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# A high-resolution late Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate

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## **ABSTRACT**

A high resolution proxy record of precipitation and evaporation variability through the past 1700 yr from  $\delta^{18}\text{O}$  analysis of a varved lake sequence from central Turkey shows rapid shifts between dry periods (AD 300–500 and AD 1400–1950) and wetter intervals (AD 560–750 and AD 1000–1350). Changes are consistent with changes in instrumental and proxy records of the Indian monsoon, dry summers in the Eastern Mediterranean being associated with periods of enhanced monsoon rainfall. In addition major shifts in the record are coherent with changes in North Atlantic winter climate with cold, wet periods in the Alps occurring at times of dry Turkish climate.

**Keywords:** Turkey, paleoclimate, monsoon, isotopes, lake sediments, North Sea Caspian Index.

## INTRODUCTION

Water is a politically sensitive resource in the Eastern Mediterranean and understanding long-term hydrological variability is therefore important for the sustainable management of regional water resources. Studying pre-instrumental time periods allows the recognition of climate cycles and patterns on decadal and centennial time scales that are not clearly observable over the length of time available in most instrumental records. Knowledge of these sub-millennial climatic variations is important if future changes in climate and natural resource availability are to be accurately predicted.

In the Mediterranean region climate proxy archives, such as lake sediments (e.g., Stevens et al., 2001) and tree rings (e.g., Touchan et al., 2003), are likely to respond primarily to changes in hydrology. However there are few continuous, high-resolution, proxy climate records from the Eastern Mediterranean region, the longest spanning only the past 660 yr (Touchan et al., 2003). Lake oxygen isotope ( $\delta^{18}\text{O}$ ) records from Eastern Mediterranean lakes have been shown to measure predominantly changes in the precipitation: evaporation ratio, the key control over regional water balance (e.g., Leng et al., 1999; Jones et al., 2002). Here we present a high-resolution  $\delta^{18}\text{O}$  record from a varved lake sediment sequence through the past 1700 yr.

Studies of instrumental climate records during the 20<sup>th</sup> century have identified linkages between the Mediterranean and Indian monsoon climate systems during the Northern Hemisphere summer (Liu and Yanai, 2001; Raicich et al., 2003) and connections with North Atlantic climate patterns during the winter (Cullen and deMenocal, 2000). Detailed proxy records of past climate variability, as presented here, allow further analyses of these relationships and an assessment of how persistent they are through time. It also allows further discussion on the forcing mechanisms behind these systems.

## **STUDY AREA**

Nar Gölü is a climate-sensitive crater lake in the Cappadocian region of central Turkey (34°27'30''E; 38°22'30''N; 1363 masl). The varved record gives a robust time scale, the lake has a relatively simple hydrology, with no surface inflows or outflows, and the small catchment has undergone minimal late Holocene human disturbance that could have masked any relationship between the proxy record and climate. There are no carbonates in the watershed of this volcanic crater lake so the oxygen isotope record will not have been significantly affected by allogenic input.

The study area is semi-arid (precipitation = 0.32 myr<sup>-1</sup>; evaporation = 1.1 myr<sup>-1</sup>) and characterised by steppe-dry forest vegetation (Türkeş, 2003). Data from the nearest meteorological station to Nar, at Derinkuyu (25 km east), show that summers are very dry with rainfall in August and September, the driest months, accounting for only 2% of the annual total. April and May are the wettest months with 27% of the annual precipitation. The current Mediterranean-type climate of Turkey results from the seasonal alternation between mid-latitude frontal depressions, associated with polar air masses, during the winter and subtropical high pressure systems, from subsiding maritime and continental tropical air masses during the summer. In addition the north-western extension of the Asiatic monsoonal circulation causes very dry and hot conditions over the Middle East region, including the southern and central parts of Turkey (Türkeş, 1990).

## **METHODOLOGY**

A 3.76 m core sequence obtained using Glew and Livingstone samplers from the deepest part of Nar Gölü (26 m water depth) consists of 1725 couplets of summer precipitated calcium carbonate and diatom-rich organic layers deposited between autumn and spring. Sediment traps,

along with  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  dating of the top 50 cm of this sequence, show these couplets to be annual (Jones et al., 2005). Dating of the rest of the core sequence is therefore based on varve counts given in varve years before AD 2001 converted to a calendar time scale. The varve counts were replicated in two additional cores from different parts of the basin. Comparisons of these three counts show that varve ages from the sequence have a maximum possible uncertainty of 2.5% of the given age.

