if this is not uniform. The most common paradigm to interpret the precipitation regime in the Mediterranean – a North Atlantic Oscillation-like pattern – is not completely satisfactory to interpret the selected data.

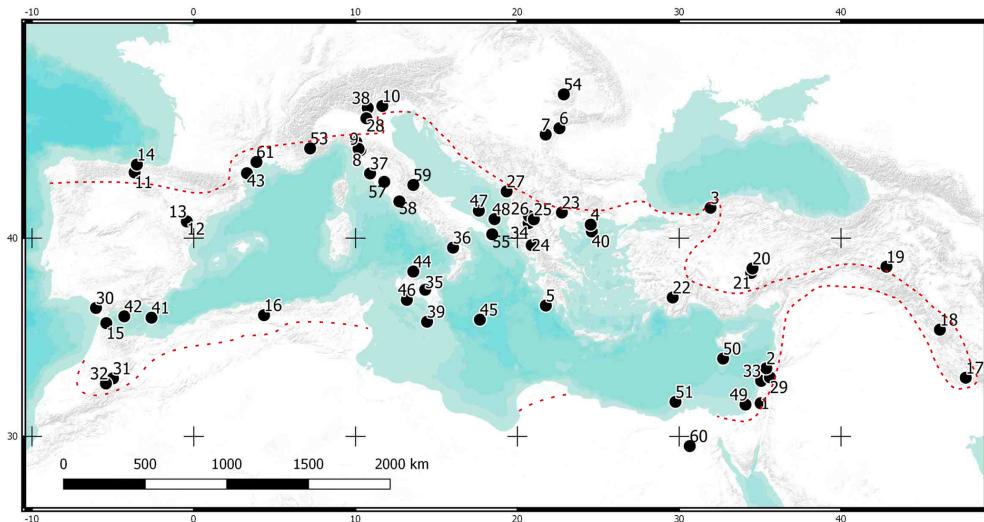
## 1 Introduction

In recent years, it has become paradigmatic that the Holocene was a relatively stable climatic epoch when compared to the last glacial period (e.g., Dansgaard et al., 1993). However, long-term, astronomically driven changes in insolation produced changes in temperature (Marcott et al., 2013, but see also Marsicek et al., 2018), associated with a progressive southward shift of the Intertropical Convergence Zone (ITCZ) and a weakening of Northern Hemisphere summer monsoon systems (e.g., Wright et al., 1993; Fleitmann et al., 2003; Braconnot et al., 2007). A number of short, multidecadal- to centennial-scale climatic events, the origin of which often remains unclear, are superimposed over this long-term trend (e.g., Denton, and Karlén, 1973; Bond et al., 1997; Mayewski et al., 2004; Wanner et al., 2011). At the regional-to-global scale, some events appear synchronous and linked to specific changes in circulation patterns (e.g., Trouet et al., 2009; Dermody et al., 2012; Zanchetta et al., 2014). A good example is the Medieval Climate Anomaly in the Atlantic region, which has been explained in terms of an anomalously persistent positive mode of the North Atlantic Oscillation (NAO) (Trouet et al., 2009). However, the synchronicity and therefore the origin of many such events remain challenging. A major and much-discussed example of a multidecadal- to century-scale event is the so-called “4.2 ka BP Event”. The detection of this event over an extensive region, and its common expression as an interval of cooling and drying (e.g., Cullen et al., 2000; Drysdale et al., 2006; Dixit et al., 2014), points to a global “megadrought” (Weiss, 2015, 2016). The significance of the climate event at 4.2 ka at the global scale has been accepted recently as the formal boundary of Late and Middle Holocene at 4250 ka b2k (<http://www.stratigraphy.org/>, last access: 11 March 2019). Despite its near-pervasive recognition, the timing, duration, and progression of this event have yet to be defined in detail, whilst its origin in terms of changes in ocean and atmospheric circulation remains elusive (Booth et al., 2005; Zanchetta et al., 2016; Carter et al., 2018). Moreover, not all the palaeoclimate records preserve evidence of the 4.2 ka BP Event, at least as a prominent feature of the Late Holocene (e.g., Seppa et al., 2009; Göktürk et al., 2011; Roland et al., 2014) and not necessarily as a cold and dry event (e.g., Railsback et al., 2018). Some researchers have suggested that this event is best described as a complex succession of dry/wet events, rather than a single long, dry event (Magny et al., 2009; Railsback et al., 2018), further complicating the matter. The Mediterranean region shows some of the most consistent evidence of the 4.2 ka BP Event. It is mostly recognized as a dry interval and is identified in pollen records (e.g., Magri and Parra, 2002; Di Rita and Magri, 2009; Kaniewski et al., 2013), speleothems (Drysdale et al., 2006; Cheng et al., 2015; Zanchetta et al., 2016; Finné et al., 2017), lakes (e.g., Zanchetta et al., 2012b), and marine sediments (e.g., Margaritelli et al., 2016). However, the chronology of the event

is not precisely defined and, in many records, the event is not evident (Finné et al., 2011), challenging the view of a generalized period of significant drought. In this paper, we review the evidence, nature and chronology of the 4.2 ka BP Event in the Mediterranean region by comparing different marine and terrestrial proxy records. This will serve to identify gaps in the regional coverage, to expose aspects that should be addressed in future research on this topic, and to determine if coherent regional/subregional climatic patterns are present, what their links are to regions further afield, and if such patterns can be plausibly explained in a coherent meteoclimatic framework.

## 2 Methods and terminology

In this paper, we use the term “4.2 ka BP Event” to indicate a period of time between approximately 4.3 and 3.8 ka cal BP (close to the definition of Weiss (2015, 2016), whilst being mindful that this does not necessarily correspond to the true temporal evolution of the climatic event but the chronological interval where often this event is recognized. We have considered a large set of records for this review. In the end, the records selected for inclusion are those possessing robust age models and high-resolution time series (i.e., at least subcentennial). It has been recognized that chronology for some Mediterranean records could be problematic, as demonstrated, for instance, using tephra layers as chronological points (Zanchetta et al., 2011, 2016, 2018). However, in the absence of these chronological control points, the question of exclusion or inclusion of records involves a degree of subjectivity. For example, we argue that only records dated by radiocarbon using terrestrial remains should be selected. Marine records dated using radiocarbon on foraminifera can show millennial-scale change of the reservoir effect (Siani et al., 2001), and different degrees of bioturbation, which can complicate comparisons between different archives. Some speleothem records, dated in the past with uranium–thorium (U–Th) methods, have chronologies inconsistent with more recent accurate age determinations (e.g., Grotta di Ernesto; McDermott et al., 1999; Scholz et al., 2012). However, to have a wide regional coverage with proxy records, we have also included records with relatively low resolution and with age control that is not necessarily optimal. With this in mind, we are also aware that our selection of records could appear incomplete for some archives/proxies. Among a copious number of data showing, even if with different expression, the 4.2 ka BP Event and its impact in the Mediterranean Basin (e.g., Magny et al., 2009; Margaritelli et al., 2016; Blanco-Gonzalez et al., 2018), we have decided to select only the proxies that can give, in our opinion, more complete information on the hydrological variability like oxygen isotope composition of continental carbonates (e.g., Roberts et al., 2010) and on the temperature conditions at regional scale, as reconstructed by pollen data and marine proxies



**Figure 1.** Location of selected records discussed in the text. For the numbers and references, refer to Table 1. The dotted red line corresponds to the limit of the growth of olive trees, taken as a rough indication of Mediterranean climate.

(Jalali et al., 2016; Kaniewski et al., 2018). It is obvious that many archives are suitable for a multiproxy approach, but some proxies can be related more to local processes and correlate with climatic variables less directly than others can. Moreover, it would be useful to use similar proxies in different environments, even if they do not necessarily have the same meaning (Roberts et al., 2010). We must also consider that the scale and longevity of human activity around the Mediterranean may create locally serious difficulties in distinguishing climate change from human impact (e.g., deforestation, erosion) in many proxy records of past environmental change (England et al., 2008; Roberts et al., 2004, 2010). The 4.2 ka BP Event in the Mediterranean (including the Levant) is strictly related to complex societal evolution and development at the basin scale (Weiss, 1993; Zanchetta et al., 2013), and care is necessary in interpreting proxy records where local factors override regional climate changes. Pollen records are surely one of the most important sources of information on past environment in the Mediterranean and they will be used in this review, but they are one of the proxies that have been suggested to be seriously compromised by human activity (e.g., Roberts et al., 2004; Fyfe et al., 2015, 2018). Given the importance of having estimates of past temperature and precipitation reconstruction, we have selected pollen-based quantitative reconstructions (e.g., Peyron et al., 2017). In terrestrial archives, in addition to pollen data, we selected the oxygen isotope composition of lacustrine carbonates and speleothems as the main proxies of past climate due to their potential for preserving strong hydrological signals (Bar-Matthews et al., 1996; Roberts et al., 2008, 2010). For marine records, sea-surface temperature (SST) reconstruction was preferred to oxygen isotope composition of planktonic foraminifera, for the unavoidable limitation of the latter to represent the mixing signal of tem-

perature and changes in local seawater isotopic composition (i.e., salinity). These are the main proxies considered for our reconstruction: they show the largest coverage and the most complete, in our opinion, climate information. These proxies also permit, to some extent, the disentanglement of climate signals between the cooler and warmer seasons, as we will propose. We are aware that there are limitations in this, but it is necessary to understand more details about the 4.2 ka BP Event. There are other proxies which can give potentially further important information, like lake-level changes (Magny et al., 2007, 2011) and, although discontinuous, isotopes on paleosols (Zanchetta et al., 2000, 2017) or paleofloods (Zielhofer and Faust, 2008). Although rare, dust records appear of particular relevance in informing about past circulation patterns and hydrological conditions (e.g., Zielhofer et al., 2017b). However, these records still have low regional coverage and will only be referred to briefly in the discussion.

## 2.1 Selected archives and proxies

Table 1 and Fig. 1 show the complete list of selected records, including the original references and the proxies considered.

### 2.1.1 Speleothems

The number of speleothem records covering the Holocene with appropriate resolution has dramatically increased in recent years, although they are geographically unevenly distributed (e.g., McDermott et al., 2011; Deininger et al., 2017). Multiple proxies obtained from speleothem calcite are often interpreted as hydrological indicators and, in particular, the oxygen isotope composition ( $\delta^{18}\text{O}$ ) is the most common proxy utilized (Lachniet, 2009). In the Mediterranean Basin, in many instances, the  $\delta^{18}\text{O}$  records are seen

**Table 1.** Sites and proxy records selected in this paper for investigating the 4.2 ka BP Event. Resolution is reported only for selected proxies and is intended as the average during the Holocene.

No.	Site (archive)	Proxy	Resolution (years)*	Region	Reference
<b>Caves</b>					
1	Soreq Cave	$\delta^{18}\text{O}$	16	Israel	Almogi-Labin et al. (2009); Bar-Matthews and Ayalon (2011)
2	Jeita Cave	$\delta^{18}\text{O}$	16	Lebanon	Cheng et al. (2015)
3	Solufar Cave	$\delta^{18}\text{O}$	8	Turkey	Göktürk et al. (2011)
4	Skala Marion Cave	$\delta^{18}\text{O}$	20	Greece	Psomiadis et al. (2018)
5	Mavri Trypa Cave	$\delta^{18}\text{O}$	6	Greece	Finné et al. (2017)
6	Ascunsa Cave	$\delta^{18}\text{O}$	55	Romania	Drăgușin et al. (2014)
7	Poleva Cave	$\delta^{18}\text{O}$	76	Romania	Constantin et al. (2007)
8	Corchia Cave	$\delta^{18}\text{O}$ , Mg/Ca	12	Italy	Regattieri et al. (2014); Zanchetta et al. (2007)
9	Renella Cave	$\delta^{18}\text{O}$ , Mg/Ca	9	Italy	Drysdale et al. (2006); Zanchetta et al. (2016)
10	Grotta di Ernesto	$\delta^{18}\text{O}$	–	Italy	Scholz et al. (2012)
11	Kaite Cave	$\delta^{18}\text{O}$	10	Spain	Dominguez-Villar et al. (2017)
12	Ejulve Cave	$\delta^{18}\text{O}$ , Mg/Ca	13	Spain	Moreno et al. (2017)
13	Molinos Cave	$\delta^{18}\text{O}$ , Mg/Ca	17	Spain	Muñoz et al. (2015)
14	Cueva de Asiul	$\delta^{18}\text{O}$	15	Spain	Smith et al. (2016)
15	Grotte de Piste	$\delta^{18}\text{O}$ , Mg/Ca	15	Morocco	Wassenburg et al. (2016)
16	Gueldaman Cave	$\delta^{18}\text{O}$	13	Algeria	Ruan et al. (2016)
<b>Lakes</b>					
17	Lake Mirabad	$\delta^{18}\text{O}$ end. calcite	258	Iran	Stevens et al. (2006)
18	Lake Zeribar	$\delta^{18}\text{O}$ end. calcite	188	Iran	Stevens et al. (2001)
19	Lake Van	$\delta^{18}\text{O}$ end. calcite	90	Turkey	Wick et al. (2003)
20	Lake Acıgöl	$\delta^{18}\text{O}$ end. calcite	88	Turkey	Roberts et al. (2001)
21	Nar Gölü	$\delta^{18}\text{O}$ end. calcite/aragonite	19	Turkey	Dean et al. (2015)
22	Lake Gölhısar	$\delta^{18}\text{O}$ end. calcite	97	Turkey	Eastwood et al. (2007)
23	Lake Dojran	$\delta^{18}\text{O}$ end. calcite	89	Republic of Macedonia	Francke et al. (2013)
24	Ioannina (Lake Pamvotis)	$\delta^{18}\text{O}$ ostracod	149	Greece	Frogley et al. (2001); Roberts et al. (2008)
25	Lake Prespa	$\delta^{18}\text{O}$ end. calcite	157	Republic of Macedonia	Leng et al. (2010)
26	Lake Ohrid	$\delta^{18}\text{O}$ end. calcite	38	Republic of Macedonia	Lacey et al. (2015)
27	Lake Shkodra	$\delta^{18}\text{O}$ end. calcite	28	Albania/Montenegro	Zanchetta et al. (2012)
28	Lago del Frassino	$\delta^{18}\text{O}$ freshwater mollusk	136	Italy	Baroni et al. (2006)
29	Lake Hula	$\delta^{18}\text{O}$ end. calcite	287	Israel	Stiller and Hutchinson (1980)
30	Laguna de Medina	$\delta^{18}\text{O}$ ostracod	130	Spain	Roberts et al. (2008)
31	Lake Sidi Ali	$\delta^{18}\text{O}$ ostracod; dust record	144	Morocco	Zielhofer et al. (2017a, b)
32	Lake Tiguelmamine	$\delta^{18}\text{O}$ ostracod	278	Morocco	Roberts et al. (2008)

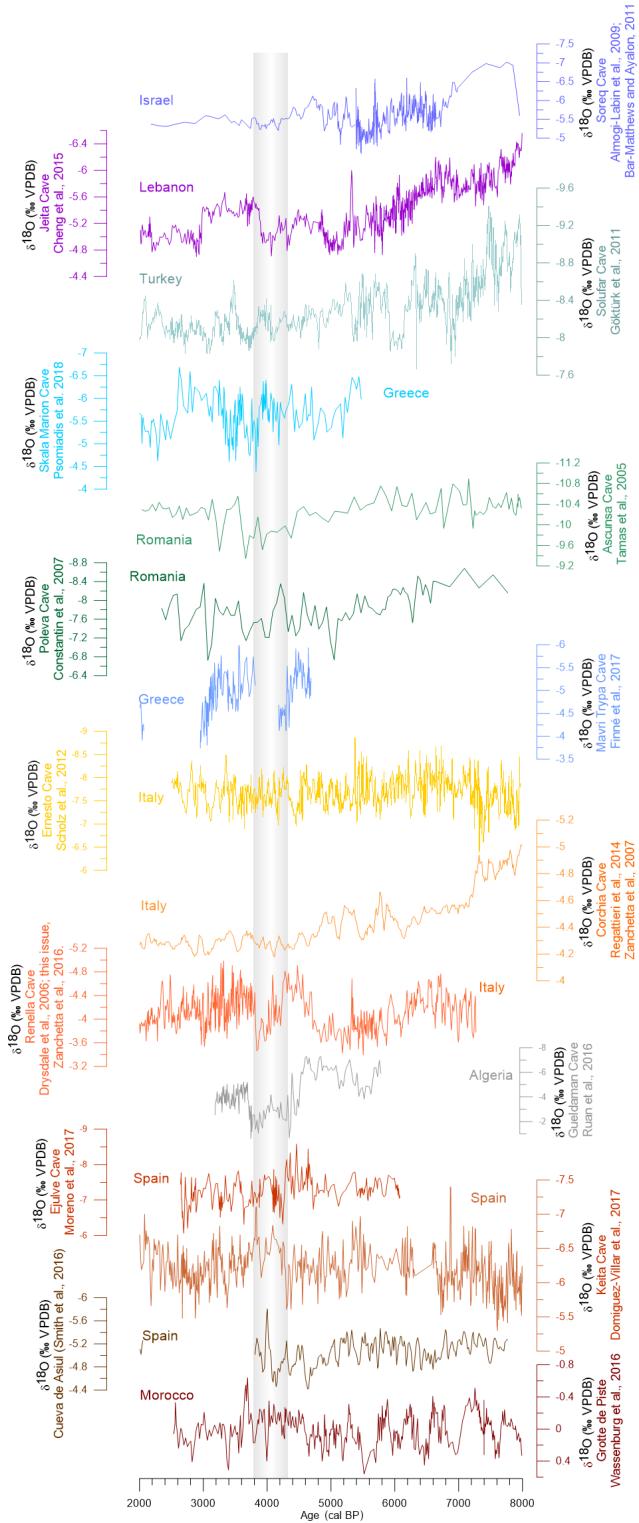
**Table 1.** Continued. “P” indicates precipitation and “T” indicates temperature.

