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Emerging multi-proxy records of Late Quaternary Palaeoclimate dynamics in Turkey and the surrounding region

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Abstract: We present an overview of selected papers published since 2000 that interpret Late Quaternary multi-proxy palaeoclimate records from Turkey and the surrounding region of the Near-Middle East and Mediterranean region. Existing records in Turkey are rather limited in their resolution, and the locations studied thus far reflect a limited spatial and temporal distribution. Because Turkey is a very large country with numerous mountains that affect local weather conditions and create complex feedbacks, it is difficult to correlate trends across the broad landscape, and beyond. Published instrumental records are too short, and most palaeoclimate proxy records, including many lakes studied in Cappadocia and Konya, are low resolution. The Anatolian peninsula is sensitive to spatial and temporal shifts in the configuration, strength and persistence of global circulation patterns affecting the Mediterranean climate zone, including the mid-latitude westerlies, the continental climate system anchored over northern Asia and Siberia, and the Afro-Asian monsoonal system. As such, there is a strong need for additional new, high quality, well dated, and high-resolution multi-proxy records from more sites in Turkey. Deciphering the complexities of environmental change in central-interior and eastern regions of Turkey is particularly problematic, due to the paucity of published records. Additional observations of climate variability at the decadal-to-centennial scale are essential to better understand the ascendant controls on climate variation, the influence of rapid climate changes (RCCs) recognized in the marine record, and the causal mechanisms involved. Because the IPCC models forecast desiccation for Turkey and other drought-prone regions, it is particularly important to understand the natural baseline of hydroclimate variation across the broader Middle East and Mediterranean region. Additional study of past conditions has tremendous potential to inform the policy and practices of the future.

Key Words: abrupt hydroclimatic variation, multi-proxy records, Rapid Climate Changes (RCCs), marine records, continental archives, sea surface temperatures (SSTs), Turkey

1. Introduction

Various high-resolution ice-core records from Greenland (Dansgaard *et al.* 1993; Grootes & Stuiver 1997) suggest that the Holocene period of the past ~10,000 years was characterized by climate stability in the northern hemisphere. Multiple proxies preserved in these polar records such as dust, sulphates, and isotopes indicate that the post-glacial interval was rather stable, with one widespread rapid climate change event occurring at 8,200 cal BP (Alley *et al.* 1997; Alley & Ágústsdóttir 2005) (Figure 1). One review of palaeoclimate records even described the Holocene as “largely complacent as far as climate variability is concerned” (Maslin *et al.* 2000).

However, a significant number of studies based on the analyses of short- and medium-term ocean core records from the north Atlantic Ocean and Mediterranean Sea have demonstrated that the Holocene climate experienced significant variations (e.g., Ariztegui *et al.* 2000; Arz *et al.* 2003; Sbaffi *et al.* 2004, Kothoff *et al.* 2008 a and b, 2011; Peyron *et al.* 2011; Schmiedl *et al.* 2010). Some variations seem to have occurred very rapidly over decadal time scales; researchers are currently exploring the expression of such rapid climate changes, or RCCs (Mayewski *et al.* 2004). Reconstructing patterns of regional and local climate change and interpreting palaeo-temperatures and former precipitation patterns is presently a key objective of interdisciplinary research (PAGES 2009). Assessing what drives these rapid climate change events, their spatial expression, and temporal duration during the Holocene is an important goal of ongoing research.

This paper has three main goals. First, we highlight some of the recently published proxy records for the Late Quaternary palaeoclimate of the Middle-Near East and Mediterranean regions. Our survey of the past decade of

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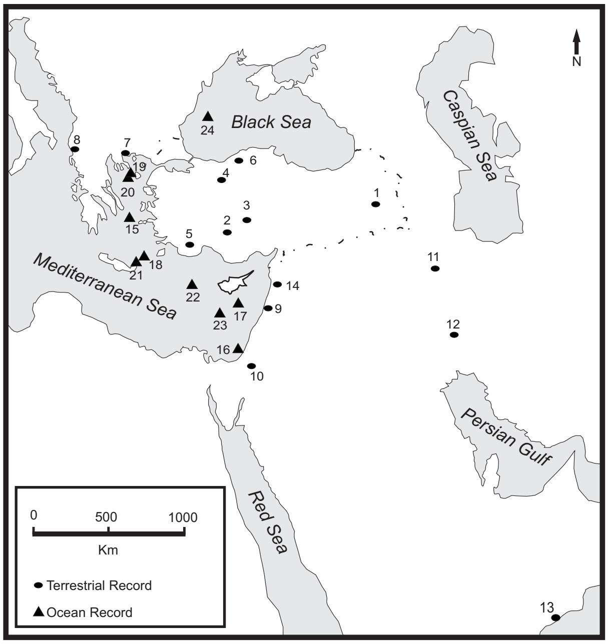

Figure 1. Map of Turkey within the region discussed in the eastern Mediterranean sector of the Near-Middle East. Numbered site localities of some of the key palaeoclimate archives discussed in the text, and presented in Table 1.

research is critical to outline the emerging themes that are particularly relevant for ongoing and future work in Turkey. Then we briefly discuss whether records in Turkey preserve evidence for rapid climate changes (or RCCs) occurring over the past 10,000 years as described in Mayewski *et al.* (2004). Furthermore, we identify some limitations of existing records, and discuss the potential of doing additional research in Turkey.

2. A brief survey of recent Palaeoclimate publications

Several published studies have addressed the palaeoenvironment in Turkey and the nature of regional climate change, with most emphasis on Late Quaternary records since the Last Glacial Maximum (or LGM ~20,000 years ago) through to the present day. The existing literature reports inferences from a wide range of proxy records and indicators for climate, including sediments (e.g., varved deposits, clay minerals, dusts), biota (e.g., fossil pollen, diatoms, ostracodes), and geochemical tracers (e.g., element abundance, stable isotope analyses). Multi-proxy studies typically derive interpretations from more than one type of proxy record for hydroclimate reconstruction.

