Jones, Matthew D. and Roberts, C. Neil (2008) Interpreting lake isotope records of Holocene environmental change in the Eastern Mediterranean. Quaternary International, 181 (1). pp. 32-38. ISSN 1040-6182

Jones, M.D. and Roberts, C.N. 2008. Interpreting lake isotope records of Holocene environmental change in the Eastern Mediterranean. Quaternary International, 181, 32-38. doi:10.1016/j.quaint.2007.01.012

Interpreting lake isotope records of Holocene environmental change in the Eastern Mediterranean

Matthew D. Jones[1*] and C. Neil Roberts[2]

1. School of Geography, University of Nottingham, University Park, Nottingham, NG7 2RD. UK.

2. School of Geography, University of Plymouth, Drake Circus, Plymouth, PL4 8AA. UK.

* Author for correspondence. tel: 00 44 115 8468406 fax: 00 44 115 9514249
e-mail: matthew.jones@nottingham.ac.uk

Abstract

Oxygen isotope records from lake sediment archives are becoming an increasingly common tool for palaeoenvironmental reconstruction. We discuss their interpretation in the Eastern Mediterranean region with particular reference to three records, Zeribar, Van and Eski Acıgöl during the Holocene. The latter two records have been interpreted as controlled by changes in the precipitation to evaporation ratio, and the first due to changes in precipitation seasonality. In light of recent isotope work in the region and comparison with other proxy data from the same lakes, we show both of these initial interpretations to be oversimplified. Careful interpretations of complex lake isotope systems are therefore required in order that palaeoclimatic inferences are drawn correctly.

Keywords

lake, isotopes, Mediterranean, Holocene.

1. Introduction

Lake records provide continuous, potentially high resolution, terrestrial archives of environmental change. They therefore play an important role in the reconstruction of past climate and environment and allow comparison with other continuous archives such as marine sediments and ice cores. The use of oxygen isotopes recorded from biogenic or sedimentary hosts within lake sediments has become an increasingly common technique (Leng and Marshall, 2004) and a large number of lake isotope records from across the Mediterranean basin have now been published (Roberts and Jones, 2002). If fully understood these records have the potential to provide a regional picture of hydrological and climatic change. However, because there are multiple controls over the isotopic composition of lake waters, the interpretation of these records is far from straight forward and requires careful analysis.

Here we review oxygen isotope records from lake carbonates ($\delta^{18}O_c$) and their interpretations from lakes in the Eastern Mediterranean with reference to three key Holocene records; Lake Zeribar in western Iran (Stevens et al., 2001), Lake Van in eastern Turkey (Lemke and Sturm, 1997) and Eski Acıgöl (Roberts et al., 2001) in the Cappadocian region of central Turkey. These records have been interpreted in different ways and raise questions as to the "real" meaning of such $\delta^{18}O_c$ records.

The values of $\delta^{18}O_c$ precipitated from lake waters are determined by the temperature and isotopic value of the water (δ_l). Recent reviews by Leng and Marshall (2004) and Leng et al., (2006) discuss the controls on these systems in detail and so they will only be briefly outlined here. In open lake systems, with short residence times, lake waters generally have similar oxygen isotope values to the weighted average of precipitation. δ_l changes through time are caused by changing temperature, seasonality of precipitation or changes in the location and/or δ_l of the rainfall source area (Gat et al., 2001). Increases in temperature will lead to a net movement to more positive $\delta^{18}O_c$ (precipitation values change by +0.7‰ per 1°C increase in temperature although this is offset by a -0.24‰ per 1°C increase in temperature in the fractionation from δ_l to $\delta^{18}O_c$ (Stuiver, 1970)). Winter (cold) precipitation tends to have more negative isotope values and a change to more winter dominated precipitation will therefore push δ_l towards lower values. Sites further along given rain tracks tend to have more negative values as the heavier isotope (^{18}O) is preferentially rained out.

In closed systems, with a long residence time, evaporation plays a further role in changing δ_l (Li and Ku, 1997) by preferentially removing the lighter isotope (^{16}O) from the system and therefore shifting δ_l to more positive values. In regions of the world where evaporation exceeds precipitation, such as large parts of the Eastern Mediterranean, this is an important driver of lake isotope change.

2. Site descriptions and isotope records

The location of the three sites on which discussion in this paper is focussed can be seen in Figure 1 and the respective Holocene isotope records are shown in Figure 2. In all cases, stable isotope measurements were taken from bulk sediment samples rather than biogenic hosts such as molluscs or ostracods. The three sites represent a range of lake sizes, shapes and hydrological states (Table 1 and discussion below).

Eski Acıgöl (38°33'N, 34°32'E) is a former crater lake lying within a larger caldera in the Cappadocian region of central Turkey. The formerly brackish lake was drained in 1972. The record is dated using U/Th age estimates determined from the carbonate sediments (Roberts et al., 2001). Lake Van (38°32'N, 42°48'E) is a large deep saline lake in eastern Turkey. The core sequence was dated by varve counting (Lemke and Sturm, 1997). Lake Zeribar (35°32'N, 46°07'E) is a small-medium sized, relatively shallow freshwater lake located in north-western Iran. The sequence was dated by a number of calibrated radiocarbon dates (Stevens et al., 2001). Precipitation at Eski Acıgöl is lower than that at Zeribar and Van (Table 1) with Van sitting at the transition between rainfall regimes of the Anatolian plateau, as at Eski Acıgöl, and those of the Taurus/ Zagros mountains, as at Zeribar.