No.	Site (archive)	Proxy	Resolution (years)*	Region	Reference
<b>Pollen</b>					
33	Acre	Pollen (P, T)	85	Israel	Kaniewski et al. (2013)
34	Maliq	Pollen (P, T)	87	Albania	Bordon et al. (2009); Peyron (this paper)
35	Lake Pergusa	Pollen (P, T)	154	Italy	Sadori et al. (2013); Peyron et al. (2017)
36	Lago Trifoglietti	Pollen (P, T)	73	Italy	Peyron et al. (2013)
37	Lago dell’Accesa	Pollen (P, T)	97	Italy	Peyron et al. (2013)
38	Ledro	Pollen (P, T)	66	Italy	Peyron et al. (2013)
39	Burmarrad	Pollen (P, T)	138	Aegean Sea	Gambin et al. (2016); Peyron et al. (2017)
40	SL152	Pollen (P)	76	Aegean Sea	Dormoy et al. (2009); Peyron et al. (2017)
41	MD95-2043	Pollen (P)	106	Alboran Sea	Peyron et al. (2017)
42	ODP-976	Pollen (P)	129	Alboran Sea	Dormoy et al. (2009); Peyron et al. (2017)
<b>Marine</b>					
41	MD95-2043	Alkenone SST	110	Alboran Sea	Cacho et al. (2001)
42	ODP-976	Alkenone SST, Mg/Ca SST	34	Alboran Sea	Martrat et al. (2014); Jimenez-Amat and Zahn (2015)
43	KSGC-31	Alkenone SST	15	Gulf of Lion	Jalali et al. (2016)
44	BS79-38	Alkenone SST	59	Tyrrhenian Sea	Cacho et al. (2001)
45	M25/4-KL11	Alkenone SST	260	Ionian Sea	Emeis et al. (2000)
46	M40/4-SL78	Alkenone SST	160	Ionian Sea	Emeis et al. (2000)
47	MD90-917	Alkenone SST	40	Adriatic Sea	Essallami et al., 2007
48	AD91-17	Alkenone SST	190	Adriatic Sea	Giunta et al. (2001)
49	GeoB 7702-3	Alkenone SST	210	Levantine Basin	Castaneda et al. (2010)
50	ODP 160-967D	Alkenone SST	94	Levantine Basin	Emeis et al. (2000)
51	MD04-2726	Alkenone SST	57	Nile prodelta	Jalali et al. (2017)
<b>Other records</b>					
52	Mohos Bog	Dust record		Romania	Longman et al. (2017)
53	Petit Lac	Detrital fraction		France	Brisset et al. (2013)
54	Scărișoara Ice Cave	D excess in ice		Romania	Perșoiu et al. (2017)
55	Alimini Piccolo	Pollen		Italy	Di Rita and Magri (2009)
56	Gemini Lake	July T		Italy	Samartin et al. (2015)
57	Lake Mezzano	Pollen		Italy	Sadori (2018)
58	Lakes Albano and Nemi	Pollen		Italy	Mercuri et al. (2002)
59	Calderone glacier	Glacier record		Italy	Zanchetta et al. (2012b)
60	Lake Qarun	Lake level		Egypt	Marks et al. (2018)
61	BP-06	Storminess record		France	Sabatier et al. (2012)
62	Tunisia	Flood record		Tunis	Zielhofer and Faust (2008)

\* Average resolution during the Holocene.

as an indicator of the amount of precipitation recharging the cave (the so-called “amount effect”; Bar-Matthews et al., 1996; Bard et al., 2002; Zanchetta et al., 2014; Finné et al., 2017), with higher (lower)  $\delta^{18}\text{O}$  values of calcite indicating drier (wetter) conditions. This is true only when considered in terms of long-term changes in the isotopic composition of seawater sources of the precipitation (“source

effect”; e.g., Cheng et al., 2015). The interpretation of the  $\delta^{18}\text{O}$  record as an indicator of hydrological changes is supported, in some instances, by other proxies like trace elements (Drysdale et al., 2006; Regattieri et al., 2014; Wassenburg et al., 2016) which should be more common in the future. More refined interpretations indicate that the  $\delta^{18}\text{O}$  composition of cave recharge is in some cases related to NAO



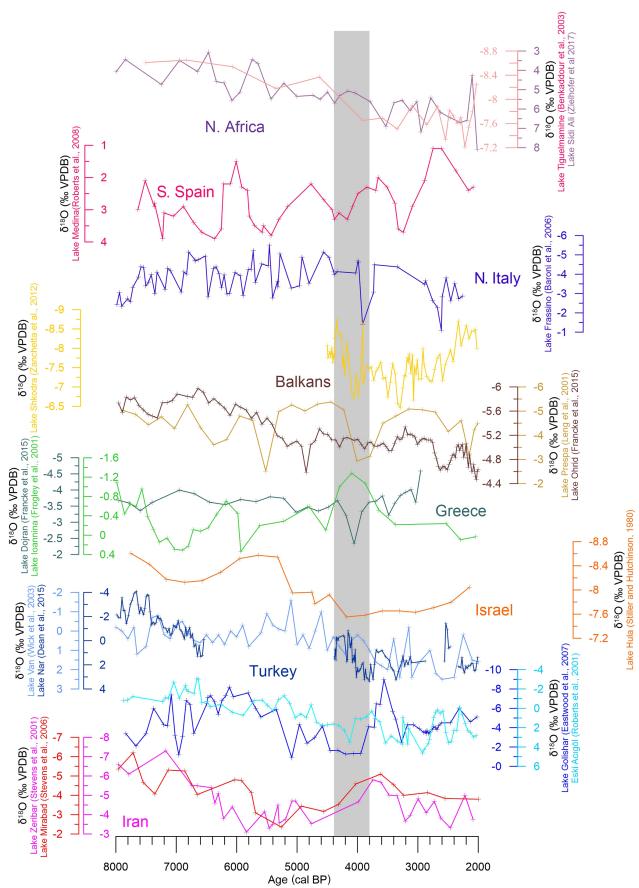
**Figure 2.** Selected speleothem  $\delta^{18}\text{O}$  records. For location, refer to Fig. 1 and for references to Table 1.

(Smith et al., 2016; Wassenburg et al., 2016), even if investigations of  $\delta^{18}\text{O}$  composition of precipitation do not always reproduce a fidelity with NAO pressure patterns (Field, 2010; Baldini et al., 2008). Dominguez-Villar et al. (2017) suggest that most of the isotopic signal in Iberian speleothems is not principally related to the amount of precipitation but rather to changes in the ratio of recycled precipitation, and is correlated to pressure patterns over the North Atlantic. Therefore, some authors suggest that the  $\delta^{18}\text{O}$  of the speleothem calcite is a direct expression of the North Atlantic influence and state, especially in the western Mediterranean (e.g., Smith et al., 2016; Wassenburg et al., 2016) during winter months. However, a change in provenance of precipitation (Holmes et al., 2010) and precipitation amount during winter and summer months can further complicate the interpretation of the  $\delta^{18}\text{O}$  records. Therefore, a unifying and completely satisfactory explanation for  $\delta^{18}\text{O}$  of calcite is probably not yet available throughout the Mediterranean area and surrounding regions (Moreno et al., 2014). It is important also to remember that the  $\delta^{18}\text{O}$  signal is skewed towards the period of calcite precipitation and its relation with cave recharge. As anticipated, the authors tend to assume that most of the cave recharge occurs during winter (or autumn–winter) and most of the  $\delta^{18}\text{O}$  signal should be related to this condition (Deininger et al., 2017). In some instances, the complex interpretation of  $\delta^{18}\text{O}$  as a direct climatic proxy has led different authors to prefer  $\delta^{13}\text{C}$  of speleothem calcite as a better hydrological indicator of local conditions (e.g., Genty et al., 2006; Göktürk et al., 2011). The number of factors influencing the final  $\delta^{13}\text{C}$  value of a speleothem (e.g., Mühlunghaus et al., 2009) make this proxy probably just as, if not more, complicated as  $\delta^{18}\text{O}$ , and in addition, for the strong influence of soil- $\text{CO}_2$  production on the final  $^{13}\text{C}/^{12}\text{C}$  ratio on speleothems, a change in land use and deforestation can have a particularly prominent effect, making it particularly sensitive to human impact above and within the cave. It is usually reported that speleothems possess a superior chronology compared to other archives thanks to the U–Th technique (e.g., Richards and Dorale, 2003). However, this assumption is strictly true for speleothems acting as a closed system for the uranium (Bajo et al., 2016) and with only minor clastic contamination (Hellstrom, 2006). For this review, we have selected 16 records (Fig. 2; Table 1). The main reason for excluding some records is the presence of long hiatuses (thousands of years) over the 4.2 ka BP Event that may not necessarily relate to climatic conditions, e.g., Villars, Chauvet, and La Mine caves (Genty et al., 2006) and Carburangeli Cave (Frisia et al., 2006). Some records have been rejected for their U–Th chronologies, as shown in later studies (e.g., Savi Cave; Frisia et al., 2005), with ages disputed in Belli et al. (2013). However, shorter hiatuses coherent with isotopic changes are considered here as evidence of particularly dry and potentially cooler climate conditions (i.e., Mavri Trypa Cave; Finné et al., 2017). In this regard, Stoll et al. (2013) interpreted the growth cessation of many speleothems at ap-

proximately 4.1 ka in northwest Spain to be caused by increased aridity since this time. However, this is a general signal and not specifically related to a short interval, suggesting that eventual increasing in aridity during the 4.2 ka BP Event is within a general frame of increasing aridification.

### 2.1.2 Lacustrine settings

The oxygen isotope composition of lacustrine carbonates in the Mediterranean region is usually interpreted as mainly being controlled by changes in the isotopic composition of lake water (Roberts et al., 2008), which is controlled by different factors, including changes in the isotopic composition of precipitation and the degree of evaporation (Zanchetta et al., 2007b; Leng et al., 2010a). Each lacustrine setting has a different set of responses and different water  $\delta^{18}\text{O}$  enrichment (Roberts et al., 2008; Leng et al., 2010a, b) due to evaporative effects, which depend on several factors, namely temperature, relative humidity, wind fetch and strength, and residence time of body water (e.g., Craig et al., 1965). Different types of carbonates (e.g., ostracods, freshwater shells, bio-induced carbonates) may precipitate during different parts of the year, with bio-induced calcite (endogenic) often related to spring–summer algal bloom (Leng and Marshall, 2004). Therefore, the  $\delta^{18}\text{O}$  of endogenic carbonate will tend to be weighted towards the summer conditions, although care is necessary for their interpretation and more complex options have been proposed (e.g., Zielhofer et al., 2018). Endogenic carbonates can be contaminated by clastic carbonates (Leng et al., 2010b) and/or early diagenetic minerals (i.e., siderite; Lacey et al., 2016), which can degrade the paleoclimate signal and must be carefully evaluated case by case. Despite these possible complications, trends toward higher (lower)  $\delta^{18}\text{O}$  values are generally explained as an indication of drier (wetter) conditions (Zanchetta et al., 1999, 2007b; Roberts et al., 2008; Leng et al., 2010a, 2013). Reduction in general lake recharge and particularly arid conditions during the warmer part of the year favor higher  $\delta^{18}\text{O}$  values of endogenic carbonate. As is the case of speleothem records, lacustrine  $\delta^{18}\text{O}$  records are unevenly distributed over the Mediterranean Basin (Fig. 1, Table 1) and this represents an important limitation to regional interpretations. Following the list proposed in the important review of Roberts et al. (2008), very few new lacustrine records have been added since, e.g., Lake Ohrid (Lacey et al., 2015), Lake Prespa (Leng et al., 2010a, 2013), Lake Yammouneh (Develle et al., 2010), Lake Shkodra (Zanchetta et al., 2012b), and Sidi Ali (Zielhofer et al., 2017a). Some of the records reported in Roberts et al. (2008) and some new records that were too short or with too-low resolution or poor chronologic accuracy (e.g., Lake Pergusa, Zanchetta et al., 2007b; Valle di Castiglione, Zanchetta et al., 1999; Lake Yammouneh, Develle et al., 2010) have been excluded from this review. We have to note that some records (particularly in the past) used different kinds of organic matter and carbon (i.e., shells) for radiocarbon dating

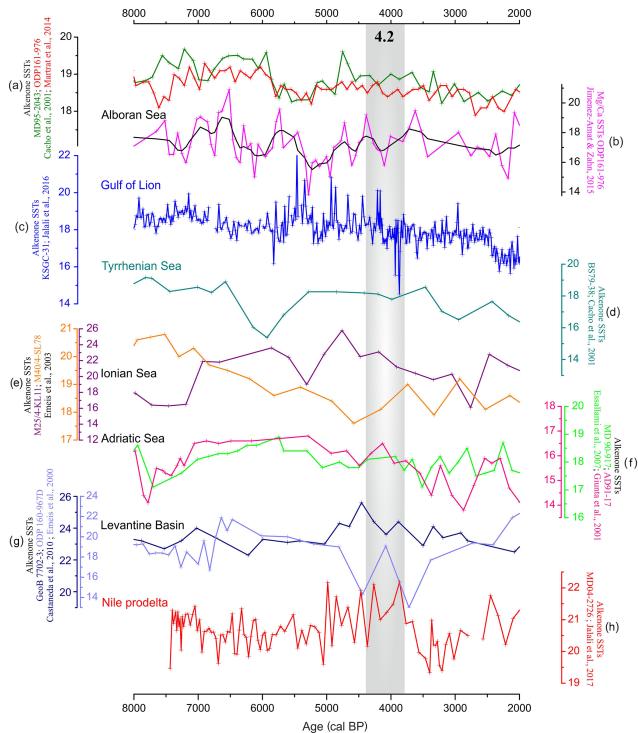


**Figure 3.** Selected lacustrine  $\delta^{18}\text{O}$  records. For location, refer to Fig. 1 and for references to Table 1.

(e.g., Baroni et al., 2006), which can be affected by different reservoir and hard-water effects of unknown amount, leading to significant offsets between records. Figure 3 shows the selected lacustrine records.

### 2.1.3 Marine records

For marine records, we selected SST. Figure 4 shows a compilation of 12 published SST records from coastal and deep-sea sites of the Mediterranean Sea. Apart from Fig. 4b, which is based on the Mg/Ca ratios in planktonic foraminifera *Globigerina bulloides*, all the records are based on alkenone paleothermometry. As for other archives, the comparison of multiple proxies and site compilation require consideration of potential seasonal biases (Emile-Geay et al., 2017). Maximum production of alkenones in the Ligurian, Alboran, and Adriatic seas would take place mainly in spring and autumn (Ternois et al., 1997; Totti et al., 2000; D'Ortenzio and Ribera d'Alcalà, 2009), while in other sub-basins, such as the Balearic Sea and the Bannock Basin, primary production exhibits a less clear pattern, with maximum algal blooms during spring (D'Ortenzio and Ribera d'Alcalà, 2009; Ziveri et al., 2000). However, several high-resolution alkenone-derived



**Figure 4.** Selected SSTs ( $^{\circ}$ C). For location, refer to Fig. 1 and for references to Table 1.

SST records, which overlap with the post-industrial period and allow comparison with SST observations, highlight a consistent match between alkenone SST and average annual sea-surface temperature (Sicre et al., 2016; Jalali et al., 2018; Nieto-Moreno et al., 2013; Moreno et al., 2012; Cisneros et al., 2016). The single Mg/Ca SST record from the Alboran Sea is mainly believed to reflect spring SSTs (Jiménez-Amat and Zahn, 2015). Cisneros et al. (2016) observe that modern regional oceanographic data indicate that *Globigerina bulloides* Mg/Ca is mainly controlled by SST of April–May related to the primary bloom productivity.

