

Fig. 2: Simulated (ECHAM4) seasonality of temperature, precipitation and  $\delta^{18}\text{O}$  over Central Greenland. Between 11 kyr BP and 14 kyr BP there is a pronounced reduction of winter precipitation, which is responsible for the strong bias of the isotope paleothermometer to warmer summer temperatures during near- and full-glacial conditions.

fairly equally distributed over the year, with a slight maximum in early autumn. A contrasting situation exists under near- or full-glacial conditions, marked by reduced precipitation overall, and most particularly during winter, thus strong-

ly biasing the water isotope signal towards that of the summer. This mechanism explains about 70% of the difference between the simulated spatial and temporal isotope-temperature gradients - the latter being unreasonably low (in the or-

der of  $0.2\text{‰}/^{\circ}\text{C}$ ) in the absence of correction for seasonality, which increases the gradient to about  $0.4\text{‰}/^{\circ}\text{C}$ . This provides a graphic example of the utility of isotopic-GCMs as “thinking tools”, since this profound shift in the temporal isotope-temperature relation can be related directly to the extreme southward shift of the winter polar front under glacial conditions and the concomitant suppression of meridional moisture transport to central Greenland, thus offering a clear mechanistic explanation for the apparent failure of the isotope paleothermometer across the glacial-interglacial transition (e.g., see Cuffey et al., 1995; Dahl-Jensen et al., 1998; Severinghaus et al., 1998; Lang et al., 1999).

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## Towards a Regional Synthesis of Mediterranean Climatic Change Using Lake Stable Isotope Records

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The Mediterranean basin is a climate-sensitive region with an exceptionally long and rich history of human use and abuse, stretching back to the advent of Neolithic farming in Southwest Asia around 10 kyr ago. These factors have led to a great interest in the environmental history of the region, especially through the last glacial-interglacial transition and the Holocene. However, the long and complex history of cultural-environmental relations has created some difficulties in distinguishing climate change from human impact in many palaeoenvironmental proxy records, for example through pollen analysis.

Unlike pollen, isotope-based records from non-marine settings are unlikely to be compromised by human impact, and a substantial volume of work from continental archives from the region is now appearing in the literature, in particular from lake records (Fig. 1).

This number of isotope records has the potential to allow comparison of environmental change across the Mediterranean basin. However, which specific climatic and environmental factors drive the changes in stable isotope ratios - as measured from various biogenic and authigenic fractions of lake sediment - remains under debate.

### Possible Controls on Isotope Values

One common feature of records for all but the most dilute, short residence-time lakes is a shift to more negative  $\delta^{18}\text{O}$  values during the late Pleistocene to early Holocene climatic transition (Fig. 2). Such a shift is precisely the reverse of the isotopic trend which characterises the same transition in lakes from the Alpine region and most of Central Europe and therefore demonstrates the relative unimportance of temperature as a driver of Mediterranean lake isotopic records over this time scale. A similar oxygen-isotope shift occurred in lakes at start of the last (MIS 5e) interglacial, and is also a feature of cave speleothem records, for example from Israel.

This leads to two main questions; firstly, if temperature is not the primary driver of isotope change in Mediterranean lake waters what is? Secondly, are all Mediterranean lakes driven by the same primary controlling mechanism?

Evaporation is an important factor in Mediterranean lake-water balance, particularly in the summer months. Lakes which have no outflow lose most of their water through evaporation and this has been shown to be a major factor in controlling both oxygen and carbon stable isotope values (Talbot, 1990). However, lakes which have an outflow and cannot therefore be classed as hydrologically "closed" systems, have none the less been shown to be evaporatively enriched in  $^{18}\text{O}$  during the summer months (Leng et al., 1999). This is probably due to the seasonal water balance in the lake, with evaporation being the dominant pathway for water loss during the summer, the time of the year when most authigenic carbonates are precipitated. Lakes may also become seasonally "closed" with surface outflow cut off due to lake-level fall during summer months. Significantly, these open but isotopically-enriched lakes have stayed chemically dilute. This means that