The isotopic records from Zeribar and Eski Acıgöl both show their lowest $\delta^{18}O_c$ values in the early Holocene increasing to higher values in the mid Holocene, at Eski Acıgöl c. 4 ka and c. 6ka BP at Zeribar (Fig. 2). The record at Zeribar shows a return to more negative values ~3 ka BP although values do not return to those of the early Holocene. The mean values of $\delta^{18}O_c$ from Zeribar are ~ 4‰ more negative than those from Eski Acıgöl.

The most negative isotope values at Van occur between 8 ka and 4 ka, later than at Eski Acıgöl and Zeribar. Early Holocene values i.e. before 8 ka are slightly more negative than those in the late Holocene, post 4 ka. Mean Holocene $\delta^{18}O_c$ values from Van are similar to those at Eski Acıgöl (Fig. 2).

Although the early-mid Holocene is characterised by lower isotope values and the late Holocene has a period of higher $\delta^{18}O_c$ in each record, detailed comparisons of the Holocene isotope shifts are difficult due to uncertainties with the age-depth models from all three sites. There are at least 1000 years missing from the Holocene varve sequence at Van (Wick et al., 2003), there are potential hard water errors in the radiocarbon age estimates from Lake Zeribar (Stevens et al., 2001) and there are large standard errors on the U-series age estimates from Eski Acıgöl (Roberts et al., 2001). We therefore make no attempt here to compare the precise timing of shifts in the records.

3. Interpretations

The records from Lake Van and Eski Acıgöl have previously been interpreted as changes in the precipitation evaporation ratio (P:E). Periods of net water loss

(E>P) lead to removal of the lighter isotope resulting in more positive isotope values. Alternatively during periods of P>E, isotope values become more negative. In both cases the early-mid Holocene isotope values are relatively negative compared to the late Holocene and are therefore interpreted as representing wetter climatic conditions. Additionally, mass-balance modelling used in the interpretation of the Van $\delta^{18}O_c$ record (Lemke and Sturm, 1997) showed that relative humidity was an important driver of P:E (specifically E) and suggested that the $\delta^{18}O_c$ record could be used to quantitatively reconstruct relative humidity through time.

Stevens et al. (2001) interpreted changes through the Holocene part of the Zeribar $\delta^{18}O_c$ record as due to changes in the predominant seasonality of rainfall at the site. They showed that increases in the percentage of precipitation falling in the winter months would lead to more negative isotope values of the annual weighted precipitation. As at Eski Acıgöl and Van, the record from Zeribar also shows more negative values in the early Holocene and more positive values in the mid to late Holocene. However, here the early Holocene was interpreted as a period of more winter dominated rainfall rather than as a period of more favourable P:E ratio.

4. Discussion

Although every lake must be interpreted on its own merits two broad schools of interpretation have emerged from these three sites. All records have relatively negative $\delta^{18}O_c$ values in the early-mid Holocene with a shift to more positive values by the late Holocene. The record from Zeribar has been interpreted from pollen and other proxies as showing a generally dry early Holocene with a wetter mid-Holocene (Stevens et al., 2001). Changes in $\delta^{18}O_c$ were interpreted as the result of changes in the seasonality rather than the amount of rainfall. This interpretation would be consistent with the environmental reconstructions from other pollen records across the eastern Mediterranean including central and eastern Turkey (e.g. van Zeist and Bottema, 1991). However the records from Lake Van and Eski Acıgöl, although showing similar overall isotope trends to Zeribar, have been interpreted as having a wet early Holocene and drier mid to late Holocene, with changes in $\delta^{18}O_c$ driven by changes in the precipitation: evaporation ratio (P:E). Resolving these two potentially contradictory interpretations is important for fully understanding Holocene climatic change in the eastern Mediterranean. We review and re-evaluate these interpretations in light of other proxy records, including the pollen data, from these and other archive sites as well as more recent work on $\delta^{18}O_c$ records in the region.

All three of the sites will be affected by changes in δ_l of the rainfall source area. Bar-Matthews et al. (2003) show that over the last two glacial-interglacial cycles changes in the isotope values of terrestrial precipitation, recorded in Israeli speleothems, have followed changes in Mediterranean sea waters, as recorded by marine foraminifera. Over the Holocene values of Mediterranean δ_l change by 2‰ towards more positive values and this may be the cause of some of the change seen in lake records. However, the magnitude of the shifts in the lake records are significantly larger (Fig. 2) than 2‰ and site specific processes are therefore likely to be the dominant control on $\delta^{18}O_c$ change.