Palaeoclimate records are sampled from the marine domain, namely the offshore and ocean locations, or the terrestrial realm, which includes the nearshore and onshore. Terrestrial archives are derived from lakes, rivers, glaciers, and various other environments within the landscape. This section presents an overview of some recent palaeoclimate publications relating to Turkey and its surrounding region. (Figure 1 & Table 1). Owing to the depth of the emerging scholarship and the volume of the available literature, as well as the space limitations of this paper, our discussion must be cursory and incomplete. As such, we highlight "state-of-the-science of palaeoclimatology," focusing on the past decade of contributions relating to Turkey, many written by Turkish scholars.

2.1. Marine core records

Offshore records are among the best-studied proxy records of palaeoclimate that exist over deep timescales, and trends have been correlated with those from the Greenland Ice Sheet. In the Near-Middle East, and for the eastern Mediterranean region, an advantage of marine cores is that the sediments are often laminated, and these often provide uninterrupted records due to continuous sedimentation in the ocean. Figure 2 depicts the length of various proxy records, and shows the long temporal duration of marine cores as compared to terrestrial records. Terrestrial archives tend to be more sensitive recorders of subtle changes affecting the landscape, but there are typically more gaps in terrestrial records.

Several cores exist from the three main domains of the Mediterranean Sea – the Ionian, Aegean and Levantine sub-basins. These have yielded insights about the nature of climate forcing, deep-water formation and benthic ecosystem changes since the Last Glacial Maximum (LGM). There are perhaps hundreds of reports and papers conveying study results. Among the notable publications about marine records since 2000 are those by Ariztegui *et al.* 2000; Emeis *et al.* 2000, 2003; Schilman *et al.* 2001; Rohling *et al.* 2002; Sbaffi *et al.* 2004; Ehrmann *et al.* 2007; Essallami *et al.* 2007; Hamann *et al.* 2008; Kothoff *et al.* 2008 a and b; Schmiedl *et al.* 2010; Peyron *et al.* 2011; and Kotthoff *et al.* 2011. Evidence of Holocene climate instability in both the western and eastern domains of the Mediterranean have been interpreted as 1-2° C variations in sea surface temperatures, which appear to be closely linked with the more extended events observed in the north Atlantic Ocean (Rohling *et al.* 2009; Sbaffi *et al.* 2004).

Findings published about the Mediterranean cores complement the work done in the Marmara Sea (e.g., Mudie *et al.* 2002 and references therein) and the nearby Red Sea (e.g. Arz *et al.* 2003). Cores from the Black Sea (Kwiecien *et al.* 2009) record climate dynamics since the Pleistocene, and indicate that the North Atlantic is the major control on moisture in the region. Fouache *et al.* (2011, *in press*) discuss the Late Holocene evolution of the Black Sea, and critique the so-called Phanagorian regression. Müller *et al.* (2011) relate the influence of Dansgaard-Oeschger climate variability and Heinrich events on Eastern Mediterranean climate dynamics. Robinson *et al.* (2006) and Jalut *et al.*

Table 1. Selected archives mentioned in this paper. Key: L= lake archive; C = cave; OC = ocean core; d = diatoms; f = foraminifera; i = isotope record; ms = magnetic susceptibility; p = pollen material; s = sediments, mineralogy and geochemistry.

# on Map	Site name	Location	Length of record (ka cal BP)	Archive type – multi-proxy data	Selected key references
1	Lake Van	E Turkey	2.6 – 0 ; >20 – 3	L – i, d, p, ms	Litt *et al.* 2009; Wick *et al.* 2003
2	Konya Basin	Central Turkey	>25 – 21; 17 – 0	L – i, d, p, s, f	Fontugne *et al.* 1999; Roberts *et al.* 1999;
3	Eski Acıgöl	Central Turkey	>20 – 1	L – i, d, p	Roberts *et al.* 2011; Woldring and Bottema 2003
4	Lake Abant	NW Turkey	>9 – 0.2	L – p	Roberts *et al.* 2011; Bottema *et al.* 1993/1994
5	Gölhisar	SW Turkey	>9 – 0.3	L – i, d, p, s, ms	Eastwood *et al.* 1999
6	Sofular Cave	NW Turkey	>26 – 0	C – i	Göktürk *et al.* 2011
7	Tenaghi Philippon	E Greece	10 – 6	L – p	Peyron *et al.* 2011; Pross *et al.* 2009
8	Ioannina	NW Greece	>20 – 0.7	L – i, p	Lawson *et al.* 2004; Frogley *et al.* 2001
9	Jeita Cave	Lebanon	>11– 4.3; 4.1 – 3.9; 3.6 –1.4	C – i	Göktürk *et al.* 2011; Verheyden *et al.* 2008
10	Soreq Cave	Israel	>25 – 0	C – i, p	Göktürk *et al.* 2011; Bar-Matthews *et al.* 2003
11	Lake Zeribar	W Iran	>9 – 0.2	L – i, p	Wasylikowa *et al.* 2006; Stevens *et al.* 2001
12	Lake Mirabad	SW Iran	>9 – 0.1	L – i	Roberts *et al.* 2011; Stevens *et al.* 2006
13	Qunf Cave	S Oman	10.5 – 2.7; 1.5 – 0.5	C – i	Fleitmann *et al.* 2007
14	Dead Sea - Lisan	Israel	>25 – 0	L – i	Kolodny *et al.* 2005; Bartov *et al.* 2003
15	GeoTü SL 31	N Aegean Sea	20 – 1	OC – p, f	Schmiedl *et al.* 2010; Abu-Zied *et al.* 2008
16	GeoTü SL 112	SE Levantine Sea	22 – 0	OC – p, f	Schmiedl *et al.* 2010; Ehrmann *et al.* 2007
17	GeoTü SL114	E Levantine Sea	20 – 3	OC – p, f	Schmidt 2007
18	GeoTü SL123	SE Aegean Sea	22 – 0	OC – p, f	Schmiedl *et al.* 2010
19	GeoTü SL 148	N Aegean Sea	21 – 0	OC – i, p, f	Schmiedl *et al.* 2010; Ehrmann *et al.* 2007
20	GeoTü SL 152	N Aegean Sea	21 – 0	OC – p	Göktürk *et al.* 2011; Kotthoff *et al.* 2008
21	LC 21	S Aegean Sea	22 – 4; 3 – 1	OC – i, p, f	Schmiedl *et al.* 2010; Abu-Zied *et al.* 2008
22	LC 31	N Levantine Sea	22 – 0.5	OC – p, f	Schmiedl *et al.* 2010; Abu-Zied *et al.* 2008
23	ODP 967	E Levantine Sea	>25 – 0	OC – i	Emeis *et al.* 2003; 2000; 1998
24	GeoB 7608–1	NW Black Sea	>25 – 14.5	OC – i	Kwiecien *et al.* 2009; Bahr *et al.* 2006