#### 2.1.4 Pollen data

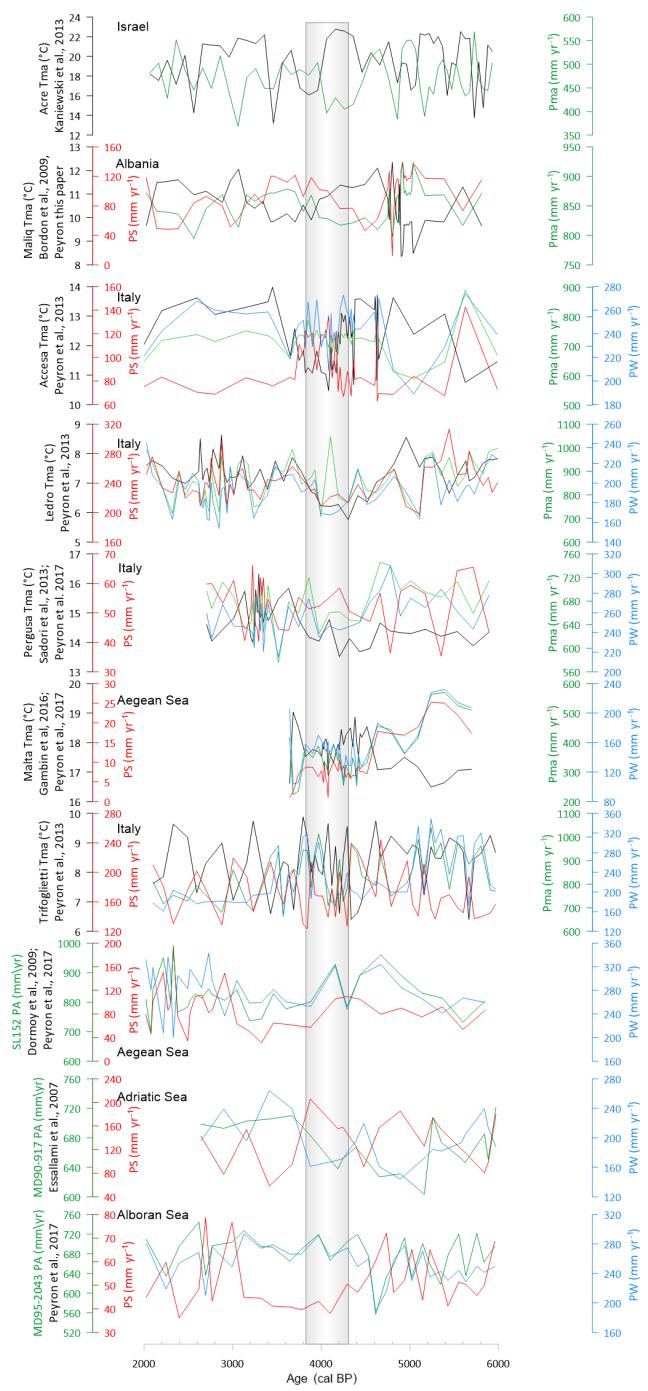
The selection of pollen data is probably more complex considering the elevated number of the sedimentary successions analyzed over the basin and in different settings (marine and lacustrine cores). Using only records with acceptable resolution (i.e., resolution chronologically higher than the interval considered; Peyron et al., 2017), with the reconstruction of precipitation and temperature, the number of records is, however, strongly reduced. The basic assumption in the pollen-based climate reconstructions (assemblage approach or transfer function) is that modern-day observations and relationships can be used as a model for past conditions and that the pollen–climate relationships have not changed with time (Birks, 2005). Among the main approaches available to quantitatively reconstruct past climate from pollen data,

most of the selected records have been performed using the modern analogue technique (MAT) (Guiot, 1990), an “assemblage approach” frequently used in climate reconstructions. This method was successfully used for the Holocene climate reconstructions from terrestrial and marine records (e.g., Peyron et al., 2011, 2017; Mauri et al., 2014, 2015). MAT is based on a comparison of past assemblages to modern pollen assemblages. An important requirement is the need for a high-quality training set of modern samples. The training set should be representative of the likely range of variables, of highest possible taxonomic detail, of comparable quality and from the same sedimentary environment (Brewer et al., 2013). It must cover a wide environmental range. Limitations of using MAT are the occurrence of no analogues or multiple analogues (Birks et al., 2010), and the potential problem of the spatial autocorrelation with MAT but also in the transfer functions (Telford and Birks, 2005). All these interpretations hold if minor human impact is considered in vegetation and pollen production, which may be a major concern for some reconstructions (Fyfe et al., 2015, 2018). Figure 5 shows the reconstructed temperatures (annual) and precipitation (annual, winter, and summer) through the 4.2 ka BP Event.

## 3 Discussion

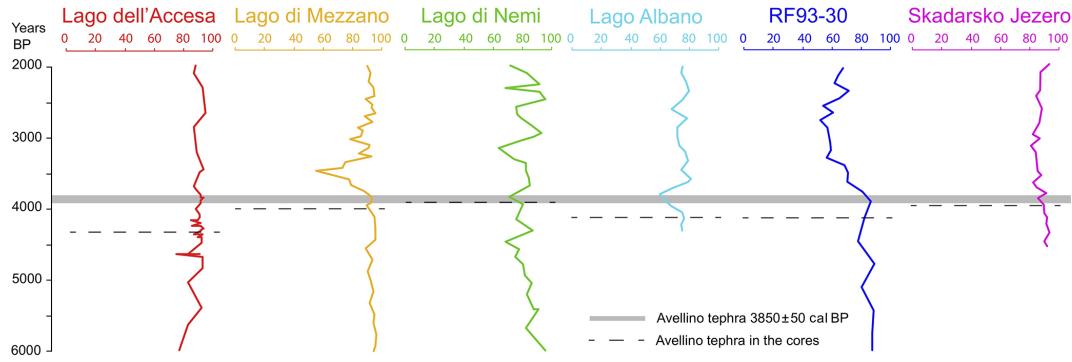
### 3.1 Chronology: the Achilles heel of the problem

The first general observation is that, for many of the records, chronological uncertainties and different, and sometimes poor, chronological resolution are the main obstacles in the precise identification of the event, its timing, duration, and progression. At this stage, both aspects seem to be an unavoidable limitation for an in-depth understanding of this interval. For example, we show selected pollen records (arboreal pollen, AP %) containing the Avellino tephra plotted with their published age model (Fig. 6) in the central Mediterranean. Quite apparent are the century-scale differences in age models presented, considering the well-constrained ages of this tephra layer (approximately 3.8 ka; see discussion and references in Zanchetta et al. (2018)). It is reasonable to assume that similar levels of uncertainties may be present in other records. We note that, in Fig. 6, the identification of the 4.2 ka BP Event appears problematic (at least using AP % signal), which is not the case for other pollen records in Italy (Magri and Parra, 2002; Di Rita and Magri, 2009; Di Rita et al., 2018a), the Iberian Peninsula (e.g., Blanco-Gonzalez et al., 2018; Lillios et al., 2016), or the Levant (e.g., Kaniewski et al., 2013, 2018). Interestingly, some records may suggest that the 4.2 ka interval is characterized by several important oscillations rather than one simple long interval of specific (usually drier) climatic conditions (see, for instance, Skala Marion and Solufar or GLD1 in Fig. 2, or SST in the Gulf of Lion and Alboran Sea in Fig. 4), as it has been suggested for other parts of the world



**Figure 5.** Selected temperature ( $T$ ,  $^{\circ}\text{C}$ ) and precipitation ( $P$ ,  $\text{mm year}^{-1}$ ) records obtained from pollen records. Tma: mean annual temperature; Pma: mean annual precipitation; PS: average summer precipitation; PW: average winter precipitation. For location, refer to Fig. 1 and for references to Table 1.

(Railsback et al., 2018) and in this issue (Kaniewski et al., 2018). However, there is no clear and coherent evidence of this in many of the different selected records. A good example of the complexity of the evidence and the link to chronological accuracy is the lake-level record at Lago dell' Accesa. This was used as the archetypal example to demonstrate that, in reality, the event is “tripartite” (Magny et al., 2009), where a phase characterized by drier conditions at approximately 4100–3950 cal BP appeared bracketed by two phases marked by wetter conditions and dated to approximately 4300–4100 and 3950–3850 cal BP, respectively (Magny et al., 2009). Magny et al. (2009) reported a significant number of records over the Mediterranean showing reasonably the same climatic evidence. However, subsequent works using tephra layers (Avellino and other tephras are present in Lago dell' Accesa; Magny et al., 2007) showed the inconsistency of this detailed correlation, and the 4.2 ka BP Event should be dominated by lower lake level (Zanchetta et al., 2012a, b, 2016), supporting the existence of a prominent drier phase. To circumvent some of the complex issues related to chronological problems, the authors have used two different approaches. The first, and the most common, is an accurate selection of records which show conspicuous and chronologically consistent evidence of the event (e.g., Drysdale et al., 2006; Magny et al., 2009; Kaniewski et al., 2018). Records in which the expression of the event is equivocal are usually removed. A different approach is more “climatostratigraphic”, which is used instead of a simple chronological selection of a time window to correlate the event on the basis of similarity of the climatic curve. This has the obvious limitation that any regional articulation and/or timing progression will be lost. For instance, we can force the correlation of Skala Marion  $\delta^{18}\text{O}$  record with those of the Renella, Mavri Trypa, and Solufar caves (Fig. 7; for instance, Psomiadis et al., 2018, implicitly followed this approach in their Fig. 6, for Skala Marion, Renella, and Solufar cave records), to assume that the interval at approximately 3.9–3.4 ka characterized by higher  $\delta^{18}\text{O}$  values at Skala Marion corresponds to a similar interval at approximately 4.3–3.8 ka that is well identified in Renella and Mavri Trypa. Therefore, we are aware that the chronological issue can heavily contaminate the following discussion. In the following sections, we separate proxies on the basis of their presumed meaning: annual average vs. seasonal component. Maps are produced (Fig. 8) specifying the local record condition (i.e., warmer/cooler and/or drier/wetter). For reasons that may depend on chronology, proxy sensitivity, and/or local response to climatic change, it is not always obvious to define the specific environmental conditions of the considered interval. In some instances, changes lasted longer than the interval considered, or during the interval there is a clear change in conditions, or the interval is characterized by invariant conditions and/or by trends. Once again, some margin of subjectivity may have existed in the evaluation of a single record. Generally, for each site, if most of the interval is dominated by specific conditions (wetter, drier, colder,



**Figure 6.** Compilation of pollen records containing the Avellino tephra layer (dated at approximately 3.8 ka; for review, see Zanchetta et al., 2018). All the records are plotted with their original age model: Lago dell'Accesa (Drescher-Schneider et al., 2007); Lago di Mezzano (Sadori, 2018); Lago Albano and Lago di Nemi (Mercuri et al., 2002); RF93-30 (Mercuri et al., 2012). For core RF93-30, the correlation with Avellino tephra is not certain (Lowe et al., 2007).

and/or warmer), this is represented in the maps accordingly. If the environmental trend moves toward a specific state, the site is defined by this trend (e.g., if the trend during the interval is toward drier conditions, the site is deemed “drier” during the event). Ambiguities are still possible and are indicated where appropriate.

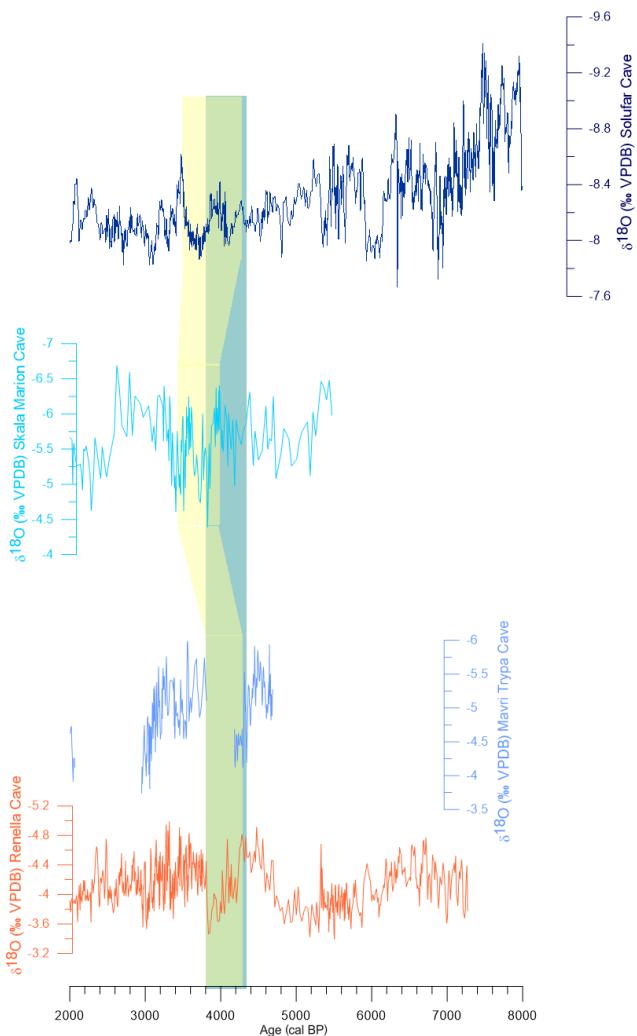
### 3.2 The annual average conditions

Based on SST and pollen reconstructions, it is possible to gain some insights on the average conditions during the 4.2 ka interval (Fig. 8a and b). As can be seen from Fig. 4, SST records from 8000 to 2000 BP show strong differences in their temporal resolution. Some poorly resolve the 4.2 ka BP Event (e.g., Fig. 4d, e). In the Alboran Sea cores, MD95-2043 and ODP-976 show substantially invariant alkenone temperatures, despite their rather high resolution, whereas the Mg/Ca SSTs record from the Alboran Sea (ODP-976, Fig. 4b; Jiménez-Amat and Zahn, 2015) documents a cooling during spring rather than the mean annual conditions. The cooling in the Alboran Sea has been confirmed by high-resolution Mg/Ca SST by Català et al. (2018). The alkenone SSTs from the Gulf of Lion (Jalali et al., 2016) (Fig. 4c) indicate several SST oscillations with some important cooling in the final part of the interval. BS79-38 in the Tyrrhenian Sea (Fig. 4d) shows essentially invariant SSTs, whereas in the Ionian Sea, cores M25/KI11 and M40/4-SL78 (Fig. 4f), despite their low resolution, show an opposite trend. In the Adriatic Sea, an apparent modest warming is present only in core AD91-17 (Giunta et al., 2001). In the Levantine Basin, an apparent general tendency for cooling seems to be present in core GeoB7702-3 (Fig. 4g) (Castaneda et al., 2010), after a phase of warming even if the interval considered comprises the descending part of a longer SST trend. In the Nile prodelta area, a warmer interval seems to be present in core MD04-2726 (Fig. 4h) (Jalali et al., 2017), even if with some oscillations.

Figure 5 shows reconstructed annual average temperatures in different parts of the basin using pollen records. Most of the central Mediterranean records (except Lago Trifoglietti, which shows some intermediate behavior, with a tendency of warming) show a cooling at this time. Lake Maliq shows a long-term cooling, rather a precise interval of cooling. In contrast, in the Acre record, there is first a period of warmer conditions, followed by a later period with a prominent cooling, and this trend, according to Kaniewski et al. (2018), is consistent with other sites in the eastern Mediterranean. Figure 8a shows that the few records selected show generally lower average temperatures in the western–central Mediterranean, whereas towards the eastern part higher temperatures seem to prevail. Annual precipitation estimated from pollen shows several records with clear evidence of reduced precipitation (Maliq, Lake Pergusa, Lago Trifoglietti, Acre), even if this signal is generally complex (Fig. 5), with part of the selected records not suggesting drier conditions (e.g., Malta, SL152, MD95-2043). Indeed, Fig. 8b highlights that poor data coverage for estimating past annual precipitation prevents any detailed considerations.