4.1 Eski Acıgöl

Interpretation of $\delta^{18}O_c$ records from lakes must take into account the hydrological and morphological conditions of the given lake. Leng and Marshall (2004) suggest that different hydrological types and sizes of lakes will respond differently to common forcing mechanisms. In general hydrologically closed (i.e. non-outlet) basins will have higher average $\delta^{18}O_c$ values and will have larger amplitude shifts due to changes in temperature, via evaporation, than open short-residence basins that respond primarily to changes in δ_p. Larger closed lakes will have smaller shifts than small closed systems as there is a larger amount of water to damp any change. Eski Acıgöl has relatively high average $\delta^{18}O_c$ values (Fig. 2), typical of closed lake basins.

At Eski Acıgöl, records of other proxies taken from the same core sequence support the interpretation of a deeper, less evaporated lake and wetter early Holocene climate followed by a lake-level fall and drier mid to late Holocene (Roberts et al., 2001). Diatom-inferred conductivity is at its lowest throughout the early Holocene and increases during the mid Holocene to higher conductivities, associated with more negative water balance. Arboreal pollen increases throughout the early Holocene suggesting that conditions were becoming increasingly favourable for tree growth. The early Holocene sediments are laminated showing that lake waters were deep enough to be stratified compared to late Holocene sediments which are non-laminated, indicating a fall in lake levels.

In addition an annually resolved $\delta^{18}O_c$ record from carbonate varves from Nar Gölü (38°22' N, 34°27' E; 1363 m a.s.l.), a nearby analogue for Eski Acıgöl, has been compared to instrumental climate records and analysed using isotope mass balance modelling (Jones et al., 2005). It was found that both the amount of evaporation and precipitation were important in controlling $\delta^{18}O_c$, with a large (5‰) shift associated with a period of decreased evaporation and increased precipitation in the latter half on the 20th Century. Comparison of a 2 millennia long year record from this site (Jones et al., 2006) also showed links to both winter (wet) and summer (dry) climate regimes in Anatolia, suggesting the balance of these two was the driving mechanism behind lake isotope change.

On the other hand, modelling of the Eski Acıgöl isotope record (Jones et al., in press) indicates that controls on the $\delta^{18}O_c$ record are not simply a P:E story. Over the last glacial – interglacial transition, the $\delta^{18}O_c$ record has a stronger relationship with ground water outflow and lake depth/ volume than with P:E. It appears that it is the volumetric flux of water flowing through the lake, and the balance between water lost through evaporation and via ground water that are the dominant controls in this system. In contrast with the modelling of Lake Van (Lemcke and Sturm, 1997) the calculations from Eski Acıgöl suggest relative humidity has relatively little control on evaporation compared to shifts in temperature. Although E and P are clearly important underlying controls on this system the explanation is not as simple as originally postulated.

4.2 Van

As at Eski Acıgöl $\delta^{18}O_c$ values from Lake Van are relatively positive, typical of closed lake basins. Theoretically Lake Van would be expected to have the smallest range in $\delta^{18}O_c$ as it is a much larger lake than Eski Acıgöl and Zeribar and therefore changes are damped. This is indeed the case (Fig. 2) although given that Lake Van is a magnitude larger in size and volume compared to Eski Acıgöl the difference in $\delta^{18}O_c$ range between the two sites is relatively small, only ~ 2‰.

There is independent evidence, in the form of the Ca-Mg ratio in lake carbonates, that confirms significant changes took place in evaporation-driven lake water salinity at the same time as the shifts in $\delta^{18}O_c$ (Lemke and Sturm, 1997). Wick et al. (2003) compared these isotope and geochemical data against the pollen record from Van. As at Eski Acıgöl, the pollen record showed a rapid increase in grasses at the beginning of the Holocene followed by a slower increase in trees. There is little change in the pollen record associated with the mid to late Holocene dry period inferred from $\delta^{18}O_{c,}$ although the pollen record is also likely to have been affected by human land-use change in the late Holocene.

Lemcke and Sturm (1997) describe a direct relationship between the Lake Van $\delta^{18}O_c$ record and relative humidity. Jones et al. (2005) have shown that there is a strong relationship between relative humidity, temperature and precipitation on the Anatolian Plateau during the present day. Increased temperatures are associated with decreasing relative humidity, and decreasing precipitation, as the volume of air holding a given volume of water increases. However over glacial-interglacial time scales increasing temperatures lead to increases, not decreases, in relative humidity and therefore, more precipitation, due to higher evaporation. These differences would not matter if relative humidity were the sole controller of the $\delta^{18}O_c$ record, however it would affect interpretation if, as elsewhere, it is a balance of precipitation and evaporation that is important.

In the contemporary scenario increasing temperatures should lead to increasing evaporation and deceased precipitation, both of which would lead to higher $\delta^{18}O_c$. In the glacial - interglacial scenario increasing temperatures lead to both increasing evaporation and increased rainfall, two changes which drive isotope change in opposite directions. These scenarios are further complicated by the fact that evaporation and precipitation dominate in distinct seasons in the Mediterranean, driven by different climate systems. Changes in relative humidity in one season are unlikely to change climate conditions in another. It is therefore unlikely that the relationship between relative humidity and $\delta^{18}O_c$ in these lakes is constant over different timescales.