Each of the top 900 carbonate varves was individually analyzed for  $\delta^{18}\text{O}$  with the following 825 varves analyzed from contiguous bulk samples at a 5 yr resolution.  $\delta^{18}\text{O}$  was measured using classical vacuum techniques and an Optima duel inlet mass spectrometer with analytical precision better than  $\pm 0.1\%$ .

## **RESULTS AND INTERPRETATION**

Comparison of the Nar  $\delta^{18}\text{O}$  record (Fig. 1B) and summer evaporation calculated from instrumental climate data between 1926 and 2001 shows a close relationship, including the large shift in isotope values between 1960 and 1980 which is associated with a reduction in summer temperatures and an increase in relative humidity. However, modeling of the lake stable isotope hydrology showed that an increase in precipitation was also required to produce the amplitude of isotope value change recorded in the latter half of the 20<sup>th</sup> century (Jones et al., 2005). Although insufficient precipitation data were available from the immediate study area to verify this, precipitation data from the same climate region, at Ankara, do show an increase in precipitation of the magnitude implied by the model.

The Nar Gölü  $\delta^{18}\text{O}$  record can therefore be considered as a proxy for regional water balance. The large shift c. AD 530 is probably due to an increase in winter rainfall and decrease in summer evaporation, as shown during the instrumental time period, while the shifts at AD

1400 and AD 800 must therefore have been due to a decrease in winter rainfall and an increase in summer evaporation. In addition calcium carbonate mineralogy changes through the core, with aragonite deposition during periods of more positive isotope values i.e., pre AD 530 and between AD 1400 and 1960. During periods of more negative isotope values (AD 530 to AD 1400) calcite is precipitated. This independently confirms the role of evaporation as a controlling factor on long term trends in  $\delta^{18}\text{O}$  values at this site as aragonite is more typical of evaporated systems (Kelts and Hsu, 1978). Changes in mineralogy, which occur during the major shifts in the  $\delta^{18}\text{O}$  record accounts for up to 0.6‰ of the change due to the differences between calcite-water and aragonite-water fractionation (Leng and Marshall, 2004).

The major changes in the record therefore suggest that during the period AD 1400–1960 and prior to AD 500 summer drought intensity increased and winter rainfall decreased in central Anatolia. This contrasts with a period of generally lower summer evaporation and increased winter rainfall between AD 530 and AD1400, with a short term shift to drier conditions c. AD 800.

The lower amplitude, multi-decadal variability which is evident in the Nar isotope record, could be driven by changes in summer evaporation, winter precipitation, or both. Understanding which of these is the dominant control can be further investigated by looking at connections with other climate and proxy records.

## **SUMMER TELECONNECTIONS**

Comparison of the Turkish lake  $\delta^{18}\text{O}$  record with records of monsoon rainfall from India (Parthasarathy et al., 1995) through the instrumental time period (Fig. 2) show that increased periods of monsoon rain are associated with more positive isotope values at Nar, that is, periods of increased Eastern Mediterranean summer evaporation, and vice versa. Previous work has

shown links between the contemporary Mediterranean climate and the Indian Monsoon system (Liu and Yanai, 2001). Deepening low pressure over southern Asia, which leads to increased monsoon rainfall, strengthens the north and north-easterly airflows (the meltemi [meltem], or etesian [poyraz] winds) sourced in the warm, dry continental Central Asian region (Raicich et al., 2003) and increases summer drought in the Eastern Mediterranean.

The Nar Gölü oxygen isotope record allows this relationship to be tested through time with annual to decadal precision. Previous stable isotope records of late Holocene climate change from Eastern Mediterranean lakes, speleothems and deep sea sediments have lacked the chronological resolution to allow robust comparisons with high-resolution proxy records of the Indian monsoon, having only one or two data points per century (e.g., Lemke and Sturm, 1997; Bar Matthews et al., 1997; Stevens et al., 2001; Schilman et al., 2001).