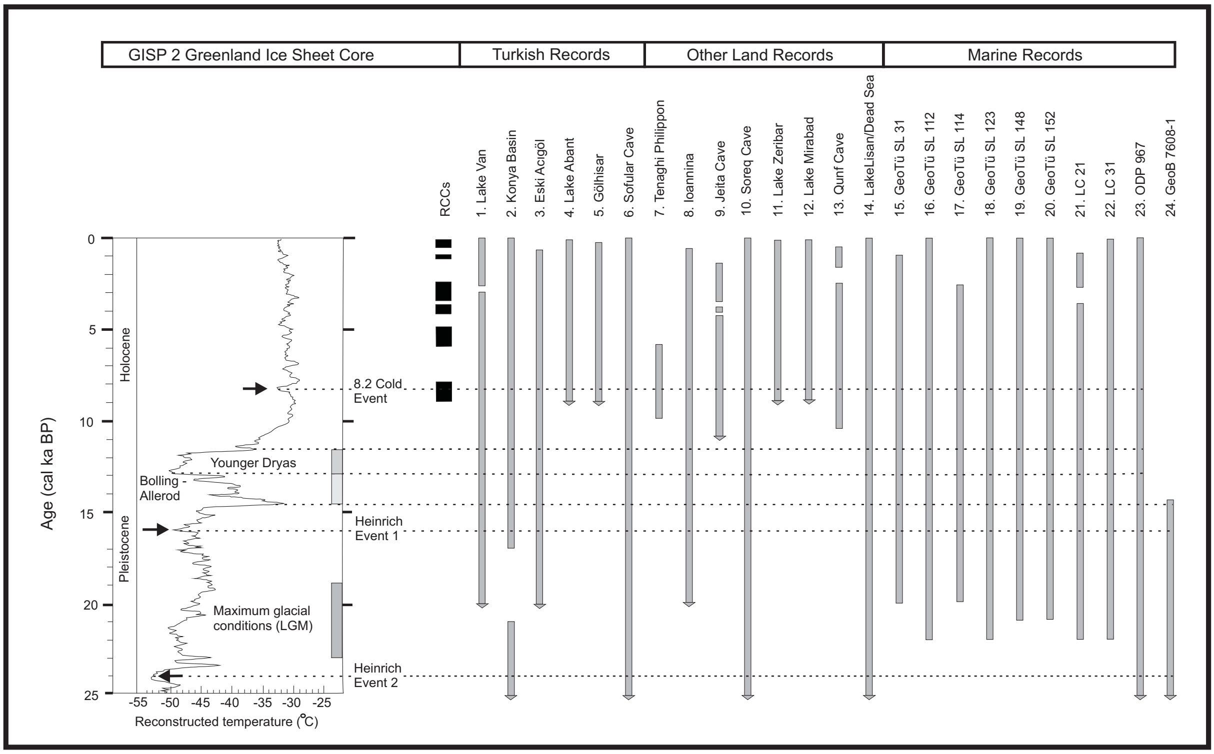

Figure 2. Reconstructions of air temperatures from isotopic analyses of the GISP 2 ice core, Greenland (Alley 2000); 8,200 event after Rohling & Pälike (2005). Rapid Climate Change events (RCCs) after Mayewski *et al.* (2004). Temporal coverage of selected palaeoclimate archives, listed by location (Table 1).

(2009) synthesized trends around the Mediterranean, and discussed the primary causal mechanisms affecting climate in the region over Quaternary timescales.

2.2. Cave archives and speleothems

Recently published interpretations from terrestrial archives in the region include speleothems and other carbonates from the Sofular cave in northern Turkey, which is a high-resolution record extending back to the Pleistocene (Göktürk *et al.* 2011; Fleitmann *et al.* 2009). Jex *et al.* (2010) relate modern rainfall trends to the isotope hydrology of carbonate deposition at Akçakale Cave south of Trabzon, Turkey. Calibration studies in which modern sediments are directly linked with observed hydroclimatic conditions is important for the interpretation of speleothems and the reconstruction of palaeo-precipitation and past temperature patterns (McGarry *et al.* 2004; Lachniert 2009).

South of Turkey, there are other important cave records in the region; the closest one is from Jeita in Lebanon (Verheyden *et al.* 2008). Israel cave sites include the salt caves at Mount Sedom (Frumkin *et al.* 1991, 1999), and carbonate caves near Jerusalem (Frumkin *et al.* 2000; Frumkin & Stein 2004), Maále Efraim, Tzavoa (Vaks *et al.* 2003, 2006), and Soreq (Bar-Matthews *et al.* 1997; Ayalon *et al.* 1999; Bar-Matt hews *et al.* 2003; Bar-Matthews & Ayalon 2011); various interpretations of these archives have been discussed in Schilman *et al.* (2001) and Enzel *et al.* (2008). Farther away, the cave records in Oman and Yemen (Fleitmann *et al.* 2003, 2007) are often cited in palaeoclimate reconstructions for the Middle East region.