### 3.3 Winter records

In this reconstruction, we have included speleothems and pollen data, whilst being aware of the limitations discussed in Sect. 2.1.1 and 2.1.4. Most of the records indicate drier conditions in winter during the 4.2 ka BP Event. Speleothems are the most conspicuous record. Qualitatively, 6 out of 15 records show that during the considered interval there is a clear increase in  $\delta^{18}\text{O}$  values (Fig. 2; Jeita, Ascunsa, Poleva, Mavri Trypa, Renella, and Gueldaman caves). Soreq and Carchia can be added to this group (stalagmite CC26), showing a modest increase of values at that time. Two caves (Grotte de Piste and Kaite) show a clear interval of decreasing  $\delta^{18}\text{O}$  values (Fig. 2). Solufar and Skala Marion show a similar pattern of oscillating behavior, with an important part of the



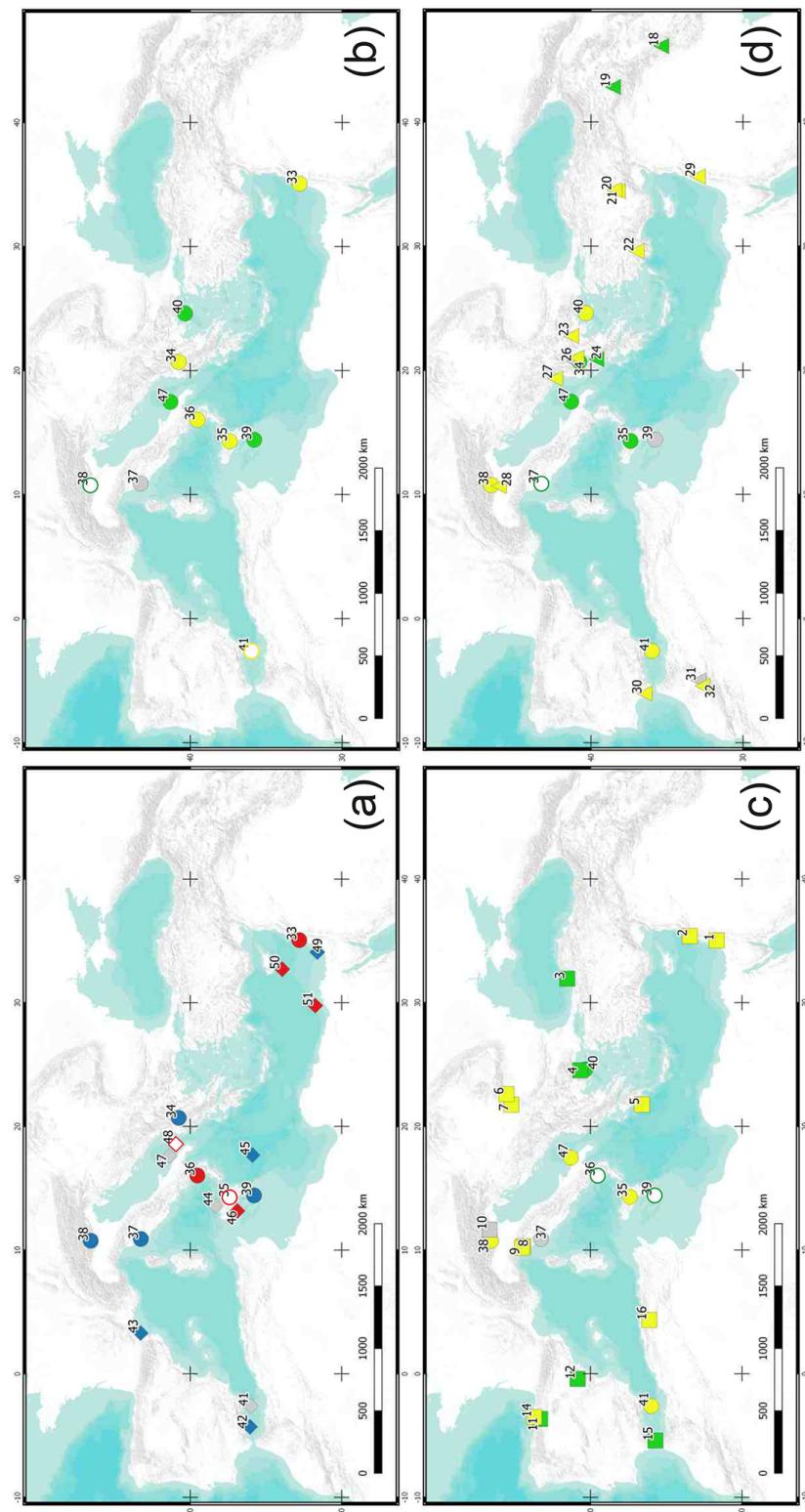
**Figure 7.** Chronologic approach (green field) and climatostratigraphic approach (yellow field) applied on speleothem records (based on Psomiadis et al., 2018): Renella Cave (after Zanchetta et al., 2016); Mavri Trypa Cave (after Finné et al., 2017); Skala Marion Cave (after Psomiadis et al., 2018); Solufar Cave (after Göktürk et al., 2011).

period characterized by a marked decrease in the  $\delta^{18}\text{O}$  values. A similar, but not identical, pattern is present in the Iberian caves, Ejulve and Cueva de Asiul. Invariance defines the Grotta di Ernesto record. This apparently contradictory behavior is regionally well defined with the central Mediterranean (Algeria, central Italy, Romania, and western Greece) and part of the Levant, characterized by the most marked and significant interval characterized by higher  $\delta^{18}\text{O}$  values. Instead, the north Iberian Peninsula and north Morocco show a tendency to lower or oscillating values, as does the opposite end of the basin with the records from the Solufar and Skala Marion caves. Accepting the fact that  $\delta^{18}\text{O}$  represents the amount of precipitation during the winter recharge period, we observe that the central part of the basin, with some exten-

sion to the Balkans and Romania, shows decisively drier conditions compared to the other analyzed sectors, where they show wetter or at least more variable conditions. Winter precipitation reconstructed from pollen shows clear indications of decreased precipitation at Ledro, Lake Pergusa, MD90-917, and MD95-2043 (even if modest). Drier conditions are evident for most of the interval at Lago Trifoglietti (with a late recovery toward wetter conditions), whereas in Malta most of the interval shows wetter conditions compared to the previous period. Lago dell'Accesa shows a strong oscillatory behavior, with the central part of the drier interval bracketed by two wetter intervals. However, the general trend of Lago dell'Accesa cannot be classified unambiguously as wetter or drier. Figure 8c shows the prevailing precipitation conditions (wetter/drier for the interval considered) during winter for the proxy in question. Geographically, it seems quite consistent that most of the Mediterranean records show drier conditions during winter. Despite the poor coverage, the possible exceptions are Morocco and the Iberian Peninsula, as well as some sectors of the eastern Mediterranean, possibly indicating a regional articulation.

### 3.4 Summer conditions

As discussed in Sect. 2.1.2, endogenic lacustrine carbonates can be considered reasonably as a first-order hydrological (precipitation minus evaporation) signal of summer, even if influenced by the effect of recharge during previous periods. Some records (Sidi Ali, Ohrid, Hula) show no peculiar trends during the period considered, although for a very short interval centered at approximately 4.2 ka, Zielhofer et al. (2018) observe a minor oscillation in  $\delta^{18}\text{O}$  values interpreted as increased winter recharge (Fig. 3). Other records show a clear peak towards more positive values (Medina, Frassino, Shkodra, Prespa, Dojran, Nar Gölü, Gölhissar), whereas others show a tendency to decrease values (e.g., Van) or a clear peak of lower  $\delta^{18}\text{O}$  values (i.e., Ioannina). Instead, Zeribar and Mirabad records show a trend towards lower  $\delta^{18}\text{O}$  values, even if the resolution of the two records for this interval is rather poor. A number of records show a well-marked peak of increasing  $\delta^{18}\text{O}$  values within the considered interval but show a different duration, possibly due to differences in age models and resolution. It is surprising to note that the two sister lakes (Prespa and Ohrid) (Lacey et al., 2015; Leng et al., 2010a, b, 2013) exhibit, for this interval, significantly different trends (Fig. 3). This can be explained by the effect of higher residence time and more damped isotopic composition of the lake water at Lake Ohrid due to its large recharge by karst springs (more than 50%; Wagner et al., 2017) in comparison to Lake Prespa (Leng et al., 2010a). This renders the latter much more sensitive to hydrological changes, as demonstrated by its dramatic lowering of lake-level changes in recent years (van der Schriek and Giannakopoulos, 2017). Regional, and consistent with Lake Prespa, are the data from Lake Dojran and Shkodra (Fig. 3), which show drier condi-



**Figure 8.** Maps of (a) annual average temperature, (b) annual average precipitation, (c) winter precipitation, and (d) summer precipitation. See Figs. 2–5 and Table 1 for data. Circles indicate data from pollen, lozenges indicate data from alkenones, squares indicate data from speleothems, and triangles indicate data from the lake. Meaning of filled symbols: blue indicates colder conditions, red indicates warmer conditions, yellow indicates drier conditions, green indicates wetter conditions, and grey indicates unchanged conditions; unfilled symbols: symbols with a red border indicate likely warmer conditions, those with a yellow border indicate likely drier conditions, and those with a green border indicate likely wetter conditions.

tions. Interestingly, the Ioannina record shows a very marked phase of lower  $\delta^{18}\text{O}$  values in an almost perfect antiphase with the other nearby lakes. We note that Ioannina is a record obtained using ostracods; instead, the others were obtained by measuring the isotopic composition of endogenic calcite, which may integrate the isotopic signal of a number of years. Possibly, the Ioannina record intercepts a period of particularly pronounced snow melting in spring, while the other lakes record a significantly longer period of evaporated waters during spring/summer. Progressive trends towards lower values shown by Zeribar and Mirabad are difficult to interpret because of their relatively low resolution, although there is regional coherence. Some pollen reconstructions show evidence of drier conditions (Fig. 5; Ledro, Lago Trifoglietti, SL152-PA, and MD95-2043, even if the last is within a longer period of summer-reduced precipitation), but others indicate a tendency towards increasing precipitation and/or are decisively wetter than the previous interval (Fig. 5; Maliq, Lago dell'Accesa, Lake Pergusa, and MD95-2043). Figure 8d shows the regional pattern of the considered summer conditions. Despite the large gaps in record coverage, once again, most of the records indicate drier conditions, even if, in the central sector (Italian Peninsula and possibly some sectors of Greece) and in the eastern end, a tendency toward wetter conditions may exist.

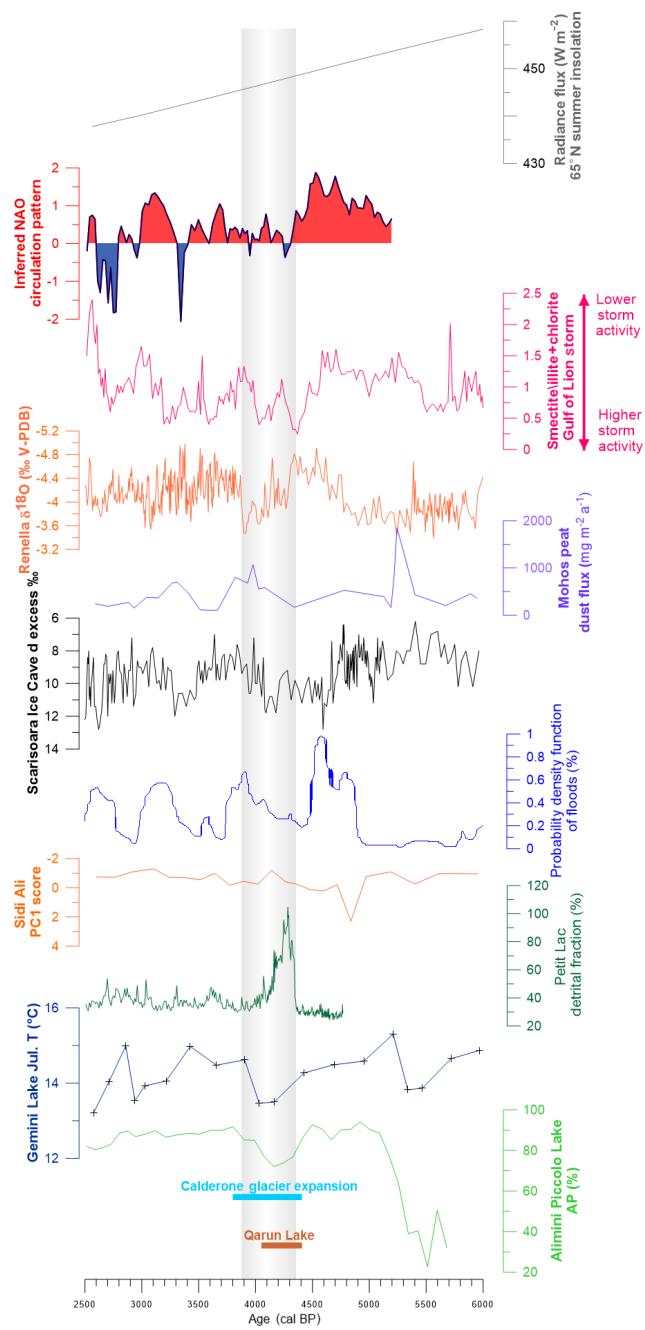
### 3.5 Is a synthesis possible?

The Mediterranean Basin is located in a transitional zone between north Africa and the Arabian arid regions, dominated by the subtropical high-pressure system, and central and northern Europe where midlatitude westerly circulation dominates. The basin is also exposed to the indirect effect of the Asian and African monsoons in summer and to western Russian/Siberian High systems in winter (e.g., Lionello et al., 2006, and references therein). Therefore, to look for a simple mechanism for explaining the 4.2 ka BP Event is not a simple task. The uneven distribution of many proxy records, and the previously discussed concerns on chronology, can make general conclusions and detailed regional articulation difficult. It is beyond the scope of this contribution to discuss the detailed mechanism and forcing; however, considering the discussion made in previous sections regarding the limitations of proxies and our approach in their interpretation, some interesting points emerge. Based on Fig. 8a, the average annual temperature seems to show a tendency of cooling for most of the basin. Even when moving from west to east, there seems to be an increase in the number of records showing an increase in temperature, instead of cooling, suggesting a possible coherent trend. Data for average annual precipitation are sparse and make syntheses difficult (Fig. 8b). Figure 8c shows the situation regarding winter precipitation inferred from speleothem  $\delta^{18}\text{O}$  records and pollen reconstructions. They are of particular relevance for most of the basin, which is strongly controlled by NAO, in particu-

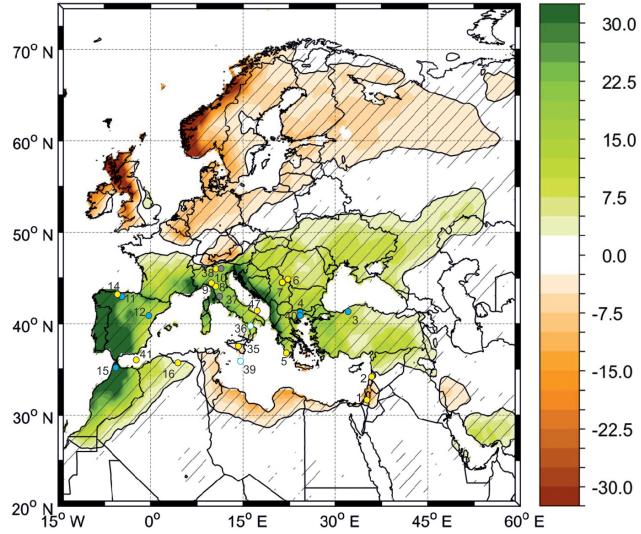
lar in the western and central parts of the basin (Lionello et al., 2006; López-Moreno et al., 2011), with winter precipitation being negatively correlated with NAO. On the contrary, areas of the southeastern Mediterranean show an anticorrelation with western Mediterranean precipitation, resulting in a seesaw pattern known as the Mediterranean Oscillation (MO; e.g., Conte et al., 1989). This clearly opens the possibility that seemingly complex patterns in precipitation are not just an artifact of the proxies and/or chronology but can be a real and robust climatic pattern.

On the other hand, the present climatic configuration can have different past regional expressions due to a combination of multiple factors. Indeed, antiphasing between different sectors of the Mediterranean Basin has been found during the Medieval Climate Anomaly and the Little Ice Age between the Iberian Peninsula and Turkey, with the latter not the present-day center of action of the MO (Roberts et al., 2012). This has also been suggested during several Late Holocene oscillations including the 4.2 ka BP Event, in antiphase in the southwestern and the south-central Mediterranean regions (Di Rita et al., 2018b). The pattern described in Fig. 8c, with the main distribution indicating pervasive drier conditions over most of the Mediterranean during winter, is consistent as a NAO-like positive mode, where westerly sourced vapor masses shift northward due to a pronounced Azores High. NAO positive mode during this period is also supported by the concentration of terrestrial n-alkanes (TERR-alkanes) in the Gulf of Lion shelf sediment (Jalali et al., 2016). However, the presence of a pole of possibly wetter conditions over Morocco (as indicated by the Grotte de Piste; Figs. 6 and 8c, and partly also by Sidi Ali) and the northern Iberian Peninsula, and a less evident and questionable wetter area in the eastern sector (Solufar and Skala Marion caves; Fig. 2), suggests a different configuration. Indeed, at Grotte de Piste, periods characterized by lower  $\delta^{18}\text{O}$  values have been interpreted as a period of negative NAO-like conditions (Wassenburg et al., 2016), which is also suggested by other authors for this period (e.g., Di Rita et al., 2018a). However, this interpretation runs counter to the speleothem evidence from central Mediterranean indicating drier conditions (Renella, Corchia, and Mavri Trypa; Drysdale et al., 2006; Regattieri et al., 2014; Finné et al., 2017).