4.3 Zeribar

As the freshest of the lakes discussed here Zeribar has the lowest average $\delta^{18}O_c$ value (Fig. 2) but also the largest range of $\delta^{18}O_c$ of the three sites. If Zeribar were a fully open system, with water losses dominated by surface and/or ground water outflows, it would not be expected to show such a large range in isotope values. This suggests that either Zeribar loses a significant fraction of its water through evaporation or that $\delta^{18}O$ of the waters entering the lake are controlled by factors other than temperature. A shift of 7‰, the range of Holocene $\delta^{18}O_c$ values, would require a change in temperature of 15 ºC for an open lake system controlled only by changes in temperature (see Introduction).

This unlikely necessary shift in temperature is one of the lines of evidence taken by Stephens et al. (2001) to explain changes in $\delta^{18}O_c$ record as due to changes in the seasonality of rainfall at Zeribar. Change in precipitation isotope values (δ_p) can also occur if the source area of precipitation alters. Rindsberger et al. (1983) show that the isotope values of the three major rain baring air masses that reach Israel have distinct δ_p values. The range between the two extreme air masses is ~6‰. Changing the dominant storm tracks at Zeribar may have also therefore changed δ_p over the Holocene.

Carbonates tend to precipitate in lakes following increases in photosynthetic activity (Seigenthaler and Eicher, 1986) often in the early summer months following the spring diatom bloom (Jones et al., 2005). The relationship between temperature, $\delta^{18}O_c$ and δ_l is known (equation 1).

$$T = 13.8 - 4.58\ (\delta_c - \delta_l) + 0.08\ (\delta_c - \delta_l)^2 \qquad (1)$$

where T is the lake water temperature in degrees centigrade, δ_c is the isotope value of carbonate VPDB and δ_l is the isotope value of lake water VSMO (Leng and Marshall, 2004).

Mean temperatures in the Zeribar region today range between 2℃ in January and 28℃ in July (Wright, 1961). Given the $\delta^{18}O_c$ of surface sediments from Zeribar (-3‰) and precipitating water temperatures of 20 ± 5°C (estimated early summer temperatures), the carbonates in Zeribar are likely to have been precipitated from lake waters with values around -2‰ (Fig. 3). This compares to δw values of ~0.3‰ for Eski Acıgöl and Lake Van (given the same temperatures and δc values of +1‰). These values are significantly higher than the range of precipitation values specified by Stevens et al. (2001) i.e. -10 to -14‰ for Zeribar. These values of δ_p were calculated from data from Senyurt in Eastern Turkey. Precipitation at Zeribar is further along the winter storm tracks than at Senyurt and the actual values of δ_p are therefore likely to be even lower, due to preferential rainout of heavier isotopes.

Given that the isotope values from the sediments in Zeribar range between -3 and -8‰ VPDB during the Holocene, using a range of temperatures it is possible to compare the values of lake waters from which the carbonates were produced and the range in possible δ_p (Fig. 3). Temperatures during carbonate precipitation are likely to have been well within the range 10 to 30°C throughout the Holocene. At these temperatures, lake water at Zeribar during the Holocene would have been between -9 and 0‰ VSMOW during the period of carbonate precipitation. It is therefore hard to escape the conclusion that the waters from which the Zeribar carbonates formed were evaporatively enriched during at least the second half of the Holocene, and probably earlier also. Of the lake records discussed here, Zeribar is the one that will have been most sensitive to change in δ_p. However, it also seems highly likely that evaporation has been a significant control on the Zeribar isotope record during the Holocene.

Even though lake Zeribar is chemically dilute relative to Eski Acıgöl and Van, and the diatom evidence shows it to have stayed fresh throughout the Holocene (Snyder et al., 2001), it seems certain that it experiences a significant degree of evaporation, at least during the summer months. Even if precipitation and lake levels are high in the winter, during which time the lake may be open, by the early summer, when the carbonate is likely to be precipitated, it seems likely that the lake will have become closed and evaporated. Field reports indicate that the lake outflow dries up in summer (Löffler, 1961) when ground water outflow and lake evaporation therefore become the only pathways for water loss.

There are other East Mediterranean lake records with similar Holocene $\delta^{18}O_c$ values from Greece (Ioannina; Frogley et al., 2001) and Turkey (Gölhisar; Eastwood et al., in press). These are also shallow lakes with relatively large surface areas, similar to Zeribar, and have contemporary summer season lake waters that are evaporatively enriched relative to $\delta^{18}O_p$ by 6-7‰.

However the interpretation of the Zeribar $\delta^{18}O_c$ record is supported by records for other proxies from Zeribar. For example, the plant macrofossil record shows large numbers of aquatic plant species during the early Holocene, which has been interpreted as indicating relatively low lake levels at this time (Wasylikowa, 2005).

Records from Lake Mirabad, also in western Iran, show very similar isotopic trends to those from Zeribar (Stevens et al., in press). Comparison with Sr/Ca evidence has led Stevens et al. (in press) to infer - as at Zeribar - that more negative $\delta^{18}O_c$ values during the early Holocene were due to winter-dominated rainfall but within a climate that was dry overall.