Here the 1700 yr record from Nar is compared to proxy records of Indian monsoon rainfall from a speleothem  $\delta^{18}\text{O}$  record from Qunf cave, Oman (Fleitmann et al., 2003; Fig. 1C) and a varve thickness record from the Arabian Sea (von Rad et al., 1999; Fig. 1D). Although the speleothem record does not cover the full time period covered by the Nar Gölü sequence, the records imply that the relationship observed during the instrumental time period has also operated through the past 1400 yr, with increased summer aridity in central Turkey occurring at times of enhanced Indian monsoon rainfall.

The varve thickness record from the Arabian Sea has been inferred to indicate a period of relatively low monsoonal rainfall between c. AD 600 and c. AD 1500, a period of reduced evaporation at Nar, and periods of increased monsoon rain between AD 200 and 600 and between AD 1600 and the present day, periods of negative water balance at Nar Gölü. The major difference between the two records is the time taken for the transition between these wet and dry



periods. The Arabian Sea record shows transitions in the order of 200 yr compared to the 60–90 yr the transitions take at Nar. These differences are not fully understood but may reflect the rapid and nonlinear response of some lakes to large-scale changes in monsoon climate compared to other proxy archives (Fleitmann et al., 2003).

As well as the abrupt, high-amplitude shifts and centennial trends in the Nar record, decadal scale cyclic variability is also evident. Spectral analysis of the isotope data shows significant periodicities at 135, 58 and 33 yr (Fig. 3). Similar periodicities are also observed in the instrumental record of Indian rainfall (64 yr), the varve thickness record (125 and 57 yr; von Rad et al., 1999), and in aluminum variability (~54 yr; Agnihotri et al. 2002) in the Arabian Sea, another proxy of monsoon rainfall.

## **WINTER TELECONNECTIONS**

Although there appears to be a persistent link with Indian monsoon variability through time this cannot account fully for the spring and winter dominated changes in precipitation, required to explain the large shifts in the Nar isotope record. Changes in winter precipitation in Turkey are most likely driven by variability in North Atlantic climate patterns. Changes in glacier extent in the Alps show very similar trends to the centennial scale variability recorded at Nar (Holzhauser et al., 2005), with periods of glacier advance recorded at the same time as the more positive isotope values at Nar (Fig. 1A). This suggests that there must have been major changes in Northern Hemisphere circulation at these times leading to glacier advance in the Alps, i.e., cool and wet conditions, and to negative water balance in Turkey, i.e., relatively dry winter climate conditions. Meeker and Mayewski (2002) also showed a significant shift in Arctic storminess at AD 1400 which occurs at the same time as the shift in the Nar isotope record, again suggesting a link between the Nar record and North Atlantic variability.

There is a slight difference in timing between the start of the Alpine glacier advance at AD 1300 and the shift in the Nar record ~100 yr later. Both these systems require change in temperature (evaporation) and precipitation to effect large-scale change and this may account for some of the difference in event timing. The Nar record requires change in both winter and summer conditions before a shift of the magnitude observed would occur.

Some of the North Atlantic variability leading to these changes may be associated with changes in the North Atlantic Oscillation (NAO) as this is known to control precipitation variability in Turkey (Cullen and deMenocal, 2000), particularly in winter (Türkeş and Erlat, 2005), and in the Alps (Holzhauser et al., 2005), although the influence on Alpine climate is less clear as it sits between the influence of both zonal (positive NAO) and meridional (negative NAO) air flow. In Turkey, periods of predominantly meridional flow lead to wetter winters.

However, changes in the NAO alone would not account for the shifts observed in the Nar record. The post AD 1400 period has been shown to be characterised by generally negative NAO conditions (Jones et al., 2001), which would suggest winters would have been wetter in Turkey. This is not supported by the Nar record, which shows a period of drier climate through this time period. The NAO index also becomes more positive through the latter half of the 20<sup>th</sup> century, a period of increased rainfall at Nar.