This is further confirmed by new speleothem data (stable isotopes and trace elements) reported by Isola et al. (2019), from Apuan Alps in central Italy. Figure 9 shows the NAO index inferred by Olsen et al. (2011); during the 4.2 ka BP Event, the NAO is mostly positive, if not particularly prominent, suggesting that NAO configuration alone would not be particularly useful to interpret this period of time. Moreover, Fig. 10 shows that a negative NAO-like configuration with a similar pattern of precipitation like today is unlikely considering the data of Fig. 8c. It is interesting to note that the distribution of Figs. 8c and 10 seems to find some similarity with the reconstruction proposed by Dermody et al. (2012) during Roman time. According to Der-



**Figure 9.** Selected additional records to illustrate the general situation over the basin during the 4.2 ka BP Event. Summer insolation curve at 65° N (Berger and Loutre, 1991); NAO index (Olsen et al., 2011); storm activity in the Gulf of Lion (Sabatier et al., 2012); Renella Cave (Zanchetta et al., 2016); Mohos peat dust flux (Longman et al., 2017); Scărișoara Ice Cave, d excess in the ice cave (Peršou et al., 2017); probability flood frequency from north Tunisia (Zielhofer and Faust, 2008); Sidi Ali dust flux (Zielhofer et al., 2017b); clastic input at Petit Lac (Brisset et al., 2013); Gemini Lake July temperature (Northern Apennines) (Samarin et al., 2017); Alimini Piccolo arboreal pollen (AP %) record (Di Rita and Magri, 2009); Calderone glacier expansion (Zanchetta et al., 2012a); Qarun Lake (Marks et al., 2018).



**Figure 10.** Correlation between the December–January–February NAO index (modified after Peršou et al. (2018)) and precipitation amount during negative NAO conditions. A negative correlation (brown) indicates that during negative conditions precipitation amounts are lower than usual, while a positive correlation (green) indicates that, during negative NAO conditions, precipitation is above average. Yellow circles: records indicating drier conditions during winter; blue circles: records indicating wetter conditions during winter (see Fig. 8c).

mody et al. (2012), the dominant pattern of variability in humidity between 3.3 and 1.0 ka shows a seesaw pattern with Spain and Israel on one side and the central Mediterranean on the other. The patterns in climatic humidity are similar to precipitation anomalies associated with the east Atlantic/west Russia pattern, which today represents a secondary mode of precipitation pattern during winter within the dominance of the NAO pattern (Xoplaki et al., 2004). It is clear that the center of action of the seesaw pattern may have changed in time with configuration not precisely similar to today. It is interesting to note that Peršou et al. (2018) suggested that part of the drier and cold conditions over the Mediterranean during the 4.2 ka BP Event was caused by the strengthening and expansion of the Siberian High, which effectively blocked the moisture-carrying westerlies and enhanced outbreaks of cold and dry winds. Summer proxies (Fig. 8d) indicate a prolongation of drier conditions also during the warmer part of the years, suggesting a persistent Azores High during summer.

However, in the central Mediterranean, some records indicate a possible increase of precipitation, possibly as incursions of North Atlantic perturbations, which suggests weakening of the Azores High for some areas, possibly as an effect of change in its positions (e.g., Di Rita et al., 2018b). Considering that the position of the ITCZ exerts a control on summer aridity and the temperature in the Mediterranean Basin (Eshel et al., 2002; Alpert et al., 2006; Gaetani et al., 2011), a southward shift of the ITCZ may have locally weakened

the Azores High, favoring incursion of wetter air from North Atlantic. A southward shift of the ITCZ during the 4.2 ka BP Event is supported by several lines of evidence (e.g., Welc and Marks, 2014; Dixit et al., 2014), and this would have an effect on summer weather over the Mediterranean. Marriner et al. (2012) have shown a decrease in Nile Delta flood-driven accretion between approximately 4.4 and 4.1 ka in response to weakening of ITCZ, related to changes in El Niño–Southern Oscillation (ENSO)-type variability. This may indicate an indirect influence of ENSO variability on climate of the Mediterranean during 4.2 ka BP Event. Brayshaw et al. (2010) discussed the influence of the position of the midlatitude westerly jet (MLWJ) over the winter precipitation in the Mediterranean. Their modeling indicates a southward shift of the MLWJ during the second part of the Holocene, with related changes in cyclogenesis over Mediterranean. The importance in the shift of the position of the MLWJ is also documented in dust proxy records from the Middle East and east Asia (e.g., Nagashima et al., 2011; Sharifi et al., 2015, 2018). According to Sharifi et al. (2018), evidence from the dust record from the Neor peat mire in Iran and climate modeling shows that at approximately 4.2 ka there is a migration of the main axis of the MLWJ towards the Equator allowing the transport of higher fluxes of dust from west Asia as well as from the northeast Africa. This indicates a complex but possibly correlated interplay between the ITCZ, MLWJ, and Mediterranean precipitation. Despite evidence being weak, it is also reasonable to assume that conditions during summer are also important in defining the final “feature” of the 4.2 ka BP Event. Evidence of environmental and climatic deterioration around or coincident with the 4.2 ka BP Event is apparent but chronologically compromised considering a different selection of records (Fig. 9; see also Fig. 1 and Table 1). Reduced temperature (Fig. 8a) is also consistent with the start of the Neoglacial over the Apennines with the first appearance during the Holocene of the Calderone glacier (Zanchetta et al., 2012a). Interestingly, exposure ages in the western Alps also indicate a first “Neoglacial advance” at 4.2 ka (Le Royet et al., 2017). This is geographically consistent with lower temperatures during summer, as inferred from chironomids from central Italy (Fig. 9; Samartin et al., 2017). Also, on the French side of the Mediterranean Alps, lakes show evidence of high-frequency environmental instabilities during this period. Rapid alternation of drop and rise of the lake level are suggested by a switch in the benthic/planktonic diatom ratio at Lac d’Allos (Cartier et al., 2019), while at Petit Lac, more frequent heavy rainfall triggered soil erosion (Fig. 9; Brisset et al., 2013) and ecosystem shift (Cartier et al., 2015). This complex pattern is well explained by oxygen isotope composition performed on diatom cells of Petit Lac that indicates that the period is marked by drier mean conditions (in terms of annual lake balance), associated with short-term heavy rainfall (Cartier et al., 2019) rather than just wetter conditions. This is in good agreement with the other records of the central Mediterranean.

The pollen records from Alimini Piccolo (Fig. 9; Di Rita and Magri, 2009) and from the Gulf of Gaeta (Di Rita et al., 2018b) show a prominent decrease in AP, suggesting drier conditions. Drier conditions can be inferred also from a multiproxy record from Qarun Lake in the Faiyum Oasis (Egypt; Figs. 1, 9). In Qarun, the interval between approximately 4.4 and 4.0 ka shows an increase in aridity and dust supply, as shown by several proxies (Marks et al., 2018). In northeastern Africa, there is further evidence of climate change at about 4.2 ka associated with the collapse of the ancient Old Kingdom in Egypt (Welc and Marks, 2014, and references therein). Dust deposition increases in the Eastern Carpathians, as documented by the Mohos peat succession (Longman et al., 2017), although an increase of clastic material in a peat succession in a volcanic caldera can be explained also by an increase in local soil erosion. This phase is marked by a change in the  $\delta^{13}\text{C}$  excess in the ice in the Scărișoara Ice Cave (Carpathian Mountains; Fig. 9; Perșoiu et al., 2017), suggesting a change in the arrival of cyclones sourced from the Mediterranean region. The dust record in Sidi Ali Lake (Fig. 9) suggests a measurable trans-Saharan aridity event, with increased dust transport at approximately 4.2 ka (Zielhofer et al., 2017b). Changes in circulation are also suggested by exotic pollen of cedar, arriving from north Africa, in some pollen successions of central Italy (e.g., Magri and Parra, 2002). Between approximately 4.4 and 4.0 ka, there is evidence for an increase in storm activity, as documented by several records in the central Mediterranean (Sabatier et al., 2012; Kaniewski et al., 2016; Marriner et al., 2017), possibly suggesting an increase of occasional strong southward incursion of westerlies. This is not in contrast with a trend towards increased flooding in central Tunisia in this period correlated with a colder period in the North Atlantic (Fig. 9; Zielhofer and Faust, 2008).

#### 4 Final remarks and trajectories of future research

The analyses of many records show that between 4.3 and 3.8 ka climatic and environmental changes occurred in the Mediterranean Basin. In many records, it appears evident that an important change in the hydrological regime occurred, with more arid conditions, but locally this evidence is confounded. Cooling can be inferred from different records, but this is not a common feature. Despite contradictions, which is not questioning the evidence of this event, there is the possibility that it is regionally articulated as having a locally different climatic expression. This expression would be also related to different seasonal conditions. From the selected data, the possibility emerges that this event is in reality marked by some oscillations which cannot be resolved in an unequivocal way on the basis of available records. However, regional coverage is still low, even if our record selection is incomplete. The emerging patterns need to be confirmed by future research, but well-positioned and well-resolved new records

can also change our view. By comparing the distribution of the selected records with one of the most important climatic modes like NAO, which impact Mediterranean climate, in particular in winter, we did not find complete and satisfying matches. We can agree that different working hypotheses investigating the role of potential climatic teleconnections can be inferred from single records or regionally well-constrained groups of records, but none seem convincing today. However, this review indicates that many pieces of this complex puzzle are still lacking. Most urgently, new records at a higher resolution with a firm chronological basis are required.

**Data availability.** The paper is a review and all the data have been collected from previous publications either on an open database or by requesting data directly from the authors. In only one case have data been digitized. In any case, they have been organized in a series of \*.xls files, which can be obtained by request to MB and GZ.

**Author contributions.** MB, GZ, and AP conceived the manuscript. MB and GZ organized and wrote most of the manuscript. In particular MF, RD, and II contributed to the construction and writing of Sect. 2.1.1; JRD and RC contributed to the construction and writing of Sect. 2.1.2; BJ, M-AS, IC, and FL contributed to the construction and writing of Sect. 2.1.3; OP contributed to the construction and writing of Sect. 2.1.4; FDiR, OP, DM, AM, AMM, and LS contributed to the selection and interpretation of pollen records; LM, AP, MB, FW, and CZ contributed to the selection and interpretation of different proxy records throughout the manuscript. All the co-authors participated in sharing the data and contributed to the scientific discussion.

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## References

- Almogi-Labin, A., Bar-Matthews, M., Shriki, D., Kolosovsky, E., Paterne, M., Schilman, B., Ayalon, A., Aizenshtat, Z., and Matthews, A.: Climatic variability during the last 90 ka of the southern and northern Levantine Basin as evident from marine records and speleothems, *Quaternary Sci. Rev.*, 28, 2882–2896, 2009.
- Alpert, P., Baldi, M., Ilani, R., Krichak, S., Price, C., Rodo, X., Saaroni, H., Ziv, B., Kishcha, P., Barkan, J., Mariotti, A., and Xoplaki, E.: Relations between climate variability in the Mediterranean region and the tropics: ENSO, South Asian and African monsoons, hurricanes and Saharan dust, in: *Developments in Earth and Environmental Sciences*, Elsevier, 4, 149–177, 2006
- Bajo, P., Hellstrom, J., Frisia, S., Drysdale, R., Black, J., Woodhead, J., Borsato, A., Wallace, M. W., Regattieri, E., and Haese, R.: “Cryptic” diagenesis and its implications for speleothem geochronologies, *Quaternary Sci. Rev.*, 148, 17–28, 2016.
- Baldini, L. M., McDermott, F., Foley, A. M., and Baldini, J. U.: Spatial variability in the European winter precipitation  $\delta^{18}\text{O}$ –NAO relationship: Implications for reconstructing NAO-mode climate variability in the Holocene, *Geophys. Res. Lett.*, 35, L04709, <https://doi.org/10.1029/2007GL032027>, 2008.
- Bard, E., Delaygue, G., Rostek, F., Antonioli, F., Silenzi, S., and Schrag, D.: Hydrological conditions in the western Mediterranean basin during the deposition of Sapropel 6 (ca. 175 kyr), *Earth Planet. Sc. Lett.*, 202, 481–494, 2002.
- Bar-Matthews, M. and Ayalon, A.: Mid-Holocene climate variations revealed by high-resolution speleothems records from Soreq Cave, Israel and their correlation with cultural changes, *Holocene*, 21, 163–171, 2011.
- Bar-Matthews, M., Ayalon, A., Matthews, A., Sass, E., and Halicz, L.: Carbon and oxygen isotope study of the active water–carbonate system in a karstic Mediterranean cave: implications for paleoclimate research in semiarid regions, *Geochim. Cosmochim. Ac.*, 60, 337–347, 1996.
- Baroni, C., Zanchetta, G., Fallick, A. E., and Longinelli, A.: Molluscs stable isotope record of a core from Lake Frassino (northern Italy): hydrological and climatic changes during the last 14 ka, *Holocene*, 16, 827–837, 2006.
- Belli, R., Frisia, S., Borsato, A., Drysdale R., Hellstrom, J., Zhao J.-X., and Spötl, C.: Regional climate variability and ecosystem responses to the last deglaciation in the northern hemisphere from stable isotope data and calcite fabrics in two northern Adriatic stalagmites, *Quaternary Sci. Rev.*, 72, 146–158, 2013.
- Berger, A. and Loutre, M. F.: Insolation values for the climate of the last 10 million years, *Quaternary Sci. Rev.*, 10, 297–317, 1991.
- Birks, J., Battarbee, R., Mackay, A., and Oldfield, F.: *Global Change in the Holocene*, Routledge, 544 pp., 2005.