2.3. Fluvial records

Several recent papers have advanced our understanding of the geomorphology of river (wadi) settings, and their associated palaeoenvironmental records. Ergin *et al.* (2007) have interpreted Late Quaternary climate and sea-level changes in sediment records of the Büyük Menderes River delta in the eastern Aegean Sea; this fluvial system directly responds to base-level changes forced by sea-level oscillations. Further study of the deltaic sequences along the Turkish coastline has strong potential to inform future palaeoclimate reconstructions and linkages between the marine and terrestrial systems.

Most of the fluvial archives studied in Turkey are situated at locations further inland. Studies of fluvial deposits in the Pasinler Basin are important for reconstructing hydrological changes in eastern Turkey, and resolving the natural climate signals from human impact (Collins *et al.* 2005). Maddy *et al.* (2005) ascribed the development of Early Pleistocene fluvial terraces to Milankovitch-forced obliquity cycles. Doğan (2010, 2011) documented the fluvial response to climate change in Cappadocia and across Central Anatolia. In western Turkey, studies of the Gediz River related the fluvial architecture and incision as a function of volcanism and uplift (Westaway *et al.* 2004, 2006). The need to distinguish tectonic signals from climate signals during the interpretation of fluvial archives was addressed by Demir *et al.* (2008) and Nicoll (2010).

Geomorphic studies of the Upper Dicle (Tigris) River include those by Kuzucuoğlu *et al.* (2004), Doğan (2005), Bridgland *et al.* (2007), and Nicoll (2010). Studies within the Fırat (Euphrates) River basin include those by Seyrek *et al.* (2008), and Demir *et al.* (2004, 2008). Mackin *et al.* (2002) presented a regional correlation of river archives as indicators of climate change around the Mediterranean region.

2.4. Lake records

Lake archives in the Near-Middle East and Mediterranean region are well known as sensitive recorders of hydroclimatic conditions (Erol 1978, Van Zeist & Bottema 1991, Roberts & Wright 1993). As a function of climate change, lakes may exhibit changes in their water levels and shoreline geomorphologies, which are reflected in their sediment archives. Multi-proxy records in lakes include sediment compositions and stratigraphic variations of included fossil biota (e.g., pollen, diatoms, ostracodes, plants, etc.) and measurements of geochemical attributes, such as salinity and stable isotope variations (Ruddiman *et al.* 1993).

The Lake Lisan-Dead Sea system is perhaps the best-studied lacustrine system and most cited record of post-glacial climate change in the eastern Mediterranean region. Its chronology of lake-level fluctuations and sequence of palaeoshorelines have been well dated (e.g., Bartov *et al.* 2003; Bookman *et al.* 2004; Kolodny *et al.* 2005; Migowski *et al.* 2006). Numerous lake cores, trenches, and geomorphic studies in the basin have informed palaeoclimate reconstructions of the Levant desert and surrounding regions. For example, Enzel *et al.* (2008) presented a synthesis of palaeoclimate archives from this region, and identified a framework of eastern Mediterranean atmospheric circulation patterns that interacted with the local coastal and montane landscape elements during the Late Pleistocene.

Another important palaeoclimate archive in the Levant is the Birket Ram crater lake in the Golan Heights (Schwab *et al.* 2004). In the surrounding region, Develle *et al.* (2010) documented oxygen isotope records from carbonate lake marls of Yammoûneh, Lebanon, which date to the LGM. In Iran, long-term records back through the LGM are preserved at Lakes Zeribar (Snyder *et al.* 2001; Stevens *et al.* 2001; Wasylikowa *et al.* 2006) and Mirabad (Stevens *et al.* 2006). The long lake record at Lake Urmia spans 200,000 years, and it has recently been re-evaluated (Djamali *et al.* 2008). Other new lake records are emerging from this region. Djamali *et al.* (2009) investigated a new core from Maharlou Lake in the Zagros Mountain region. The paper by Djamali *et al.* (2010) related lake dynamics and the expansion of woodland across this region during the Early Holocene as a function of enhanced monsoonal moisture inputs.

Lake-based palaeoclimate research has been conducted in Turkey for almost 50 years. In particular, the pollen preserved in various lake records has informed our inferences about Late Quaternary vegetation changes as a function of climate change since the LGM (Roberts & Wright 1993; Bottema *et al.* 1993/1994; Erol 1997; Fontugne *et al.* 1999). The two main areas that have been studied in most detail include Van, and the region of Cappadocia and Konya.

Records from Van in eastern Turkey have been studied since the 1970s (e.g., van Zeist & Woldring 1978; Bottema & Woldring 1984). Lake Van is the largest soda lake on Earth, and is the world's fourth largest endhoreic (internally-drained) terminal lake system by water volume. Papers discussing the sediments, isotopes, and fossil palaeoecological indicators recovered from Lake Van include Landmann *et al.* (1996a and b), Lemke & Sturm (1997), and Wick *et al.* (2003). The lake records at Van are long – they date beyond 15,000 years (Figure 2). Recently, new cores were obtained from the lake as part of a major Inter-Continental Drilling Project (ICDP), and new results are forthcoming (Litt *et al.* 2009; http://www.palaeovan.info/).

Lakes located in the region of Konya and Cappadocia within Anatolia have been examined since the 1980s (Roberts 1983). Key study sites presented in the recent literature include Göçü Lake (Karabıyıkoğlu *et al.* 1999); Eski Açigöl crater lake (Roberts *et al.* 2001); Tuz Lake (Kasima 2002); and Tecer Lake (Kuzucuoğlu *et al.* 2011). Roberts *et al.* (2011) reviewed many datasets from these lakes in the context of other locations around Turkey such as Abant (Bottema *et al.* 1993/1994) and Gölhisar (Eastwood *et al.* 1999).