Kutiel and Benaroch (2002) define an atmospheric teleconnection index between the North Sea and the Caspian Sea (NCPI) that has been shown (Kutiel et al., 2002) to have a significant impact on eastern Mediterranean climate. Negative phases of the NCPI are associated with increased rainfall in south west Turkey including the Cappadocia region. There is a shift from positive (drier) to negative (wetter) values of the spring NCPI, the period of maximum rainfall at Nar, between 1960 and the late 1980's (Fig. 2) during the time the Nar isotope values

become more negative and the isotope modeling suggests an increase in precipitation. There are no palaeo-reconstructions of the NCPI; however the record from Nar would suggest that the period between AD 1400 and AD 1960 was a period of dominantly positive NCPI with the period AD 500 to AD 1400 a period of predominantly negative NCPI.

Overall the Nar record shows links to both the North Atlantic (winter) and Indian monsoon (summer), with changes in both these systems leading to rapid and extreme shifts in the Nar isotope record c. AD 530 and AD 1400. In addition multi-decadal variability at Nar is consistent with changes in evaporation linked to the Indian monsoon.

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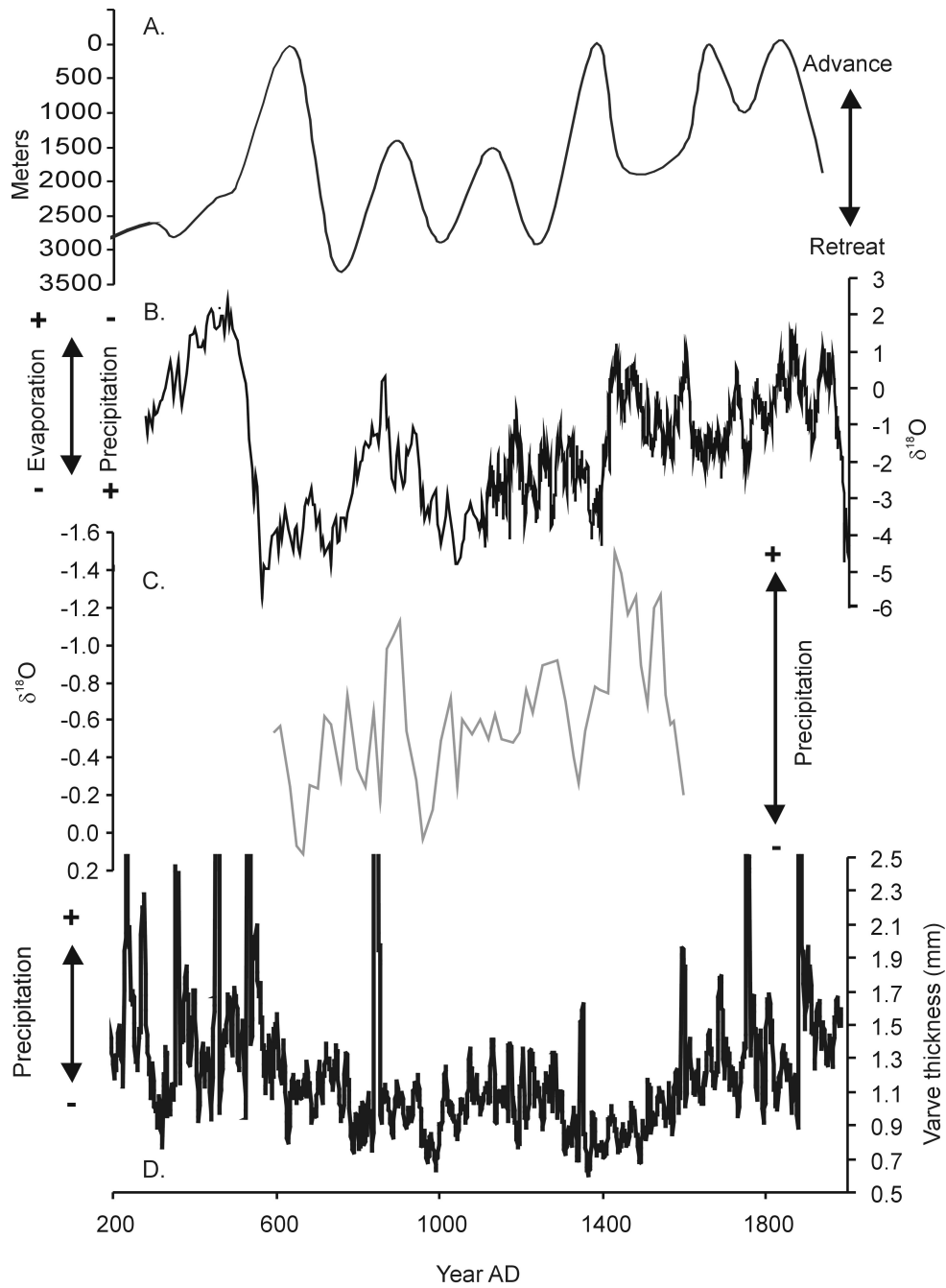