- Birks, H. J. B., Heiri, O., Seppa, H., and Bjune, A.: Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies, *Open Ecol. J.*, 3, 68–110, 2010.
- Blanco-Gonzalez, A., Lillios, K. T., López-Sáez, J. A., and Drake, B. L.: Cultural, demographic and environmental dynamics of the Copper and Early Bronze Age in Iberia (3300–1500 BC): towards an interregional multiproxy comparison at the time of the 4.2 ka BP event, *J. World Prehist.*, 31, 1–79, 2018.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G.: A pervasive millennial-scale cycle in the North Atlantic Holocene and glacial climates, *Science*, 294, 2130–2136, 1997.
- Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E., Bettis III, E. A., Kreig, J., and Wright, D. K.: A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages, *Holocene*, 15, 321–328, 2005.
- Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Laíné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, *Clim. Past*, 3, 261–277, <https://doi.org/10.5194/cp-3-261-2007>, 2007.
- Brayshaw, D. J., Hoskins, B., and Black, E.: Some physical drivers of changes in the winter storm tracks over the North Atlantic and Mediterranean during the Holocene, *Philos. Tr. R. Soc. S.-A.*, 368, 5185–5223, 2010.
- Brewer, S., Guiot J., and Barbini, D.: Pollen methods and studies, Use of Pollen as Climate Proxies, *Encyclopedia of Quaternary Science*, 805–815, <https://doi.org/10.1016/B978-0-445-53643-3.00180-1>, 2013.
- Brisset, E., Miramont, C., Guiter, F., Anthony, E.J., Tachikawa, K., Poulenard, J., Arnaud, F., Delhon, C., Meunier, J.-D., Bard, E., and Suméra, F.: Non-reversible geosystem destabilisation at 4200 cal. BP: Sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean alpine lake, *Holocene* 23, 1863–1874, 2013.
- Cacho, I., Grimalt, J. O., Canals, M., Sbaffi, L., Shackleton, N., Schönfeld, J., and Zahn, R.: Variability of the western Mediterranean Sea surface temperature during the last 25 000 years and its connection with the Northern Hemisphere climatic changes, *Paleoceanography*, 16, 40–52, 2001.
- Carter, V. A., Shinker, J. J., and Preece, J.: Drought and vegetation change in the central Rocky Mountains and western Great Plains: potential climatic mechanisms associated with megadrought conditions at 4200 cal yr BP, *Clim. Past*, 14, 1195–1212, <https://doi.org/10.5194/cp-14-1195-2018>, 2018.
- Cartier, R., Brisset, E., Guiter, F., Sylvestre, F., Tachikawa, K., Anthony, E. J., Paillès, C., Bruneton, H., Bard, E., and Miramont, C.: Multiproxy analyses of Lake Allos reveal synchronicity and divergence in geosystem dynamics during the Lateglacial/Holocene in the Alps, *Quaternary Sci. Rev.*, 186, 60–77, 2018.
- Cartier, R., Sylvestre, F., Paillès, C., Sonzogni, C., Couapel, M., Alexandre, A., Mazur, J.-C., Brisset, E., Miramont, C., and Guiter, F.: Diatom-oxygen isotope record from high-altitude Lake Petit (2200 m a.s.l.) in the Mediterranean Alps: shedding light on a climatic pulse at 4.2 ka, *Clim. Past*, 15, 253–263, <https://doi.org/10.5194/cp-15-253-2019>, 2019.
- Cartier, R., Brisset, E., Paillès, C., Guiter, F., Sylvestre, F., Ruaudel, F., Anthony, E. J., and Miramont, C.: 5000 yr of lacustrine ecosystem changes from Lake Petit (Southern Alps, 2200 m a.s.l.): Regime shift and resilience of algal communities, *Holocene*, 25, 1231–1245, 2015.
- Castaneda, I. S., Schefuß, E., Pätzold, J., Sinnige Damsté, J. S., Weldeab, S., and Schouten, S.: Millennial-scale sea surface temperature changes in the eastern Mediterranean (Nile River Delta region) over the last 27 000 years, *Paleoceanography*, 25, PA1208, <https://doi.org/10.1029/2009PA001740>, 2010.
- Català, A., Cacho, I., Frigola, J., Pena, L. D., and Lirer, F.: Holocene hydrography evolution in the Alboran Sea: a multi-record and multiproxy comparison, *Clim. Past Discuss.*, <https://doi.org/10.5194/cp-2018-163>, in review, 2018.
- Cheng, H., Sinha, A., Verheyden, S., Nader, F. H., Li, X. L., Zhang, P. A., Yin, J. J., Yi, L., Peng, Y. B., Rao, Z. G., Ning, Y. F., and Edwards, R. L.: The climate variability in northern Levant over the past 20,000 years, *Geophys. Res. Lett.*, 42, 8641–8650, 2015.
- Cisneros, M., Cacho, I., Frigola, J., Canals, M., Masqué, P., Martrat, B., Casado, M., Grimalt, J. O., Pena, L. D., Margaritelli, G., and Lirer, F.: Sea surface temperature variability in the central-western Mediterranean Sea during the last 2700 years: a multi-proxy and multi-record approach, *Clim. Past*, 12, 849–869, <https://doi.org/10.5194/cp-12-849-2016>, 2016.
- Constantin, S., Bojar, A.-V., Lauritzen, S.-E., and Lundberg, J.: Holocene and Late Pleistocene climate in the sub-Mediterranean continental environment: A speleothem record from Poleva Cave (Southern Carpathians, Romania), *Palaeogeogr. Palaeocl.*, 243, 322–338, 2007.
- Conte, M., Giuffrida, S., and Tedesco, S.: The Mediterranean Oscillation: Impact on Precipitation and Hydrology in Italy, Conference on Climate and Water Academy of Finland, 121–137, 1989.
- Craig, H. and Gordon, L. I.: Deuterium and oxygen 18 variations in the ocean and marine atmosphere, in: Proc. Stable Isotopes in Oceanographic Studies and Paleotemperatures, edited by: Tongiogi, E., V. Lischi & F. Pisa, 9–130, 1965.
- Cullen, H. M., deMenocal, P., Hemming, S., Hemming, G., Brown, F. H., Guilderson, T., and Sirocko, F.: Climate change and the collapse of the Akkadian empire: Evidence from the deep sea, *Geology*, 28, 379–382, 2000.
- Dansgaard, W., Johnsen S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdóttir, A. E., Jouzel, J., and Bond G.: Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature*, 364, 218–222, 1993.
- Dean, J. R., Jones, M. D., Leng, M. J., Noble, S. R., Metcalfe, S. E., Sloane, H. J., Sahy, D., Warren, J., Eastwood, W. J., and Roberts, N.: Eastern Mediterranean hydroclimate over the late glacial and Holocene, reconstructed from the sediments of Nar lake, central Turkey, using stable isotopes and carbonate mineralogy, *Quaternary Sci. Rev.*, 124, 162–174, 2015.
- Deininger, M., McDermott, F., Mudelsee, M., Werner, M., Frank, N., and Mangini, A.: Coherency of late Holocene European speleothem  $\delta^{18}\text{O}$  records linked to North Atlantic Ocean circulation, *Clim. Dynam.*, 49, 595–618, 2017.

- Denton, G. H. and Karlén, W.: Holocene climatic variations – Their pattern and possible cause, *Quaternary Res.*, 3, 155–205, 1973.
- Dermody, B. J., de Boer, H. J., Bierkens, M. F. P., Weber, S. L., Wassen, M. J., and Dekker, S. C.: A seesaw in Mediterranean precipitation during the Roman Period linked to millennial-scale changes in the North Atlantic, *Clim. Past*, 8, 637–651, <https://doi.org/10.5194/cp-8-637-2012>, 2012.
- Develle, A.-L., Herreros, J., Vidal, L., Sursock, A., and Gasse, F.: Controlling factors on a paleo-lake oxygen isotope record (Yamouné, Lebanon) since the Last Glacial Maximum, *Quaternary Sci. Rev.*, 29, 865–886, 2010.
- Di Rita, F. and Magri, D.: Holocene drought, deforestation and evergreen vegetation development in the central Mediterranean: a 5500 year record from Lago Alimini Piccolo, Apulia, southeast Italy, *Holocene*, 19, 295–306, 2009.
- Di Rita, F., Lirer, F., Bonomo, S., Cascella, A., Ferraro, L., Florindo, F., Insinga, D. D., Lurcock, P. C., Margaritelli, G., Petrosino, P., Rettori, R., Vallefuoco, M., and Magri, D.: Late Holocene forest dynamics in the Gulf of Gaeta (central Mediterranean) in relation to NAO variability and human impact, *Quaternary Sci. Rev.*, 179, 137–152, 2018a.
- Di Rita, F., Fletcher, W. J., Aranbarri, J., Margaritelli, G., Lirer, F., and Magri, D.: Holocene forest dynamics in central and western Mediterranean: periodicity, spatio-temporal patterns and climate influence, *Sci. Rep.*, 8, 8929, <https://doi.org/10.1038/s41598-018-27056-2>, 2018b.
- Dixit, Y., Hodell, D. A., and Petrie, C. A.: Abrupt weakening of the summer monsoon in northwest India 4100 yr ago, *Geology*, 42, 339–342, 2014.
- Dominguez-Villar, D., Wang, X., Krklec, K., Cheng, H., and Edwards, R. L.: The control of the tropical North Atlantic on Holocene millennial climate oscillations, *Geology*, 45, 303–306, 2017.
- Dormoy, I., Peyron, O., Combourieu Nebout, N., Goring, S., Kotthoff, U., Magny, M., and Pross, J.: Terrestrial climate variability and seasonality changes in the Mediterranean region between 15 000 and 4000 years BP deduced from marine pollen records, *Clim. Past*, 5, 615–632, <https://doi.org/10.5194/cp-5-615-2009>, 2009.
- D'Ortenzio, F. and Ribera d'Alcalà, M.: On the trophic regimes of the Mediterranean Sea: a satellite analysis, *Biogeosciences*, 6, 139–148, <https://doi.org/10.5194/bg-6-139-2009>, 2009.
- Drăgușin, V., Staubwasser, M., Hoffmann, D. L., Ersek, V., Onac, B. P., and Veres, D.: Constraining Holocene hydrological changes in the Carpathian–Balkan region using speleothem  $\delta^{18}\text{O}$  and pollen-based temperature reconstructions, *Clim. Past*, 10, 1363–1380, <https://doi.org/10.5194/cp-10-1363-2014>, 2014.
- Drescher-Schneider, R., De Beaulieu, J. L., Magny, M., Walter-Simonnet, A. V., Bossuet, G., Millet, L., and Drescher, A.: Vegetation history, climate and human impact over the last 15,000 years at Lago dell'Accesa (Tuscany, Central Italy), *Veget. Hist. Archaeob.*, 16, 279–299, 2007.
- Drysdale, R. N., Zanchetta, G., Hellstrom, J. C., Maas, R., Fallick, A. E., Pickett, M., Cartwright, I., and Piccini, L.: Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone, *Geology*, 34, 101–104, 2006.
- Duplessy, J. C., Bard, E., Arnold, M., Shackleton, N. J., Duprat, J., and Labeyrie, L. D.: How fast did the ocean-atmosphere system run during the last deglaciation?, *Earth Planet. Sc. Lett.*, 103, 41–54, 1991.
- Eastwood, W. J., Leng, M. J., Roberts, N., and Davis, B.: Holocene climate change in the eastern Mediterranean region: a comparison of stable isotope and pollen data from Lake Gölhısar, Southwest Turkey, *J. Quat. Sci.*, 22, 327–341, 2007.
- Emeis, K.-C., Struck, U., Schulz, H.-M., Bernasconi, S., Sakamoto, T., and Martinez-Ruiz, F.: Temperature and salinity of Mediterranean Sea surface waters over the last 16 000 years: constraints on the physical environment of S1 sapropel formation based on stable oxygen isotopes and alkenone unsaturation ratios, *Palaeogeogr. Palaeocol.*, 158, 259–280, 2000.
- Emile-Geay, J., McKay, N. P., Kaufman, D. S., Von Gunten, L., Wang, J., Anchukaitis, K. J., and Henley, B. J.: A global multi-proxy database for temperature reconstructions of the Common Era, *Sci. Data*, 4, 170088, <https://doi.org/10.1038/sdata.2017.88>, 2017.
- England, A., Eastwood, C. N., Roberts, C. N., Tuner, R., and Haddon, J. F.: Historical landscape change in Cappadocia (central Turkey): a palaeoecological investigation of annually laminated sediments from Nar lake, *Holocene*, 18, 1229–1245, 2008.
- Eshel, G.: Mediterranean climates, *Israel J. Earth Sci.*, 51, 157–168, 2002.
- Fairchild, I. J. and Treble, P.: Trace elements in speleothems as recorders of environmental change, *Quaternary Sci. Rev.*, 28, 449–468, 2009.
- Field, R. D.: Observed and modeled controls on precipitation  $\delta^{18}\text{O}$  over Europe: From local temperature to the Northern Annular Mode, *J. Geophys. Res.*, 115, D12101, <https://doi.org/10.1029/2009JD013370>, 2010.
- Finné, M., Holmgren, K., Sundqvist, H. S., Weiberg, E., and Lindblom, M.: Climate in the eastern Mediterranean, and adjacent regions, during the past 6000 years – a review, *J. Archaeol. Sci.*, 38, 3153–3173, 2011.
- Finné, M., Holmgren, K., Shen, C. C., Hu, H.-M., Boyd, M., and Stocker, S.: Late Bronze Age climate change and description of the Mycenaean Palace of Nestor at Pylos, *PLoS ONE*, 12, e0189447, <https://doi.org/10.1371/journal.pone.0189447>, 2017.
- Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter A.: Holocene Forcing of the Indian Monsoon Recorded in a Stalagmite from Southern Oman, *Science*, 300, 1737–1739, 2003.
- Fohlmeister, J., Schröder-Ritzrau, A., Scholz, D., Spötl, C., Riechelmann, D. F. C., Mudelsee, M., Wackerbarth, A., Gerdes, A., Riechelmann, S., Immenhauser, A., Richter, D. K., and Mangini, A.: Bunker Cave stalagmites: an archive for central European Holocene climate variability, *Clim. Past*, 8, 1751–1764, <https://doi.org/10.5194/cp-8-1751-2012>, 2012.
- Francke, A., Wagner, B., Leng, M. J., and Rethemeyer, J.: A Late Glacial to Holocene record of environmental change from Lake Dojran (Macedonia, Greece), *Clim. Past*, 9, 481–498, <https://doi.org/10.5194/cp-9-481-2013>, 2013.
- Frigola, J., Moreno, A., Cacho, I., Sierra, F. J., Flores, J. A., Grimalt, J. O., Hodell, D. A., and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a deepwater sediment record, *Paleoceanography*, 22, PA2209, <https://doi.org/10.1029/2006PA001307>, 2007.

- Frisia, S., Borsato, A., Spötl, C., Villa, I. M., and Cucchi, F.: Climate variability in the SE Alps of Italy over the past 17000 years reconstructed from a stalagmite record, *Boreas*, 34, 445–455, 2005.
- Frisia, S., Borsato, A., Mangini, A., Spötl, C., and Madonna, G.: Holocene climate variability from a discontinuous stalagmite record and the Mesolithic to Neolithic transition, *Quaternary Res.*, 66, 388–400, 2006.
- Frogley, M. R., Griffiths, H. I., and Heaton, T. H. E.: Historical biogeography and Late Quaternary environmental change of Lake Pamvotis, Ioannina (north-western Greece): evidence from ostracods, *J. Biogeogr.*, 28, 745–756, 2001.
- Fyfe, R. M., Woodbridge, J. E., and Roberts, N.: From forest to farmland: pollen-inferred land coverchange across Europe using the pseudobiomization approach, *Global Change Biol.*, 21, 1197–1212, 2015.
- Fyfe, R. M., Woodbridge, J., and Roberts, C. N.: Trajectories of change in Mediterranean Holocene vegetation through classification of pollen data, *Veg. Hist. Archaeobot.*, 27, 351–364, 2018.
- Gaetani, M., Pohl, B., Douville, H., and Fontaine, B.: West African Monsoon influence on the summer Euro-Atlantic circulation, *Geophys. Res. Lett.*, 38, L09705, <https://doi.org/10.1029/2011GL047150>, 2011.
- Gambin, B., Andrieu-Ponel, V., Médail, F., Marriner, N., Peyron, O., Montade, V., Gambin, T., Morhange, C., Belkacem, D., and Djamel, M.: 7300 years of vegetation history and climate for NW Malta: a Holocene perspective, *Clim. Past*, 12, 273–297, <https://doi.org/10.5194/cp-12-273-2016>, 2016.
- Genty, D., Blamart, D., Ghaleb, B., Plagnes, V., Caussed, Ch., Bakalowicz, M., Zouarif, K., Chkir, N., Hellstrom, J. C., K. Wainer, K., and Bourges, F.: 2006 Timing and dynamics of the last deglaciation from European and North African  $\delta^{13}\text{C}$  stalagmite profiles comparison with Chinese and South Hemisphere stalagmites, *Quaternary Sci. Rev.*, 25, 2118–2142, 2006.
- Giunta, S., Emeis, K. C., and Negri, A.: Sea-surface temperature reconstruction of the last 16 000 years in the Eastern Mediterranean Sea, *Riv. It. Paleont. Stratigr.*, 107, 463–476, 2001.
- Göktürk, O. M., Fleitmann, D., Badertscher, S., Cheng, H., Edwards, R. L., Leuenberger, M., Fankhauser, A., Tüysüz, O., and Kramers, J.: Climate on the southern Black Sea coast during the Holocene: implications from the Sofular Cave record, *Quaternary Sci. Rev.*, 30, 2433–2445, 2011.
- Guiot, J.: Methodology of the last climatic cycle reconstruction in France from pollen data, *Palaeogeogr. Palaeocl.*, 80, 49–69, 1990.
- Hellstrom, J. C.: U-Th dating of speleothems with high initial  $^{230}\text{Th}$  using stratigraphical constraint, *Quat. Geochronol.*, 1, 289–295, 2006.
- Holmes, J., Arrowsmith, C., Austin, W., Boyle, J., Fisher, E., Holme, R., Marshall, J., Oldfield, F., and van der Post, K.: Climate and atmospheric circulation changes over the past 1000 years reconstructed from oxygen isotopes in lake-sediment carbonate from Ireland, *The Holocene*, 20, 1105–1111, 2010.
- Isola, I., Zanchetta, G., Drysdale, R. N., Regattieri, E., Bini, M., Bajo, P., Hellstrom, J. C., Baneschi, I., Lionello, P., Woodhead, J., and Greig, A.: The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apennine Alps, central Italy), *Clim. Past*, 15, 135–151, <https://doi.org/10.5194/cp-15-135-2019>, 2019.
- Jalali, B., Sicre, M.-A., Bassetti, M.-A., and Kallel, N.: Holocene climate variability in the North-Western Mediterranean Sea (Gulf of Lions), *Clim. Past*, 12, 91–101, <https://doi.org/10.5194/cp-12-91-2016>, 2016.
- Jalali, B., Sicre, M. A., Kallel, N., Azuara, J., Combourieu-Nebout, N., Bassetti, M. A., and Klein, V.: High-resolution Holocene climate and hydrological variability from two major Mediterranean deltas (Nile and Rhone), *Holocene*, 27, 1158–1168, 2017.
- Jalali, B., Sicre, M. A., Klein, V., Schmidt, S., Maselli, V., Lirer, F., and Petrosino, P.: Deltaic and coastal sediments as recorders of Mediterranean regional climate and human impact over the past three millennia, *Paleoceanogr. Paleoc.*, 33, 579–593, <https://doi.org/10.1029/2017PA003298>, 2018.
- Jiménez-Amat, P. and Zahn, R.: Offset timing of climate oscillations during the last two glacial-interglacial transitions connected with large-scale freshwater perturbation, *Paleoceanography*, 30, 768–788, 2015.
- Jones, M. D., Leng, M. J., Eastwood, W. J., Keen, D. H., and Turney, C. S. M.: Interpreting stable isotope records from freshwater snail shell carbonate: a Holocene case study from Lake Göllhisar, Turkey, *Holocene*, 12, 629–634, 2002.
- Kaniewski, D., Van Campo, E., Morhange, C., Guiot, J., Zviely, D., Shaked, I., Otto, T., and Artzy, M.: Early urban impact on Mediterranean coastal environments, *Sci. Rep.*, 3, 3540, <https://doi.org/10.1038/srep03540>, 2013.
- Kaniewski, D., Marriner, N., Morhange, C., Faivre, S., Otto, T., and Van Campo, E.: Solar pacing of storm surges, coastal flooding and agricultural losses in the Central Mediterranean, *Sci. Rep.*, 6, 25197, <https://doi.org/10.1038/srep25197>, 2016.
- Kaniewski, D., Marriner, N., Cheddadi, R., Guiot, J., and Van Campo, E.: The 4.2 ka BP event in the Levant, *Clim. Past*, 14, 1529–1542, <https://doi.org/10.5194/cp-14-1529-2018>, 2018.
- Lacey, J. H., Francke, A., Leng, M. J., Vane, G. H., and Wagner, B.: A high-resolution Late Glacial to Holocene record of environmental change in the Mediterranean from Lake Ohrid (Macedonia/Albania), *Int. J. Earth Sci.*, 104, 1623–1638, 2015.
- Lacey, J. H., Leng, M. J., Francke, A., Sloane, H. J., Milodowski, A., Vogel, H., Baumgarten, H., Zanchetta, G., and Wagner, B.: Northern Mediterranean climate since the Middle Pleistocene: a 637 ka stable isotope record from Lake Ohrid (Albania/Macedonia), *Biogeosciences*, 13, 1801–1820, <https://doi.org/10.5194/bg-13-1801-2016>, 2016.
- Lachniet, M. S.: Climatic and environmental controls on speleothem oxygen-isotope values, *Quaternary Sci. Rev.*, 28, 412–432, 2009.
- Leng, M. J. and Marshall, J. D.: Palaeoclimate interpretation of stable isotope data from lake sediment archives, *Quaternary Sci. Rev.*, 23, 811–831, 2004.
- Leng, M. J., Baneschi, I., Zanchetta, G., Jex, C. N., Wagner, B., and Vogel, H.: Late Quaternary palaeoenvironmental reconstruction from Lakes Ohrid and Prespa (Macedonia/Albania border) using stable isotopes, *Biogeosciences*, 7, 3109–3122, <https://doi.org/10.5194/bg-7-3109-2010>, 2010a.
- Leng, M. J., Jones, M. D., Frogley, M. R., Eastwood, W. J., Kendrick, C. P., and Roberts, C. N.: Detrital carbonate influences on bulk oxygen and carbon isotope composition of lacustrine sediments from the Mediterranean, *Global Planet. Change*, 71, 175–182, 2010b.