5. Palaeoclimatic implications

Previous interpretations of Eastern Mediterranean climate based on pollen records (e.g. van Zeist and Bottema 1991, Roberts and Wright, 1993) led to the conclusion that modern levels of moisture availability were not achieved before mid-Holocene times. An increasing number of isotope records, including those from Van and Eski Acıgöl, and also non-lacustrine evidence such as speleothems and marine sapropel layers (e.g. Bar-Matthews et al.,1997; Ariztegui et al., 2000), now suggest an opposite pattern, with climatic conditions wetter than present during the first half of the Holocene. As both pollen and $\delta^{18}O_c$ records have many controlling mechanisms, arguments have been made to support both hypotheses.

It is possible that differences in the inferred histories of the three sites could be explained by a non-homogeneous pattern of climate change over the Holocene (cf. Griffiths et al., 2001). However the isotope and pollen data are similar at all three sites and also show the same patterns as many other records from the region, so that such an explanation seems improbable.

The nature of the mid Holocene climatic transition in the Eastern Mediterranean is an important issue in terms of understanding possible environmental effects upon early civilisation in the region (e.g. Rosen, 2006), and is also significant in terms of the teleconnections that control long term change in Mediterranean climate. Links between eastern Mediterranean lake records and north Atlantic and Indian Monsoon climate systems have been proposed (Bartov et al., 2003; Jones et al., 2006). The relative strengths of the summer and winter seasons are also important to whether these links have been consistent through time. Jones et al (2006), for example, show that periods of increased monsoon rainfall in the late Holocene are related to periods of increased evaporation in Anatolia. However records of the Indian monsoon (e.g. Fleitmann et al., 2003) show that the early Holocene is a period of high monsoon rainfall. The early Holocene was also relatively wet in North Africa (De Menocal et al., 2000). Given that many records now show the early Holocene in the Eastern Mediterranean to be wet this might imply that monsoon-Mediterranean teleconnections are coupled differently over different timescales (cf. Verschuren et al., 2004).

6. Conclusions

We have attempted to assess critically the range of different interpretations of isotope data from three lakes in the eastern Mediterranean and compared them against other proxy records from the same sites and elsewhere in the region. Lake isotope systems are clearly complex and each record must be interpreted on its own merits. However, previous interpretations of these systems may have been oversimplified based on general assumptions for given lake types, or driven by interpretations of other proxies, even if this was not readily explainable in terms of isotope change.

The difficulties in explaining $\delta^{18}O_c$ change are confounded by the ambiguity of some of the other proxy records from the same sites. Alternative explanations of the pollen records from these sites, for example, have already been offered elsewhere (Roberts, 2002). The different sensitivities of different proxies to evaporative enrichment, e.g. stable isotopes and aquatic biota, are also not yet fully understood. There is a lack of contemporary monitoring of these systems, although a robust understanding of the modern isotope hydrology of an individual lake is necessary to fully explain and understand past changes in isotope values. Despite this complexity, records of $\delta^{18}O_c$ provide important records of past climate and environmental change. With the increasing number of published records and an increase in process driven understanding, from models and climate calibration, the ambiguities in interpretation should diminish.

We conclude that the Holocene $\delta^{18}O_c$ records of all three lakes analysed here have been subject to some degree of evaporative enrichment. While P:E is not, *per se*, the principal direct parameter that has controlled their isotopic hydrology, both P and E (especially E) are important underlying controls on these lake systems. We have also shown that both specific controls (e.g. relative humidity) and external teleconnections (e.g. monsoon-Mediterranean) are likely to have operated differently over decadal to century as opposed to multi-millennial timescales.

7. Acknowledgements

We thank members of the ISOMED working group for early discussions regarding some of the topics discussed here. Details can be found at www.geog.plymouth.ac.uk/research/groups/is18omed.htm. Jamie Quinn is thanked for the drafting of Figure 1. An anonymous reviewer is thanked for constructive comments which improved the quality of the manuscript.

8. References

Ariztegui, D., Asioli, A., Lowe, J.J., Trincardi, F., Vigliotti, L., Tamburini, F., Chondrogianni, C., Accorsi, C.A., Mazzanti, M.B., Mercuri, A.M., van der Kaars, S., McKenzie, J.A. and Oldfield, F. (2000), Palaeoclimate and the formation of sapropel S1: inferences from Late Quaternary lacustrine and marine sequences in the central Mediterranean region. Palaeogeography, Palaeoclimatology, Palaeoecology 158, 215-240.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 1997. Late quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. Quaternary Research 47**,** 155-168.

Bartov, Y., Goldstein, S.L., Stein, M. and Enzel, Y. 2003. Catastrophic arid episodes in the Eastern Mediterranean linked with the North Atlantic Heinrich events. Geology 31, 439-442.

De Menocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L. and Yarusinsky, M. 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. Quaternary Science Reviews 19, 347-361.

Eastwood, W.J., Leng, M.J., Roberts, N. and Davis, B. (in press). Holocene climate change in the eastern Mediterranean region: a comparison of stable isotope and pollen data from a lake record in southwest Turkey. Journal of Quaternary Science.

Frogley, M.R., Griffiths, H.I. and Heaton, T.H.E. (2001), Historical biogeography and Late Quaternary environmental change of Lake Pamvotis, Ioannina (north-western Greece): evidence from ostracods. Journal of Biogeography 28, 745-756.

Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A. and Matter, A., 2003, Holocene forcing of the Indian monsoon recorded in a stalagmite from Southern Oman: Science 300, 1737-1739.

Gat, J.R., Mook, W.G and Meijer, H.A.J., 2001. Environmental Isotopes in the Hydrological Cycle; Principles and Applications. Volume 2: Atmospheric Water.

IAEA, Vienna. Accessible at http://www.iaea.org/programmes/ripc/ih/volumes/volume2.htm.
Griffiths, H. I., Schwalb, A. and Stevens, L.R. (2001) Environmental change in SW Iran: the Holocene ostracod fauna of Lake Mirabad, The Holocene 11, 757-764.
Jones, M.D., Roberts, C.N. and Leng, M.J. (in press). Quantifying climatic change through the last 21,000 years in central Turkey based on lake isotope palaeohydrology. Quaternary Research.
Jones, M.D., Leng, M.J. Roberts, C.N. Türkeş, M and Moyeed, R. 2005. A coupled calibration and modelling approach to the understanding of dry-land lake oxygen isotope records. Journal of Paleolimnology 34, 391-411.
Jones, M.D., Roberts, C.N., Leng, M.J. and Türkeş, M. 2006. A high-resolution late Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate. Geology 43, 361-364.
Lemcke, G. and Sturm, M., 1997. $\delta^{18}O$ and trace element Measurements as Proxy fro the Reconstruction of Climate Changes at Lake Van (Turkey): Preliminary Results. In: Dalfes, N.D. (ed.) Third Millennium BC Climate Change and Old World Collapse, NATO ASI Series. 149.
Leng, M.J. and Marshall, J.D., 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. Quaternary Science Reviews 23, 811-831.
Leng, M.J., Lamb, A.L., Heaton, T.H.E., Marshall, J.D., Wolfe, B., Jones, M., Holmes, J. and Arrowsmith, C. 2006. Isotopes in lake sediments. In: Leng, M. (Ed.) Isotopes in Environmental Research: Developments in Environmental Research Volume 10.
Li, H.C. and Ku, T.L., 1997. $\delta^{13}C$ – $\delta^{18}O$ covariance as a paleohydrological indicator for closed-basin lakes. Palaeogeography, Palaeoclimatology, Palaeoecology 133(1-2), 69-80.
Löffler, H. 1961. Beiträge zur Kenntnis der iranischen Binnengewässer II. Regional Limnologische Studie mit besonderer Berucksichtigung der

Crustaceenfauna. Internationale Revue der gesamten Hydrolobiologie und Hydrographie 46, 309-406.
Rindsberger, M., Magaritz, M., Carmi, I. and Gilad, D., 1983. The relation between air mass trajectories and the water Isotope Composition of Rain in the Mediterranean Sea Area. Geophysical Research Letters 10, 43-46.
Roberts, N. 2002. Did prehistoric landscape management retard the post-glacial spread of woodland in Southwest Asia? Antiquity 76, 1002-1010.
Roberts, N and Jones, M. 2002. Towards a Regional Synthesis of Mediterranean Climatic Change Using Lake Stable Isotope Records. *PAGES News* 10(2), 13-15.
Roberts, N. and Wright, H.E. Jr. (1993) Vegetational, lake-level and climatic history of the Near East and Southwest Asia, in H.E. Wright, Jr., J.E. Kutzbach, T. Webb III, W.F. Ruddiman, F.A. Street-Perrott and P.J.Bartlein (eds.) Global climates since the last glacial maximum, Minneapolis, University of Minnesota Press. pp.194-220.
Roberts, N., Reed, J., Leng, M.J., Kuzucuoğlu, C., Fontugne, M., Bertaux, J., Woldring, H., Bottema, S., Black, S., Hunt, E. and Karabıyıkoğlu, M., 2001 The tempo of Holocene climatic change in the eastern Mediterranean region: new high-resolution crater-lake sediment data from central Turkey. The Holocene 11, 719-734.
Rosen, A. in press. Civilizing Climate. Human responses to environmental change in the Ancient Near East. Altamira Press.
Siegenthaler, U. and Eicher, U., 1986. Stable oxygen and carbon isotope analyses. In: B.E. Berglund (ed.), Handbook of Holocene Palaeogeography and Palaeohydrology. John Wiley & Sons Ltd., pp. 407 - 422.
Snyder, J.A., Wasylik, K., Fritz, S.C. and Wright, H.E. (2001), Diatom-based conductivity reconstruction and palaeoclimatic interpretation of a 40-ka record from Lake Zeribar, Iran. The Holocene 11, 737-745.
Stevens, L.R., Ito, E., Schwalb, A. and Wright, H.E. Jr. (in press) Timing of atmospheric precipitation in the Zagros Mountains inferred from a multi-proxy record from Lake Mirabad, Iran. Quaternary Research.