High-resolution varved lake records such as those from Nar Gölü and Eski Acıgöl in the Central Interior region of Anatolia offer valuable opportunities to calibrate sediment archives with modern meteorological conditions (Jones *et al.* 2006; Jones *et al.* 2007; Jones & Roberts 2008; Roberts 2011). Pollen sequences in these archives provide the basis for reconstructing environmental changes as a function of seasonality and hydroclimate variables. Important new insights are emerging from various locations across the central and eastern Mediterranean (e.g., Giraudi *et al.* 2011, Peyron *et al.* 2011, Sadori *et al.* 2011); these records enable linkages across the region that will elucidate regional connections with the westerlies and North Atlantic systems that influence the eastern Mediterranean.

Stable isotope data from carbonate layers in lake sediment cores are increasingly employed as the basis for assessing climate variability, and as a basis for regional correlation with cave speleothems and deep-sea cores in the eastern Mediterranean (Roberts *et al.* 2008, 2010, 2011; Leng *et al.* 2010). Measured lake isotope values are the product of interrelated hydroclimatic factors, including temperature, season, air mass source, and storm system trajectory. The ascendant control is the local water balance, with more negative $\delta^{18}O$ values reflecting time periods characterized by a greater moisture availability or surplus, with the overprint by some local effects of topographic elevation and continentality (Jones and Roberts, 2008). Excellent papers by Jalut *et al.* (2009) and Roberts *et al.* (2008, 2011) synthesized the observed isotopic trends with other proxy records available from the Mediterranean and Near-Middle East region.

2.5. Glacial records

Glacial records in Turkey have received an increasing amount of attention in recent years, although the record is sparsely known in comparison to other regions (Çiner 2004; Akçar & Schlüchter 2005; Zahno *et al.* 2010). Glaciers respond to major climatic shifts on the millennial time-scale, and are low-resolution proxies for the main Pleistocene climate oscillations. Cosmogenic dating techniques (^{10}Be, ^{26}Al and ^{36}Cl, in particular) are increasingly employed to derive surface exposure ages and glacial chronologies, and to inform models. Most of the publications demonstrate that Anatolian glaciers are in accordance with the oscillations observed in the European Alps during the Last Glacial Maximum (LGM; ~21± 2 ka), although the oscillations are less pronounced in Anatolia (Zahno *et al.* 2010). Hughes & Woodward (2008) compared the glacial histories of montane sites in the Mediterranean. Among the glacial sites in Turkey described in recent publications: Kavron Valley (Akçar *et al.* 2007 a) and Verçenik valley (Akçar *et al.* 2007 b) in the NE; Kovuk and Karagöl valleys in Uludağ Mountain in the NW (Zahno *et al.* 2010); Mount Sandıras (Sarıkaya *et al.* 2008) and the Dedegöl Mountains (Zahno *et al.* 2009) in the SW; and Mount Erciyes in central Anatolia (Sarıkaya *et al.* 2009).

2.6. Tree-ring records

Some important high-resolution datasets in recently published literature include new tree-ring records from Turkey. Tree-ring chronologies now exist for almost a millennium, and are derived from many species, including a few regionally-extant conifers (e.g., Akkemik 2000 a and b 2003; Sevgi & Akkemik 2007) and oaks (e.g., Griggs *et al.* 2007). Tree-ring widths have been calibrated to derive standardized precipitation indices in Turkey (D'Arrigo & Cullen, 2001; Touchan *et al.* 2003, 2005 a). Published tree-ring-based precipitation reconstructions now exist over several centuries for regions in Turkey, including the northwest (Griggs *et al.* 2006; Akkemik *et al.* 2008), the southwest (Hughes *et al.* 2001; Touchan *et al.* 2003, 2005 b), the Aegean region (Griggs *et al.* 2007; Touchan *et al.* 2007), central Anatolia (Akkemik & Aras 2005; Akkemik & Aliye 2005), and the western Black Sea (Akkemik *et al.* 2005, 2008).

2.7. Instrumental records

In addition to papers based on palaeoclimatic proxies, many recent papers interpret data directly from modern meteorological measurements collected across the Mediterranean and Near-Middle East region. An understanding of modern synoptic-scale hydroclimatology is especially useful as a basis for reconstructing the past, informed by a present-day knowledge of climate controls and their variability. Palaeoclimate proxies like tree rings and isotopes, for example, are calibrated with modern hydroclimatic and meteorological attributes so that they can be transformed into quantitative estimates of former conditions and palaeo-precipitation values.

There are many new papers about the modern hydroclimate of Turkey. Karaca *et al.* (2000) assessed the variability of cyclone tracks over Turkey in relation with regional climate, and Kutiel *et al.* (2001) linked sea level pressure patterns associated with dry or wet monthly rainfall conditions. Ünal *et al.* (2003) redefined the climate zones of Turkey using cluster analysis. Evans *et al.* (2004) developed a climate simulation to elucidate the dominant processes affecting Turkey within the Middle East.

The spatiotemporal variability of precipitation has been analyzed (e.g., see Xoplaki *et al.* 2004; Göktürk *et al.* 2008) and modelled (Bozkurt *et al.* 2011). Totals over Turkey for the period 1930-2000 can be linked to the North Atlantic Oscillation or NAO (Türkeş 1996, Türkeş & Erlat 2003, Türkeş *et al.* 2009). Karabörk *et al.* (2005) extended this linkage to the Southern Oscillation, and Yurdanur *et al.* (2010) described the spatial and temporal patterns of precipitation variability for the annual, wet, and dry seasons in Turkey. Bozkurt & Şen (2010) linked precipitation patterns in the Anatolian peninsula, and determined that they are highly sensitive to increased Sea Surface Temperatures (SSTs) in the surrounding waters. Şen *et al.* (2011) linked temporal changes in the Euphrates and Tigris discharges to ascendant precipitation patterns and other teleconnections.

3. A critical look at Palaeoclimate archives from Turkey

3.1. Data availability across the region

High-resolution palaeoclimate data for the Late Quaternary exist from several localities in Western Europe, but far fewer terrestrial records exist in the eastern Mediterranean and the Near-Middle East. There are many recent publications on marine records from the Mediterranean region. By comparison, the number of analyzed terrestrial archives from Turkey is low. Israel, for example, has been densely sampled and intensively studied. The Levant area has yielded several high-resolution archives from lakes and caves, and these records form a baseline for understanding the nature of climate change in the region.