- Leng, M. J., Wagner, B., Boehm, A., Panagiotopoulos, K., Vane, C. H., Snelling, A., Haidon, C., Woodley, E., Vogel, H., Zanchetta, G., and Baneschi, I.: Understanding past climatic and hydrological variability in the Mediterranean from Lake Prespa sediment isotope and geochemical record over the Last Glacial cycle, *Quaternary Sci. Rev.*, 66, 123–136, 2013.
- Le Roy, M., Deline, P., Carcaillet, J., Schimmelpfennig, I., Ermini, M., and ASTER Team:  $^{10}\text{Be}$  exposure dating of the timing of Neoglacial glacier advances in the Ecrins-Pelvoux massif, southern French Alps, *Quaternary Sci. Rev.*, 178, 118–138, 2017.
- Lillios, K. T., Blanco González, A., Drake, B. L., and López-Sáez, J.A.: Mid-Late Holocene climate, demography, and cultural dynamics in Iberia: a multi-proxy approach, *Quaternary Sci. Rev.*, 135, 138–153, 2016.
- Lionello, P., Malanotte-Rizzoli, P., and Boscolo, R.: The Mediterranean Climate: An Overview of the Main Characteristics and Issues, Elsevier, the Netherlands, 2006.
- Longman, J., Veres, D., Ersek, V., Salzmann, U., Hubay, K., Bornmann, M., Wennrich, V., and Schäbitz, F.: Periodic input of dust over the Eastern Carpathians during the Holocene linked with Saharan desertification and human impact, *Clim. Past*, 13, 897–917, <https://doi.org/10.5194/cp-13-897-2017>, 2017.
- López-Moreno, J. I., Vicente-Serrano, S. M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., and Beniston M.: Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: Observed relationships and projections for the 21st century, *Global Planet. Change*, 77, 62–76, 2011.
- Lowe, J. J., Blockley, S., Trincardi, F., Ascoli, A., Cattaneo, A., Matthews, I. P., Pollard, M., and Wulf, S.: Age modelling of late Quaternary marine sequences in the Adriatic: towards improved precision and accuracy using volcanic event stratigraphy, *Cont. Shelf Res.*, 27, 560–582, 2007.
- Magny, M., de Beaulieu, J. L., Drescher-Schneider, R., Vannière, B., Walter-Simonnet, A. V., Miras, Y., Millet, L., Bossuet, G., Peyron, O., Brugia paglia, E., and Leroux, A.: Holocene climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake Accesa (Tuscany, Italy), *Quaternary Sci. Rev.*, 26, 1736–1758, 2007.
- Magny, M., Vanniere, B., Zanchetta, G., Fouache, E., Touchias, G., Petrika, L., Coussot, C., Walter-Simonnet, A.-V., and Arnoud, F.: Possible complexity of the climatic event around 4300–3800 cal. BP in the central and western Mediterranean, *Holocene*, 19, 1–11, 2009.
- Magny, M., Vannière, B., Calo, C., Millet, L., Leroux, A., Peyron, O., Zanchetta, G., La Mantia, T., and Tinner, W.: Holocene hydrological changes in south-western Mediterranean as recorded by lake-level fluctuations at Lago Preola, a coastal lake in southern Sicily, Italy, *Quaternary Sci. Rev.*, 30, 2459–2475, 2011.
- Magri, D. and Parra I.: Late Quaternary western Mediterranean pollen records and African winds, *Earth Planet. Sc. Lett.*, 200, 401–408, 2002.
- Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A.: A Reconstruction of Regional and Global Temperature for the Past 11,300 Years, *Science*, 339, 1198–2001, 2013.
- Margaritelli, G., Vallefouoco, M., Di Rita, F., Capotondi, L., Belucci, L. G., Insinga, D. D., Petrosino, P., Bonomo, S., Cacho, I., Cascella, A., Ferraro, L., Florindo, F., Lubritto, C., Lubritto C., Lurcock, P. C., Magri, D., Pelosi, N., Rettori, R., and Lirer, F.: Marine response to climate changes during the last five millennia in the central Mediterranean Sea, *Global Planet. Change* 142, 53–72, 2016.
- Marks, L., Salem, A., Welc, F., Nitychoruk, J., Chen, Z., Blaauw, M., Zalat, A., Majecka, A., Szymanki, M., Chodyka, M., Toloczek-Pasek, A., Sun, Q., Zhao, X., and Jiang, J.: Holocene lake sediments from the Fayum Oasis in Egypt: a record of environmental and climate change, *Boreas*, 47, 62–79, 2018.
- Marriner, N., Flaux, C., Kaniewski, D., Morhange, C., Leduc, G., Moron, V., Chen, Z., Empereur, J.-Y., and Stanley, J.-D.: ITCZ and ENSO-like pacing of Nile delta hydro-geomorphology during the Holocene, *Quaternary Sci. Rev.*, 45, 73–84, 2012.
- Marriner, N., Kaniewski, D., Morhange, C., Flaux, F., Giaime, M., Vacchi, M., and Goff, J.: Tsunamis in the geological record: making waves with a cautionary tale from the Mediterranean, *Sci. Adv.*, 3, e1700485, <https://doi.org/10.1126/sciadv.1700485>, 2017.
- Marsicek, J., Shuman, B. N., Bartlein, P. J., Shafer, S., and Brewer, S.: Reconciling divergent trends and millennial variations in Holocene temperatures, *Nature*, 554, 92–96, 2018.
- Martrat, B., Jimenez-Amat, P., Zahn, R., and Grimalt, J.-O.: Similarities and dissimilarities between the last two deglaciations and interglaciations in the North Atlantic region, *Quaternary Sci. Rev.*, 99, 122–134, 2014.
- Mauri, A., Davis, B. A. S., Collins, P. M., and Kaplan, J. O.: The influence of atmospheric circulation on the mid-Holocene climate of Europe: a data–model comparison, *Clim. Past*, 10, 1925–1938, <https://doi.org/10.5194/cp-10-1925-2014>, 2014.
- Mauri, A., Davis, B., Collins, P. M., and Kaplan, J.: The climate of Europe during the Holocene: A gridded pollen-based reconstruction and its multi-proxy evaluation, *Quaternary Sci. Rev.*, 112, 109–127, 2015.
- Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlen, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubbawer, M., Schneider, R. R., and Steig, E. J.: Holocene climate variability, *Quaternary Res.*, 62, 243–255, 2004.
- McDermott, F., Frisia, S., Huang, Y., Longinelli, A., Spiro, B., Heaton, T. H. E., Hawkesworth, C. J., Borsato, A., Keppens, E., Fairchild, I. J., van der Borg, K., Verheyden, S., and Selmo, E. M.: Holocene climate variability in Europe: evidence from  $\delta^{18}\text{O}$ , textural and extension-rate variations in three speleothems, *Quaternary Sci. Rev.*, 18, 1021–1038, 1999.
- McDermott, F., Atkinson, T. C., Fairchild, I. J., Baldini, L. M., and Matthey, D. P.: A first evaluation of the spatial gradients in  $\delta^{18}\text{O}$  recorded by European Holocene speleothems, *Global Planet. Change*, 79, 275–287, 2011.
- Mercuri, A.M., Accorsi, C.A., and Mazzanti, M.B.: The long history of Cannabis and its cultivation by the Romans in central Italy, shown by pollen records from Lago Albano and Lago di Nemi, *Veget. Hist. Archaeob.*, 11, 263–276, 2002.
- Mercuri, A. M., Mazzanti, M. B., Torri, P., Vigliotti, L., Bosi, G., Florenzano, A., and N'siala, I.M.: A marine/terrestrial integration for mid-late Holocene vegetation history and the development of the cultural landscape in the Po valley as a result of human impact and climate change. *Veg. Hist. Archaeob.*, 21(4–5), 353–372, 2012.
- Moreno, A., Pérez, A., Frigola, J., Nieto-Moreno, V., Rodríguez-Gámiz, M., Martrat, B., and Belmonte, Á: The Medieval Climate

- Anomaly in the Iberian Peninsula reconstructed from marine and lake records, *Quaternary Sci. Rev.*, 43, 16–32, 2012.
- Moreno, A., Svensson, A., Brooks, S., Engels, S., Fletcher, W., Genty, D., Heiri, I., Labuhn, O., Persoioi, A., Sadori, L., Valero-Garcés, B., Wulf, S., Zanchetta, G., and data contributors: A compilation of Western European terrestrial records 60–8 ka BP: towards an understanding of latitudinal climatic gradients, *Quaternary Sci. Rev.*, 106, 167–185, 2014.
- Moreno, A., Pérez-Mejías, C., Bartolomé, C., Cacho, I., Stoll, H., Delgado-Huertas, A., Hellstrom, J., Edwards, R. L., and Cheng, H.: New speleothem data from Molinos and Ejulve caves reveal Holocene hydrological variability in northeast Iberia, *Quaternary Res.*, 88, 223–233, 2017.
- Mühlinghaus, C., Scholz, D., and Mangini, A.: Modelling fractionation of stable isotopes in stalagmites, *Geochim. Cosmochim. Ac.*, 73, 7275–7289, 2009.
- Muñoz, A., Bartolomé, M., Muñoz, A., Sancho, C., Moreno, A., Hellstrom, J. C., Osàcar, M. C., and Chaco, I.: Solar influence and hydrological variability during the Holocene from a speleothem annual record (Molinos Cave, NE Spain), *Terra Nova*, 27, 300–311, 2015.
- Nagashima, K., Tada, R., Tani, A., Sun, Y., Isozaki, Y., Toyoda, S., and Hasegawa, H.: Millennial-scale oscillations of the westerly jet path during the last glacial period, *J. Asian Earth Sci.*, 40, 1214–1220, 2011.
- Nieto-Moreno, V., Martínez-Ruiz, F., Willmott, V., García-Orellana, J., Masqué, P., and Damsté, J. S.: Climate conditions in the westernmost Mediterranean over the last two millennia: An integrated biomarker approach, *Org. Geochem.*, 55, 1–10, 2013.
- Olsen, J., Anderson, N. J., and Knudsen, M. F.: Variability of the North Atlantic Oscillation over the past 5200 years, *Nat. Geosci.*, 5, 808–812, 2012.
- Persoioi, A., Onac, B. P., Wynn, J. G., Blaauw, M., Ionita, M., and Hansson, M.: Holocene winter climate variability in Central and Eastern Europe, *Sci. Rep.*, 7, 1196, <https://doi.org/10.1038/s41598-017-01397-w>, 2017.
- Persoioi, A., Ionita, M., and Weiss, H.: Blocking induced by the strengthened Siberian High led to drying in west Asia during the 4.2 ka BP event – a hypothesis, *Clim. Past Discuss.*, <https://doi.org/10.5194/cp-2018-161>, in review, 2018.
- Peyron, O., Goring, S., Dormoy, I., Kotthoff, U., Pross, J., de Bealieu, J. L., Drescher-Schneider, R., and Magny, M.: Holocene seasonality changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece), *Holocene*, 21, 131–146, 2011.
- Peyron, O., Magny, M., Goring, S., Joannin, S., de Beaulieu, J.-L., Brugiapaglia, E., Sadori, L., Garfi, G., Kouli, K., Ioakim, C., and Combourieu-Nebout, N.: Contrasting patterns of climatic changes during the Holocene across the Italian Peninsula reconstructed from pollen data, *Clim. Past*, 9, 1233–1252, <https://doi.org/10.5194/cp-9-1233-2013>, 2013.
- Peyron, O., Combourieu-Nebout, N., Brayshaw, D., Goring, S., Andrieu-Ponel, V., Desprat, S., Fletcher, W., Gambin, B., Ioakim, C., Joannin, S., Kotthoff, U., Kouli, K., Montade, V., Pross, J., Sadori, L., and Magny, M.: Precipitation changes in the Mediterranean basin during the Holocene from terrestrial and marine pollen records: a model–data comparison, *Clim. Past*, 13, 249–265, <https://doi.org/10.5194/cp-13-249-2017>, 2017.
- Piccini, L., Zanchetta, G., Drysdale, R. N., Hellstrom, J., Isola, I., Fallick, A. E., Leone, G., Doveri, M., Mussi, M., Mantelli, F., Molli, G., Lotti, L., Roncioni, A., Regattieri, E., Meccheri, M., and Vaselli, L.: The environmental features of the Monte Carchia cave system (Apuan Alps, central Italy) and their effects on speleothems growths, *Int. J. Speleol.*, 37, 153–173, 2008.
- Psomiadis, D., Dotsika, E., Albanakisa, K., Ghaleb, B., and Hillaire-Marcel, C.: Speleothem record of climatic changes in the northern Aegean region (Greece) from the Bronze Age to the collapse of the Roman Empire, *Palaeogeogr. Palaeocl.*, 489, 272–283, 2018.
- Railsback, L. B., Liang, F., Brook, G. A., Riavo, N., Voarintsoa, G., Sletten, H. R., Marais, E., Hardt, B., Cheng, H., and Edwards, R. L.: 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, *Quaternary Sci. Rev.*, 186, 78–90, 2018.
- Regattieri, E., Zanchetta, G., Drysdale, R. N., Isola, I., Hellstrom, J. C., and Dallai, L.: Lateglacial to Holocene trace element record (Ba, Mg, Sr) from Carchia Cave (Apuan Alps, central Italy): paleoenvironmental implications, *J. Quat. Sci.*, 29, 381–392, 2014.
- Richards, D. A. and Dorale, J. A.: Uranium-series chronology and environmental applications of speleothems, *Rev. Mineral. Geochem.*, 52, 407–460, 2003.
- Roberts, N., Reed, J., Leng, M. J., Kuzucuoğlu, C., Fontugne, M., Bertaix, J., Woltring, H., Bottema, S., Black, S., Hunt, E., and Karabiyikoğlu, M.: The tempo of Holocene climatic change in the eastern Mediterranean region: new high-resolution crater-lake sediment data from central Turkey, *Holocene*, 11, 721–736, 2001.
- Roberts, N., Stevenson, A. C., Davis, B., Cheddadi, R., Brewer, S., Rosen, A. M., Battarbee, R. W., Gasse, F., and Stickley, C. E.: Holocene climate, environment and cultural change in the circum-Mediterranean region, in: *Past climate variability through Europe and Africa*, Battarbee, R. W., Gasse, F., and Stickley, C. E., Kluwer, Dordrecht, 343–362, 2004.
- Roberts, N., Jones, M. D., Benkaddur, A., Eastwood, W. J., Filippi, M. L., Frogley, M. R., Lamb, H. F., Leng, M. J., Reed, J. M., Stein, M., Stevens, L., Valero-Garcè, B., and Zanchetta G.: Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis, *Quaternary Sci. Rev.*, 27, 2426–2441, 2008.
- Roberts, N., Zanchetta, G., and Jones, M. D.: Oxygen isotopes as tracers of Mediterranean climate variability: an introduction, *Global Planet. Change*, 71, 135–140, 2010.
- Roberts, N., Moreno, A., Valero-Garcés, B. L., Corella, J. P., Jones, M., Allcock, S., Woodbridge, J., Morellón, M., Luterbacher, J., Xoplaki, E., and Türkes, M.: Palaeolimnological evidence for an east–west climate see-saw in the Mediterranean since AD 900, *Global Planet. Change*, 84–85, 23–34, 2012.
- Roland, T. P., Caseldine, C. J., Charman, D. J., Turney, C. S. M., and Amesbury, M. J.: Was there a “4.2 ka event” in Great Britain and Ireland? Evidence from the peatland record, *Quaternary Sci. Rev.*, 83, 11–27, 2014.
- Ruan, J., Kherbouche, F., Genty, D., Blamart, D., Cheng, H., Dewilde, F., Hachi, S., Edwards, R. L., Régnier, E., and Michalot, J.-L.: Evidence of a prolonged drought ca. 4200 yr BP correlated with prehistoric settlement abandonment from the Guel-