Stevens, L.R., Wright, H.E. Jr. and Ito, E. (2001), Proposed changes in seasonality of climate during the late-glacial and Holocene at Lake Zeribar, Iran. The Holocene 11, 747-756.
Stuiver, M., 1970. Oxygen and carbon isotope ratios of fresh-water carbonates as climatic indicators. Journal of Geophysical Research 75, 5347-5257.
Verschuren, D., Briffa, K., Hoelzmann, P., Barber, K., Barker, P., Scott, L., Snowball, I., Roberts, N. and Battarbee, R.W. (2004) Holocene climate variability in Europe and Africa: a PAGES-PEPIII Time Stream 1 synthesis. In: Past climate variability through Europe and Africa, Battarbee, R.W., Gasse, F. and Stickley, C. (eds). Kluwer: Dordrecht, pp.567-582.
Wasylikowa, K. 2005 Palaeoecology of Lake Zeribar, Iran in the Pleniglacial, Late Glacial and Holocene reconstructed from plant macrofossils. The Holocene 15, 720-735.
Wick, L., Lemcke, G. and Sturm, M., 2003. 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. The Holocene 13, 665-675.
Wright, H.E. Jr 1961. Pleistocene glaciation in Kurdistan. Eiszeitalter ind Gegenwart 12, 131-164.
van Zeist, W. and Bottema, S., 1991 Late Quaternary vegetation of the Near East. Beihefte zum Tübinger Atlas des Vorderen Orients, Reihe A18, Dr L. Reichert Verlag, Wiesbaden, 156 pp.

Figures

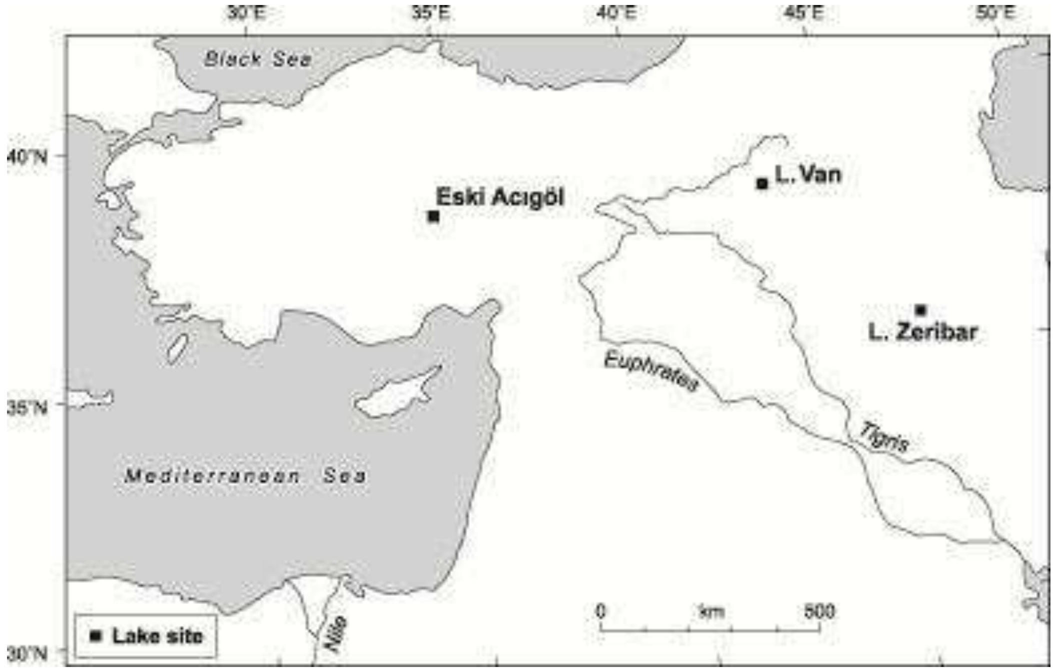

Figure 1 Map showing location of sites discussed in the text.