If we consider the location of Quaternary studies in Turkey according to the map of modern climate zones recognized by Ünal *et al.* (2003), the largest concentration of published observations is in the South-Central Anatolian region (e.g., works by Roberts, Kuzcuoğlu, Jones, and others) and in the Eastern Anatolian region at Lake Van (e.g., works by Bottema, Lemke, Landmann, Wick, Litt, and others). The areas with the fewest publications include Ankara, the Central-Interior region, and Southeastern Anatolia: these are the understudied areas within Turkey that should be targeted for future palaeoclimate research investigations.

3.2. Data quality, resolution & coherence

Correlation of different proxy records may be complicated, especially given problems of data consistency and quality. A key problem with interpreting multiple proxy datasets is that they may be ambiguous in how they record climate signals over a region; the proxy record may not pick up and record a signal, especially if characterized by low sensitivity. Furthermore, there may be noise, and/or there might be a lag period. Terrestrial records may be discordant, or have discontinuities - gaps of "missing time" that may be due to lags, non-recording events, or erosion. Additionally, the record of coverage may be patchy in terms of comparing trends spatially across a landscape. The temporal control may be limited within the archive; for example, there only a few robust dates for the record, or the degree of resolution might be low. Many terrestrial proxy records are poorly dated, with low resolution; few have long duration. Some terrestrial archives are short-duration records that are high resolution; for example, some lake varves yield isotope records for 1,700 years (Jones *et al.* 2007). Longer-term high-resolution archives from speleothems in Turkey are providing new insights (Fleitmann *et al.* 2009, Jex *et al.* 2010, Göktürk *et al.* 2011).

Some of the environmental records from the Konya Basin illustrate this point. Records from three closely spaced lakes within the Konya Basin -- Akgöl, Pınarbaşı and Süleymanhacı -- are depicted in Figure 3. The inferences made by Roberts *et al.* (1999) indicate that different conditions existed across these various locations during the same specific time intervals. Although these are closely spaced lakes located within one basin, the trends at each site are not necessarily in phase with other sites nearby. Considered individually, these archives do not reflect the same consistent pattern during the timeframe of Holocene "climatic amelioration" during the period from 11,100 – 9,650 BP (Roberts *et al.* 1999). The different responses recorded at each shallow lake site suggest that the different areas of the basin are compartmentalized, with local effects dominating the water balance at each locale.

Although the precise nature of climate oscillations might vary by terrestrial site, general patterns of similarity do emerge when comparing certain records in Turkey and across the region. Roberts *et al.* (2011) evaluated the isotope records in high-resolution cores sampled from six lakes across a regional transect from Greece in the west to Iran in the east: Ioannina, Abant, Gölhisar, Eski Acigöl, Van, Zeribar, and Mirabad (Table 1; Figure 1). Prior to 7,900 ka BP, every lake in the comparisons of Roberts *et al.* (2011) displayed $\delta^{18}O$ values more negative than their mean, indicating hydroclimatic conditions of maximum wetness. By 6,600 BP, several lakes began to dry out, and showed a shift to more positive values, although three (Gölhisar, Mirabad and Ioannina) persisted a bit longer, and later returned to lower $\delta^{18}O$ values and wetter conditions around 6,000 BP. During the period between 6,000 and 3,000 BP, a comparison of the lake isotope data indicate various wet-to-dry oscillations, with a overall trend toward increasing dryness across the region. The records indicate time periods of enhanced drought around 5,300 to 5,000 BP, 4,500 to 4,000 BP and 3,100 to 2,800 BP. These dry episodes were punctuated by short time periods when moisture availability was enhanced. In particular, all the lake records indicate that the time period from 4,000 to 3,300 BP was a wet phase within the overall cooling and drying trend that commenced during the mid-Holocene (Roberts *et al.* 2011).

4. Discussion

The existing published literature demonstrates that the palaeoclimate framework for Turkey is developmental and should remain flexible in the light of the many emerging records from the region. It is far beyond the scope of this paper to provide a thorough synthesis and new interpretation of the many diverse records of former climate conditions affecting Turkey; there are already several papers that compare and correlate records throughout this region since the LGM (e.g., Fontugne *et al.* 1999, Robinson *et al.* 2006; Jalut *et al.* 2009, Roberts, 2011, Zanchetta *et al.* 2011). The records suggest that the climate during the LGM and post-glacial period was rather variable across the region. This complexity presents significant challenges in understanding the drivers that cause the variations.

4.1. Recognizing rapid climate changes (RCCs) in archives from Turkey

Much work by palaeoclimate researchers has focused on the abrupt climate change events, especially those