Figure 1

Figure 1.  $\delta^{18}\text{O}$  record from Nar Gölü (B) compared to records of Alpine glacier advance (A; Holzhauser et al., 2005) and proxy records of the Indian Monsoon from Qunf Cave, Oman (C; Fleitmann et al., 2003) and the Arabian sea (D; von Rad et al., 1999).



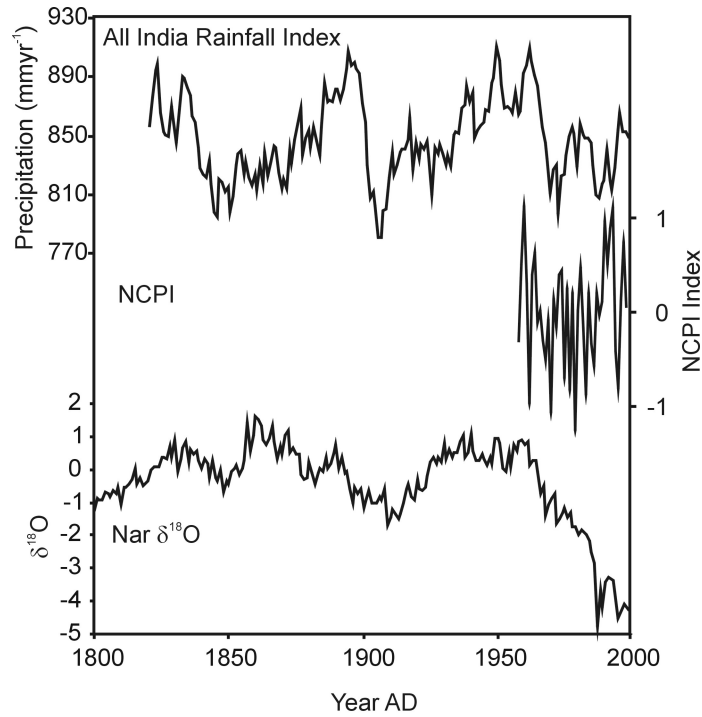


Figure 2

Figure 2. Comparison of the Nar  $\delta^{18}\text{O}$  record with the All India Rainfall Index (Parathasarathy et al. 1995) and NCPI (Kutiel and Benaroch, 2002).

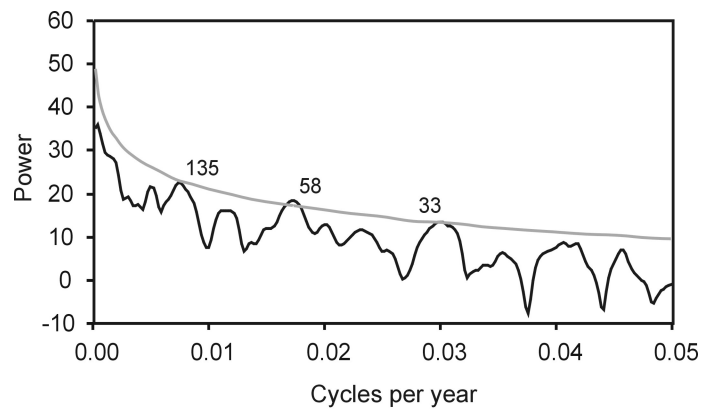


Fig. 3

Figure 3. Power spectra of the Nar  $\delta^{18}\text{O}$  record showing significant cycles ( $> 95\%$  confidence limit; gray line). Spectrum obtained from Lomb-Scargle Fourier transform using SPECTRUM (Schulz and Stettger, 1997).