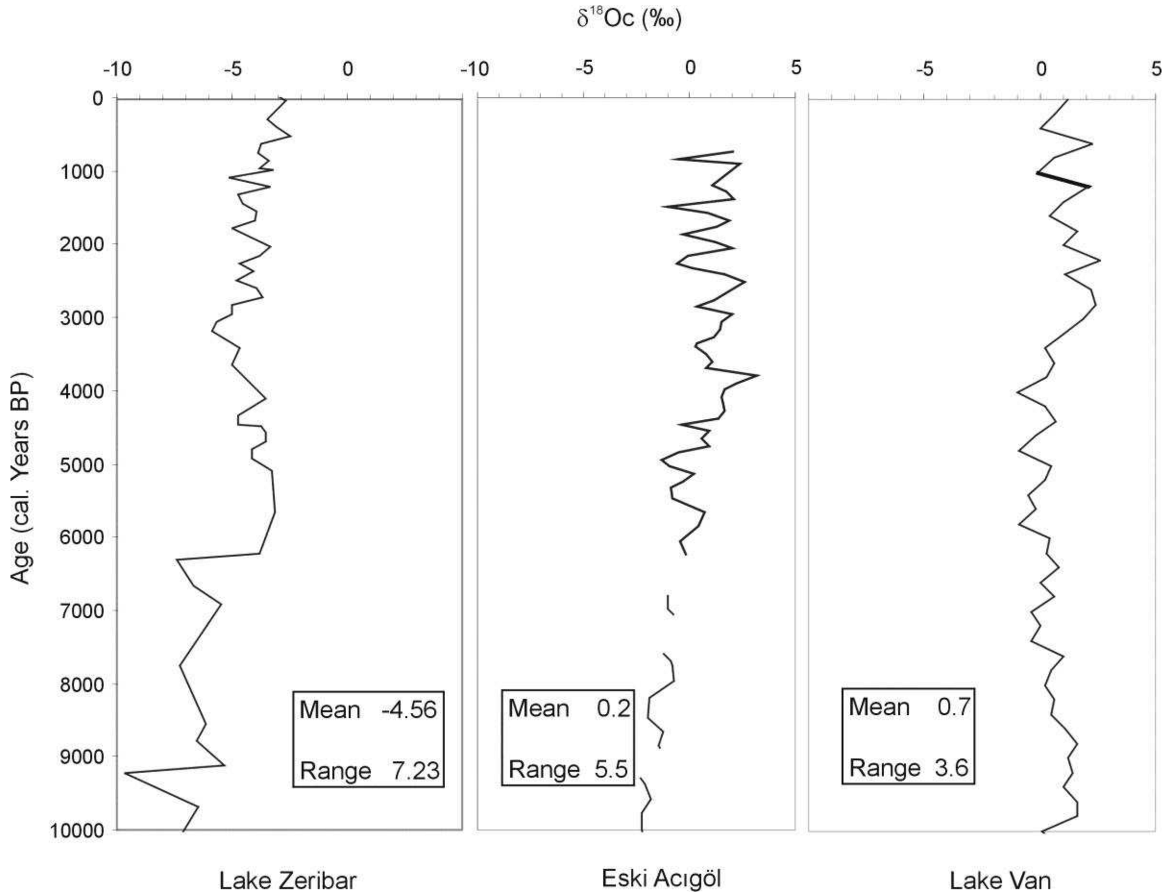

Figure 2 Lake isotope records from Lake Zeribar, Eski Acıgöl, and Lake Van. Lakes are ordered from freshest to most evaporatively enriched (Left to Right). Mean and range values from Van are estimates as the numerical data were not available.

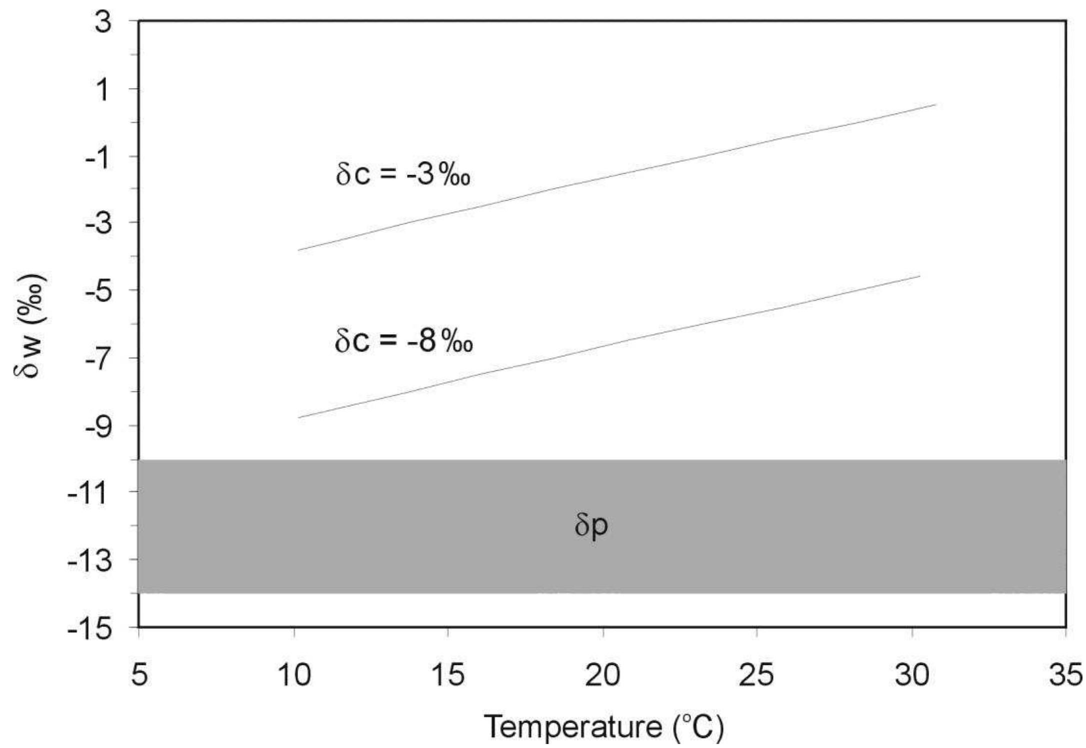

Figure 3 Possible values of δw at different temperatures given extreme Holocene values of δc from the Zeribar $\delta^{18}O_c$ record. Shaded zone shows possible values of δp from Stephens et al. (2001).

Table 1 Selected morphological and climate data from the three lakes discussed in this paper.

	Zeribar	Eski Acıgöl	Van
Lake Area (km^2)	6 - 7	0.5	3522
Max. Holocene Lake Depth (m)	5	30	460
Precipitation (mm)	800	400	400 - 800
Altitude (m a.s.l)	1300	1270	1648