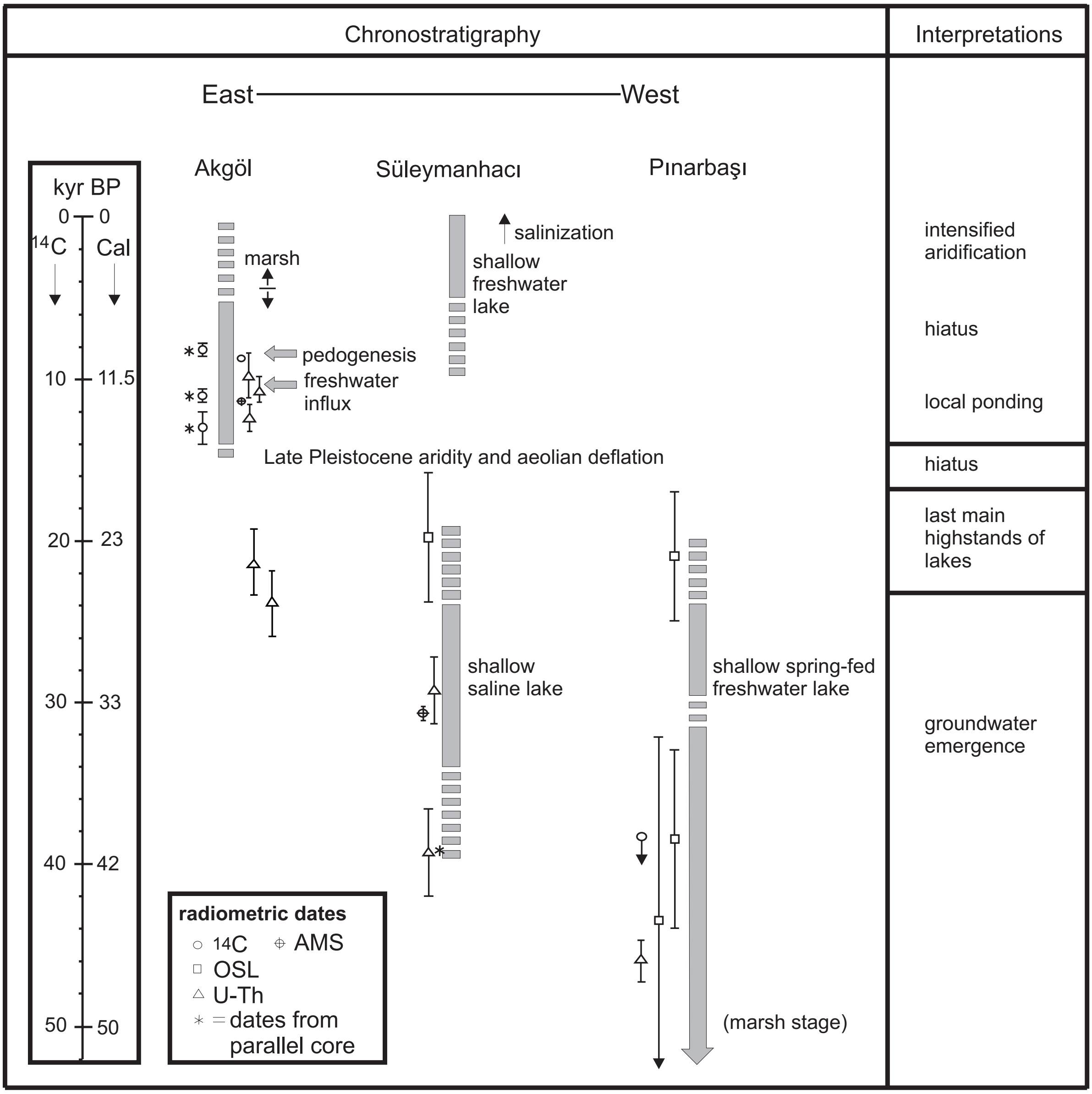

Figure 3. Chronostratigraphic interpretation of three lake sites in the Konya Basin (after Roberts *et al.* 1999).

occurring at 8,200 and 4,200 cal BP (e.g., Dalfes *et al.* 1997, Daley *et al.* 2011). These climate perturbations appear to be global in extent, and have been recognized in various archives from the poles to the tropics (see for example, Alley & Ágústsdóttir 2005, Thomas *et al.* 2007, Daley *et al.* 2011). At many localities in the Near and Middle East, these time periods of rapid climate change were associated with droughts related to lowered Sea Surface Temperatures (SSTs) (Rohling *et al.* 2009b).

In Turkey, some records preserve the 8,200 cal BP "event," whereas recognizing the 4,200 cal BP "event" is more ambiguous, especially in the terrestrial archives. Recognizing rapid climate changes in proxy archives of Turkey is complicated by a number of factors, including spatial (i.e. geographical) and temporal resolution of the records being analyzed. In addition, the sensitivity of the proxy record may "dampen" the signal as it is recorded. As previously mentioned, Turkey has been inadequately sampled, and the existing archives are rather sparsely distributed over the large landmass. In addition, many of the published records lack sufficient temporal resolution -- some archives are poorly dated, or the sampling interval is inadequate, or the nature of the archive is time-averaged.

Sample resolution is a major concern in correlating rapid events across Turkey. If an event is abrupt and takes place over a century, but the temporal resolution of the archive is imprecise or non-comparable (i.e. in this case, on the millennial scale), then any signal of the event may be aliased, or may "miss" being recorded altogether. This is perhaps one reason why a given event lasting a century or two may be inferred from only specific kinds of high-resolution terrestrial archives such as tree-rings or speleothems. The length of the 8.2 Rapid Climate Change (RCC) "event" (as it is called) calculated from the Greenland ice core chronology appears to have occurred quickly, over duration of no more than 160 years at 8200 cal BP (Thomas et al. 2007). Hence, it is not unreasonable that an abrupt event of this magnitude may have been "missed" or escaped recognition in various lake, marine and speleothem records.

Furthermore, Turkey has fewer deep time archives on land than the nearby offshore records, making it difficult to correlate these events beyond the marine realm onshore. The expression of the 8.2 RCC "event" at 8200 cal BP is prominent in marine cores, but is not consistently expressed in high-resolution terrestrial records across Turkey. In the Sofular Cave, the record of the 8.2 RCC event may be compounded by local effects. Maritime and orographic effects are thought to have affected the high-resolution Sofular Cave record along the Black Sea (Göktürk *et al.* 2011). Discrepancies raise questions about the teleconnections between synoptic controls and their expression at the regional and local scale, as well as how these signals are recorded in proxies.

The 4.2 RCC "event" (at 4200 cal BP) has received much attention in the eastern Mediterranean region and has been linked to the collapse of the Akkadian Empire. In a marine core record from the Gulf of Oman, Cullen *et al.* (2000) identified a sharp peak in the input of dolomite dust at 4.2 cal BP. Because this ocean core site lies directly downwind of Mesopotamian dust source areas, they inferred a very abrupt increase in aeolian dust and aridity in the Near Eastern region. Whether this event can be recognized across Turkey is not yet clear.