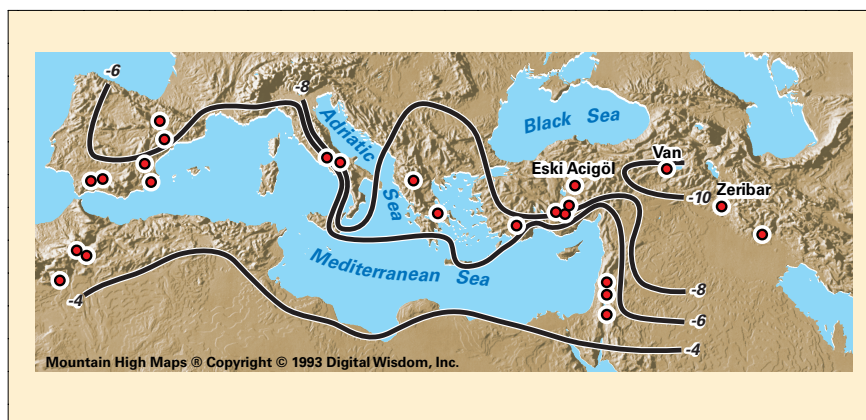


Fig. 1: Map of Late Quaternary lake-sediment stable isotope sites from the Mediterranean. Isolines show the mean weighted  $\delta^{18}\text{O}$  composition of precipitation inferred from IAEA data.

isotope-based methods may have a different, and lower, sensitivity threshold to lake water-balance changes than those based on measured or inferred lake salinity.

The flip side of the evaporation coin is precipitation. A positive shift in a stable isotope record could be due to a reduction in precipitation input to the system instead of - or as well as - an increase in evaporation. Stable isotope records from dry-land regions have therefore often been interpreted as changes in the precipitation:evaporation ratio (P:E), although it remains unclear which of the two plays the more important part in this ratio isotopically. Nor is the dominant climatic control over the amount and stable isotope composition of evaporation currently well understood.

Changes in rainfall seasonality, too, may have a significant effect on lake-water oxygen isotope values. Particularly at the eastern end of the Mediterranean basin, in a more continental setting, the differences between isotope values of summer and winter rains are large. Any change in the ratio of the amount of rainfall between these times would have a significant impact on the initial value of the waters entering the lake system.

Finally, the isotope composition of the precipitation source, especially over glacial - interglacial time scales, will also regulate the isotope value of precipitation. Mediterranean Sea waters follow the global oceanic shift from more

positive to more negative isotope values during glacial - interglacial transitions, and this may explain some of the changes observed in the lake records. On shorter time scales, marine events such as sapropel formation (as occurred during the early Holocene) can be linked to significant changes in sea-water oxygen isotope values.

All these factors, along with temperature, will affect the isotope values of lake waters and the resulting values of the carbonate preserved in the sedimentary record. The dominant control on the system will vary from lake to lake and over different time scales, and requires an understanding of the site-specific isotope hydrology of each lake basin.

### Regional Trends

Even with a range of possible factors controlling the changes in each lake isotope record, common trends do appear in different lake sediment records from across the region. However, although records show similar trends, the shifts in isotope values have been interpreted differently from site to site. Figure 2 shows the  $\delta^{18}\text{O}$  records from three East Mediterranean lakes lying in comparable climatic settings. In these examples, the negative shift in  $\delta^{18}\text{O}$  at the beginning of the Holocene at Eski Acigöl and Zeribar has been interpreted as indicating a rapid increase in precipitation at this time (Roberts et al., 2001; Stevens et al., 2001), while at Lake Van it has been linked to an increase