- daman GLD1 Cave, Northern Algeria, *Clim. Past*, 12, 1–14, <https://doi.org/10.5194/cp-12-1-2016>, 2016.
- Sabatier, P., Dezileau, L., Colin, C., Briquet, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O., and Von Grafenstein, U.: 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events, *Quaternary Res.*, 77, 1–11, 2012.
- Sadori, L., Ortú, E., Peyron, O., Zanchetta, G., Vannière, B., Desmet, M., and Magny, M.: The last 7 millennia of vegetation and climate changes at Lago di Pergusa (central Sicily, Italy), *Clim. Past*, 9, 1969–1984, <https://doi.org/10.5194/cp-9-1969-2013>, 2013.
- Sadori, L., Giardini, M., Gliozzi, E., Mazzini, I., Sulpizio, R., van Welden, A., and Zanchetta, G.: Vegetation, climate and environmental history of the last 4500 years at lake Shkodra (Albania/Montenegro), *Holocene*, 25, 435–444, 2015.
- Sadori, L.: The Lateglacial and Holocene vegetation and climate history of Lago di Mezzano (central Italy), *Quaternary Sci. Rev.*, 202, 30–44, <https://doi.org/10.1016/j.quascirev.2018.09.004>, 2018.
- Samartin, S., Heiri, O., Joos, F., Renssen, H., Franke, J., Brönnemann, S., and Tinner, W.: Warm Mediterranean mid-Holocene summers inferred from fossil midge assemblages, *Nat. Geosci.*, 10, 207–212, 2017.
- Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., and Mangini, A.: Holocene climate variability in north-eastern Italy: potential influence of the NAO and solar activity recorded by speleothem data, *Clim. Past*, 8, 1367–1383, <https://doi.org/10.5194/cp-8-1367-2012>, 2012.
- Seppä, H., Bjune, A. E., Telford, R. J., Birks, H. J. B., and Veski, S.: Last nine-thousand years of temperature variability in Northern Europe, *Clim. Past*, 5, 523–535, <https://doi.org/10.5194/cp-5-523-2009>, 2009.
- Sharifi, A., Pourmand, A., Canuel, E. A., Ferer-Tyler, E., Peterson, L. C., Aichner, B., Feakins, S. J., Daryaei, T., Djamali, M., Beni, A. N., Lahijani, H. A. K., and Swart, P. K.: 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?, *Quaternary Sci. Rev.*, 123, 215–230, 2015.
- Sharifi, A., Murphy, L. N., Pourmand, A., Clement, A. C., Canuel, E. A., Beni, A. N., Lahijani, H. A. K., Delanghe, D., and Ahmady-Birgani, H.: Early-Holocene greening of the Afro-Asian dust belt changed sources of mineral dust in West Asia, *Earth Planet. Sc. Lett.*, 481, 30–40, 2018.
- Siani, G., Paterne, M., Michel, E., Sulpizio, R., Sbrana, A., Arnold, M., and Haddas, G.: Mediterranean Sea surface radiocarbon reservoir age changes since the Last Glacial Maximum, *Science*, 294, 1917–1920, 2001.
- Siani, G., Magny, M., Paterne, M., Debret, M., and Fontugne, M.: Paleohydrology reconstruction and Holocene climate variability in the South Adriatic Sea, *Clim. Past*, 9, 499–515, <https://doi.org/10.5194/cp-9-499-2013>, 2013.
- Sicre, M. A., Jalali, B., Martrat, B., Schmidt, S., Bassetti, M. A., and Kallel, N.: Sea surface temperature variability in the North Western Mediterranean Sea (Gulf of Lion) during the Common Era, *Earth Planet. Sc. Lett.*, 456, 124–133, 2016.
- Smith, A. C., Wynn, P. M., Barker, P. A., Leng, M. J., Stephen, R., Noble, S. R., and Tych, W.: North Atlantic forcing of moisture delivery to Europe throughout the Holocene, *Sci. Rep.*, 6, 24745, <https://doi.org/10.1038/srep24745>, 2016.
- Stevens, L. R., Wright Jr., H. E., and Ito, E.: Proposed changes in seasonality of climate during the late-glacial and Holocene at Lake Zeribar, Iran, *Holocene*, 11, 747–756, 2001.
- Stevens, L. R., Ito, E., Schwalb, A., and Wright Jr., H. E.: Timing of atmospheric precipitation in the Zagros Mountains inferred from a multi-proxy record from Lake Mirabad, Iran, *Quaternary Res.*, 66, 494–500, 2006.
- Stiller, M. and Hutchinson, G. E.: The Waters of Merom: a study of Lake Huleh VI, Stable isotope composition of carbonates of a 54 m core: paleoclimatic and paleotrophic implications, *Arc. Hydrobiol.*, 89, 275–302, 1980.
- Stoll, H. M., Moreno, A., Mendez-Vicente, A., Gonzalez-Lemos, S., Jimenez-Sanchez, M., Dominguez-Cuesta, M. J., Edwards, R. L., Cheng, H., and Wang, X.: Paleoclimate and growth rates of speleothems in the northwestern Iberian Peninsula over the last two glacial cycles, *Quat. Res.*, 80, 284–290, 2013.
- Tămaş, T., Onac, B. P., and Bojar, A. V.: Lateglacial-Middle Holocene stable isotope records in two coeval stalagmites from the Bihor Mountains, NW Romania, *Geol. Q.*, 49, 185–194, 2005.
- Telford, R. J. and Birks, H. J. B.: The secret assumption of transfer functions: problems with spatial autocorrelation in evaluating model performance, *Quaternary Sci. Rev.*, 24, 2173–2179, 2005.
- Ternois, Y., Sicre, M. A., Boireau, A., and Conte, M. H.: Evaluation of long-chain alkenones as paleo-temperature indicators in the Mediterranean Sea, *Deep-Sea Res. Pt. I*, 44, 271–286, 1997.
- Totti, C., Civitarese, G., Acri, F., Barletta, D., Candelari, G., Paschini, E., and Solazzi, A.: Seasonal variability of phytoplankton populations in the middle Adriatic sub-basin, *J. Plankton Res.*, 22, 1735–1756, 2000.
- Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C.: Persistent positive north Atlantic oscillation mode dominated the medieval climate anomaly, *Science*, 324, 78–80, 2009.
- van der Schriek, T. and Giannakopoulos, C.: Determining the causes for the dramatic recent fall of Lake Prespa (southwest Balkans), *Hydrol. Sci. J.*, 62, 1131–1148, 2017.
- Wagner, B., Wilke, T., Francke, A., Albrecht, C., Baumgarten, H., Bertini, A., Combourieu-Nebout, N., Cvjetkoska, A., D'Addabbo, M., Donders, T. H., Föller, K., Giaccio, B., Grazhdani, A., Hauffe, T., Holtvoeth, J., Joannin, S., Jovanovska, E., Just, J., Kouli, K., Koutsodendris, A., Krastel, S., Lacey, J. H., Leicher, N., Leng, M. J., Levkov, Z., Lindhorst, K., Masi, A., Mercuri, A. M., Nomade, S., Nowaczyk, N., Panagiotopoulos, K., Peyron, O., Reed, J. M., Regattieri, E., Sadori, L., Sagnotti, L., Stelbrink, B., Sulpizio, R., Tofiloska, S., Torri, P., Vogel, H., Wagner, T., Wagner-Cremer, F., Wolff, G. A., Wonik, T., Zanchetta, G., and Zhang, X. S.: The environmental and evolutionary history of Lake Ohrid (FYROM/Albania): interim results from the SCOPSCO deep drilling project, *Biogeosciences*, 14, 2033–2054, <https://doi.org/10.5194/bg-14-2033-2017>, 2017.
- Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P., and Jetel, M.: Structure and origin of Holocene cold events, *Quaternary Sci. Rev.*, 30, 3109–3123, 2011.
- Wassenburg, J. A., Dietrich, S., Fietzke, J., Fohlmeister, J., Jochum, K. P., Scholz, D., Richter, D. K., Sabaoui, A., Spötl, C., Lohmann, G., Meinrat, O., Andreae, M. O., and Immenhauser,

- A.: Reorganization of the North Atlantic Oscillation during early Holocene deglaciation, *Nat. Geosci.*, 9, 602–605, 2016.
- Weiss, H.: Megadrought, collapse, and resilience in late 3rd millennium BC Mesopotamia, in: 2200 BC – A Climatic Breakdown as a Cause for the Collapse of the Old World?, edited by: Meller, H., Arz, H. W., Jung, R., and Risch, R., Landesmuseum fur Vorgeschichte, Halle, 35–52, 2015.
- Weiss, H.: Global megadrought, societal collapse and resilience at 4.2–3.9 ka BP across the Mediterranean and west Asia, 24, 62–63, 2016.
- Weiss, H., Courty, M. A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., and Curnow, A.: The genesis and collapse of third millennium North Mesopotamian civilization, *Science*, 261, 995–1004, 1993.
- Welc, F. and Marks, L.: Climate change at the end of the Old Kingdom in Egypt around 4200 BP: new geoarchaeological evidence, *Quatern. Int.*, 324, 124–133, 2014.
- Wick, L., Lemcke, G., and Sturm, M.: Evidence of Late glacial and Holocene climatic change and human impact in eastern Anatolia: high-resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van, Turkey, *Holocene* 13, 665–675, 2003.
- Wright, H. E., Kutzbach, J. E., Webb III, T., Ruddiman, W. F., Street-Perrott, F. A., and Bartlein, P. J. (Eds.): Global Climate since the Last Glacial Maximum, University of Minnesota Press, Minneapolis, London, 569 pp., 1993.
- Xoplaki, E., González-Rouco, F., Luterbacher, J., and Wanner, H.: Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends, *Clim. Dynam.*, 23, 63–78, 2004.
- Zanchetta, G., Bonadonna, F. P., and Leone G.: A 37-meter record of paleoclimatological events from stable isotope data on molluscs in Valle di Castiglione, near Rome, Italy, *Quaternary Res.*, 52, 293–299, 1999.
- Zanchetta, G., Di Vito, A., Fallick, A. E., and Sulpizio, R.: Stable isotopes of pedogenic carbonate from Somma-Vesuvius area, Southern Italy, over the last 18 ka: palaeoclimatic implications, *J. Quat. Sci.*, 15, 813–824, 2000.
- Zanchetta, G., Drysdale, R. N., Hellstrom, J. C., Fallick, A. E., Isola, I., Gagan, M. K., and Pareschi, M. T.: Enhanced rainfall in the Western Mediterranean during deposition of sapropel S1: stalagmite evidence from Corchia cave (Central Italy), *Quaternary Sci. Rev.*, 26, 279–286, 2007a.
- Zanchetta, G., Borghini, A., Fallick, A. E., Bonadonna, F. P., and Leone, G.: Late Quaternary palaeohydrology of Lake Pergusa (Sicily, southern Italy) as inferred by stable isotopes of lacustrine carbonates, *J. Paleolimnol.*, 38, 227–239, 2007b.
- Zanchetta, G., Sulpizio, R., Roberts, N., Cioni, R., Eastwood, W. J., Siani, G., Caron, B., Paterne, M., and Santacroce, R.: Tephrostratigraphy, chronology and climatic events of the Mediterranean basin during the Holocene: An overview, *Holocene*, 21, 33–52, 2011.
- Zanchetta, G., Giraudi, C., Sulpizio, R., Magny, M., Drysdale, R. N., and Sadori, L.: Constraining the onset of the Holocene “Neoglacial” over the central Italy using tephra layers, *Quat. Res.*, 78, 236–247, 2012a.
- Zanchetta, G., van Welden, A., Baneschi, I., Drysdale, R. N., Sadori, L., Roberts, N., Giardini, M., Beck, C., and Pascucci, V.: Multi-proxy record for the last 4500 years from Lake Shkodra (Albania/Montenegro), *J. Quat. Sci.*, 27, 780–789, 2012b.
- Zanchetta, G., Bini, M., Cremaschi, M., Magny, M., and Sadori, L.: The transition from natural to anthropogenic-dominated environmental change in Italy and the surrounding regions since the Neolithic: an introduction, *Quatern. Int.*, 303, 1–9, 2013.
- Zanchetta, G., Bar-Matthews, M., Drysdale, R. N., Lionello, P., Ayalon, A., Hellstrom, J. C., Isola, I., and Regattieri, E.: Coeval dry events in the central and eastern Mediterranean basin at 5.2 and 5.6 ka recorded in Corchia (Italy) and Soreq Cave (Israel) speleothems, *Global. Planet. Chan.*, 122, 130–139, 2014.
- Zanchetta, G., Regattieri, E., Isola, I., Drysdale, R. N., Bini, M., Baneschi, I., and Hellstrom, J. C.: The so-called “4.2 event” in the central Mediterranean and its climatic teleconnections, *Alp. Med. Quat.*, 29, 5–17, 2016.
- Zanchetta, G., Bini, M., Giaccio, B., Manganelli, G., Benocci, A., Regattieri, E., Colonese, A. C., Boschi, C., and Biagioli, C.: Middle Pleistocene (MIS 14) environmental conditions in the central Mediterranean derived from terrestrial molluscs and carbonate stable isotopes from Sulmona Basin (Italy), *Palaeogeogr. Palaeocl.*, 485, 236–246, 2017.
- Zanchetta, G., Bini, M., Di Vito, M. A., Sulpizio, R., and Sadori, L.: Tephrostratigraphy of paleoclimatic archives in central Mediterranean during the Bronze Age, *Quatern. Int.*, 499, 186–194, <https://doi.org/10.1016/j.quaint.2018.06.012>, 2018.
- Zielhofer, C. and Faust, D.: Mid- and Late Holocene fluvial chronology of Tunisia, *Quaternary Sci. Rev.*, 27, 580–88, 2008.
- Zielhofer, C., Fletcher, W. J., Mischke, S., De Batist, M., Campbell, J. F. E., Joannin, S., Tjallingii, R., El Hamouti, N., Junginger, A., Stele, A., Bussmann, J., Schneider, B., Lauer, T., Spitzer, K., Strupler, M., Brachert, T., and Mikdad, A.: Atlantic forcing of Western Mediterranean winter rain minima during the last 12,000 years, *Quaternary Sci. Rev.*, 157, 29–51, 2017a.
- Zielhofer, C., von Suchodoletz, H., Fletcher, W. J., Schneider, B., Dietze, E., Schlegel, M., Schepanski, K., Weninger, B., Mischke, S., and Mikdad, A.: Millennial-scale fluctuations in Saharan dust supply across the decline of the African Humid Period, *Quaternary Sci. Rev.*, 171, 119–135, 2017b.
- Zielhofer, C., Köhler, A., Mischke, S., Benkaddour, A., Mikdad, A., and Fletcher, W. J.: Western Mediterranean hydro-climatic consequences of Holocene iceberg advances (Bond events), *Clim. Past Discuss.*, <https://doi.org/10.5194/cp-2018-97>, in review, 2018.
- Ziveri, P., Rutten, A., De Lange, G. J., Thomson, J., and Corselli, C.: Present-day coccolith fluxes recorded in central eastern Mediterranean sediment traps and surface sediments. *Palaeogeogr. Palaeocl.*, 158, 175–195, 2000.