In the shorter term, the record at Sofular Cave demonstrates that the last 600 yrs prior to the 20th century were extremely dry at this location in NW Turkey, compared to the rest of the Holocene record. At the moment there are few records in Turkey with which to compare this important anomaly. With additional analytical sampling of palaeoclimate records, and better chronological resolution, it is likely that this signal and other abrupt climate variations and RCCs will be identified within the region.

4.2. Implications for reconstructing Late Quaternary palaeoclimates

Reconstructing the palaeoclimate of the Anatolian region is complex, because it involves the assessment of cause-and-effect relationships. Even today, the behaviour of the Mediterranean Sea, the Black Sea, and the Red Sea and the regional meteorological patterns are not simply related to that of the Atlantic Ocean (e.g., Lionello *et al.* 2006). Furthermore, the degree of continentality of a site is an important factor in its hydroclimate balance and surface water storage. Local controls affecting climate within Turkey today include the position of water bodies, mountains and plateaux (e.g., Kutiel *et al.* 2001; Önol & Semazzi, 2009; Türkeş *et al.* 2009), as well as storm tracks (Karaca *et al.* 2000), and oscillations (Cullen *et al.* 2000, 2002; Kahya & Karabörk 2001, Karabörk *et al.* 2005). Reconstructing these variables, their teleconnections, and the influence on the Quaternary palaeoclimate of Turkey remains an important objective.

Rapid climatic oscillations are commonly recorded in high-resolution marine cores from the Mediterranean Sea (Rohling *et al.* 2002, Sbaffi *et al.* 2004), whereas terrestrial records typically lack comparable resolution (Wanner *et al.* 2008). The cause and periodicity of observed variations and abrupt climate changes remains debated (e.g., Daley *et al.* 2011). Various mechanisms have been invoked to explain such abrupt regional and global shifts, including changes in ocean circulation and atmospheric perturbations, variation in atmospheric chemistry such as the concentrations of greenhouse gases, and changes in snow and ice cover (e.g. Bond *et al.* 1997, Alley *et al.* 1997, Ellison *et al.* 2006, Rohling *et al.* 2009). Sbaffi *et al.* (2004) noted that the Mediterranean Sea has a prominent role of enhancing, and sometimes even obliterating, evidence of these phenomena.

Given such complications, it is difficult to resolve apparent discrepancies in some of the eastern Mediterranean datasets. While most archives across the region agree on the basic timing of an early-middle Holocene wet period between 9,600 and 5,400 BP, the nature of sub-millennial variations observed on the global-scale is not well constrained across the Near-Middle East and in North Africa. Moreover, we have yet to link the marine records with high-resolution terrestrial archives sampled within the continental interior, and to fully understand the regional and local dynamics of climate changes associated with the retreat of the Afro-Asian monsoon system from its precession-forced solar insolation maximum ~10,600 cal BP (Rossignol-Strick 1999, Ziegler *et al.* 2010).

5. Conclusions and implications

Although some multi-proxy records of recent climate variability from Turkey and the surrounding region of the Near and Middle East exist, we lack a thorough understanding of former climate conditions and their main drivers over Late Quaternary timescales, especially in regard to the Holocene record of the past 11,000 years. Instrumental records are too short, and most palaeoclimate proxy records are low resolution, including the many well-studied lakes in Cappadocia and Konya. Because Turkey is a very large country with numerous mountains that affect local weather conditions and create complex feedbacks, it is difficult to correlate trends recorded at sub-millennial scales from the central interior across the broad landscape, and beyond. As such, there is a strong need for additional new, high quality, precisely dated, and high-resolution multi-proxy records from more sites in Turkey, and from locations in the surrounding region. Observations of climate variability at the decadal-to-multi-decadal scale are particularly essential to an understanding of climate dynamics over Quaternary timescales, as we aim to understand the timing and amplitude of rapid climate changes, as well as their causes (Wanner *et al.* 2008).

Further study is essential to resolve the expression of "global" rapid climate changes (RCCs) within Turkey. The inherent value of additional new palaeoclimate archives from Turkey is high. The peninsula of Anatolia is situated in the transition zone between different circulation systems, including the Mediterranean climate zone, the mid-latitude westerlies, the continental climate system anchored over northern Asia and Siberia, and the Afro-Asian monsoonal system (Wigley & Farmer 1982; Raicich *et al.* 2003; Alpert *et al.* 2006; Bozkurt & Sen 2011). As such, the region is sensitive to spatial and temporal shifts in the configuration, strength and persistence of these circulation patterns (Kostopoulou & Jones 2007a,b).

Areas of Turkey that lack detailed palaeoclimate records include Southeastern Anatolia, Northeastern Anatolia, and Central Anatolia, especially near Ankara. Overall, the landscape of Turkey has been sparsely sampled, and our knowledge of climate change across the country remains limited. To date, lake archives have provided some insights regarding the general nature of climate variations since the LGM; ongoing studies such as those at Lake Van (Litt *et al.* 2009) are expected to provide important new datasets for the reconstruction of past climate in eastern Anatolia over the past 15,000 years. There is tremendous potential for archives from Turkey to contribute to an improved understanding of climate variability across the region. In particular, archives at the sub-millennial and decadal scales of resolution would be valuable.

While it is important to reconstruct palaeoclimatic conditions and understand the related meteorological mechanisms at regional scale, it is perhaps most relevant across the Near and Middle East to improve and relate our knowledge to climate change projections for the near future (Jeftic *et al.* 1996; Mazlum 2009). Water remains as an important security issue in this region, and the past can inform the analysis of ongoing and future climate change impacts at both the regional and local scales (Jansen *et al.* 2007). High-resolution regional climate models, for example, use historical instrumental datasets to detect trends and to forward model; one such model indicates that precipitation amounts will decline 10% in the Eastern Mediterranean and Near-Middle East in the future, and half of the total water needs of this region may need to be imported by 2050 (Chenoweth *et al.* 2011). In Turkey, water availability and the accurate assessment of risk and vulnerability of water resources and agriculture is vital as the nation's growing population faces a drought-prone future (e.g., Mengü *et al.* 2008; Yağbasan &Yazıcıgil 2011).

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