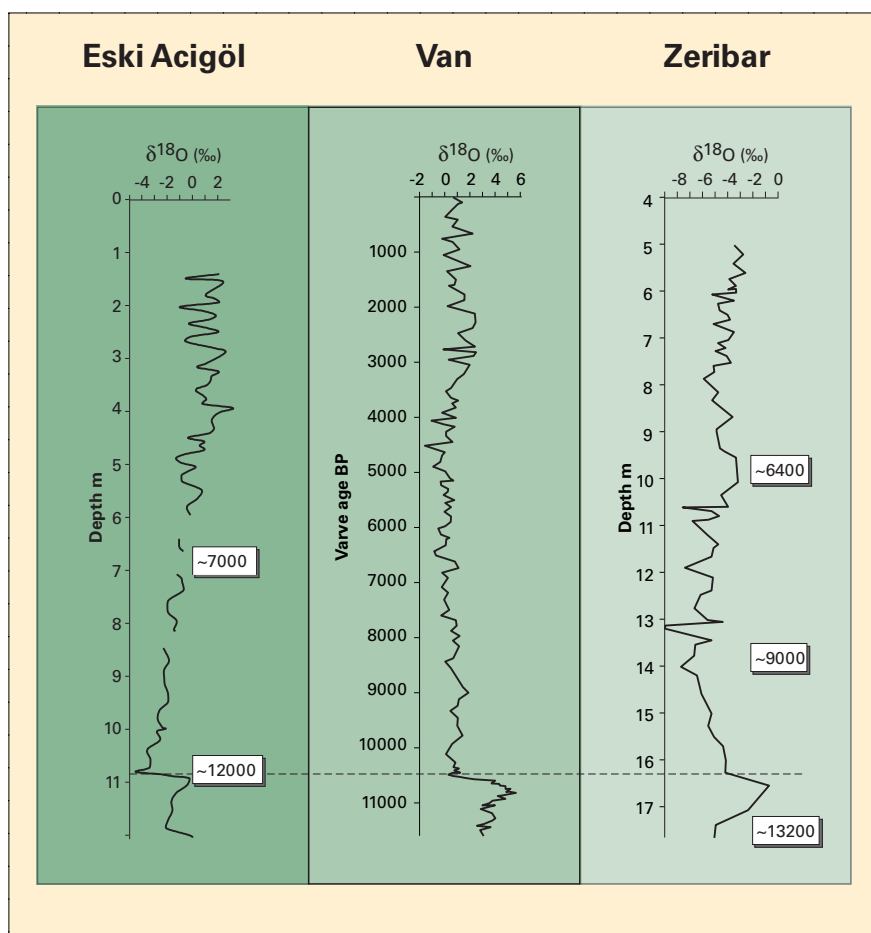


Fig. 2:  $\delta^{18}\text{O}$  records for the last ~12 kyr for three East Mediterranean lakes. The data are plotted on similar depth scales, with dates in calendar years BP. The dashed horizontal line marks the Pleistocene-Holocene boundary. Data from Roberts et al. (2001), Lemcke and Sturm (1997) and Stevens et al. (2001).

in relative humidity (Lemcke and Sturm, 1997).

A second common trend in lake records is towards more positive oxygen isotope values during the second half of the Holocene, although the precise timing of this shift appears to vary between sites. For the three lakes shown in Figure 2 rather different explanations have been proposed to explain this trend. The records from Eski Acıgöl and Van have been interpreted as representing drier climatic conditions during the later Holocene, via declining regional groundwater levels and decreasing relative humidity, respectively. In both cases, the interpretations of the stable isotope data are supported by other proxy-climate evidence of changes in water levels and salinity. The inferred wetter early-mid Holocene conditions in these lake records would have partly coincided with the last period of Mediterranean Sea sapropel

formation. By contrast, the Holocene isotopic record from Zeribar has been inferred to represent primarily changes in rainfall seasonality, rather than the P : E ratio (Stevens et al., 2001). Support for this interpretation comes from the fact that diatom, cladocera and plant macrofossil data indicate that Lake Zeribar waters have stayed dilute throughout the last ~11 kyr, and that absolute  $\delta^{18}\text{O}$  values are more negative than at the other two lakes.

### Conclusions

Due to the large number of possible controls on lake-water stable isotope values it is important that each site is interpreted independently. Knowledge of the modern stable isotope hydrology and comparison with other proxies from the same sediment sequences should allow controls on stable isotopes to be better understood.

It appears that even though potentially controlled by different dominant factors, the resulting stable isotope trends for lakes in the Mediterranean are similar through the deglacial transition as well as through the Holocene. The negative shift in  $\delta^{18}\text{O}$  at the beginning of the Holocene discounts temperature being a dominant control on Mediterranean lake systems, at least on long (>10 kyr) time scales. Indeed Mediterranean lake isotope trends share more in common with those in Africa and Tibet than they do with those in central and northern Europe.

For these issues to be resolved comparison is needed with further isotope records from well-dated sequences so that the degree of synchronicity between these trends can be established, not only in lakes but also in other archives of stable isotope hydrology such as speleothems and marine cores.

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