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Quantitative assessment of glacial fluctuations in the level of Lake Lisan, Dead Sea rift

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ABSTRACT

A quantitative understanding of climatic variations in the Levant during the last glacial cycle is needed to support archaeologists in assessing the drivers behind hominin migrations and cultural developments in this key region at the intersection between Africa and Europe. It will also foster a better understanding of the region's natural variability as context to projections of modern climate change. Detailed documentation of variations in the level of Lake Lisan – the lake that occupied the Dead Sea rift during the last glacial cycle – provides crucial climatic information for this region. Existing reconstructions suggest that Lake Lisan highstands during cold intervals of the last glacial cycle represent relatively humid conditions in the region, but these interpretations have remained predominantly qualitative. Here, I evaluate realistic ranges of the key climatological parameters that controlled lake level, based on the observed timing and amplitudes of lake-level variability. I infer that a mean precipitation rate over the wider catchment area of about 500 mm y^{-1}, as proposed in the literature, would be consistent with observed lake levels if there was a concomitant 15–50% increase in wind speed during cold glacial stadials. This lends quantitative support to previous inferences of a notable increase in the intensity of Mediterranean (winter) storms during glacial periods, which tracked eastward into the Levant. In contrast to highstands during 'regular' stadials, lake level dropped during Heinrich Events. I demonstrate that this likely indicates a further intensification of the winds during those times.

1. Introduction

The Levant is located at the intersection between Africa and Europe, and is one of a few prime routes for hominin migrations and cultural exchanges between these continents (e.g., Fernandes et al., 2006; Abbate and Sagri, 2012; and references therein). Archaeologists require a detailed and well-dated understanding of climatic variations in the region in order to assess the potential role of climate in driving or facilitating hominin migrations and cultural developments.

Implications for hominins are not the only reason for striving toward a better understanding of Levantine climate variability. Parts of the region are highly sensitive to potential aridification under global climate change (e.g., Watson et al., 1997), and future projections require a sound understanding of any underlying natural variability. Similarly, intensive anthropogenic water use (e.g., diversion of the Jordan River) and proposed engineering projects such as a Red Sea–Dead Sea canal are presenting unprecedented challenges to the environment, assessment of which may be helped by a better understanding of the region's natural variability (for evaluations of these contemporaneous issues, see for example: Salhotra et al., 1985; Stanhill, 1994; Alpert et al., 1997; Asmar and Ergenzinger, 2002a,b,c,d; 2003; Lensky et al., 2005).

The present paper focuses on natural variability during the last glacial cycle (specifically, the last 120,000 years). A recent overview (Frumkin et al., 2011), which extends on previous syntheses (e.g., Enzel et al., 2003, 2008), offers a comprehensive overview of climatic changes in the Levant based on varied evidence. This included changes in the level, sedimentology, and chemical properties of Lake Lisan (Fig. 1), cave speleothem deposits, and loess deposits in the region. In particular, reconstructions indicate a similarity between Lake Lisan level fluctuations and Northern Hemisphere climate 'cycles' as recorded in Greenland ice-core records (among many others: Bartov et al., 2002; Migowski et al., 2006; Stein and Goldstein, 2006; Waldmann et al., 2007, 2010; Lisker et al., 2009; Torfstein et al., 2009, 2013a; and Stein, Goldstein, and Enzel, pers. comm. at the Ein Gedi fieldtrip, 2012). Early work

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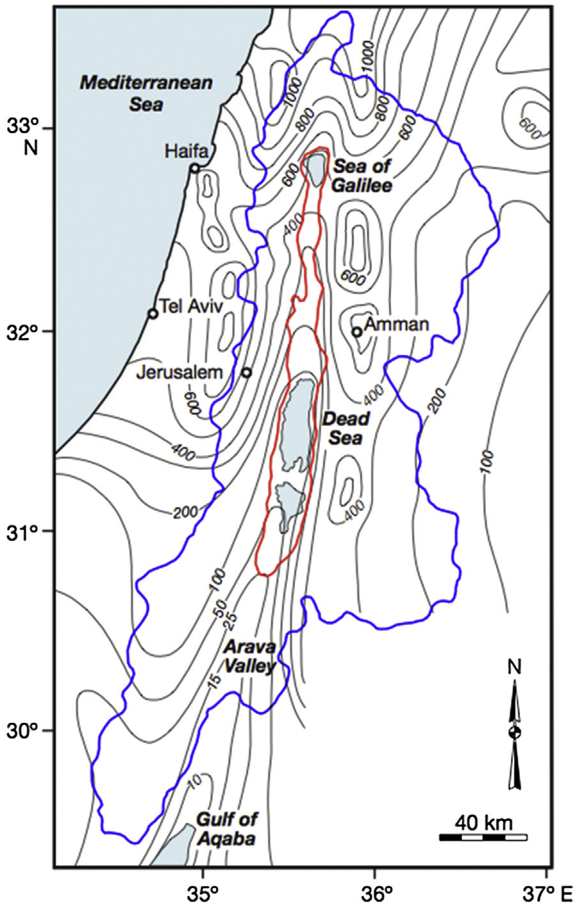

Fig. 1. Map of the Levant, with annual mean isohyets (in mm y^{-1}). The red line outlines the maximum size of Lake Lisan, and the blue line outlines the Dead Sea/Lake Lisan catchment area. Modified after Waldmann et al. (2010), with additional catchment data from FAO GEONETWORK (2010).

had suggested that cold episodes in Greenland correlated with arid conditions in the Levant on decadal to centennial timescales (e.g., Prasad et al., 2004). However, the detailed studies listed above comprehensively demonstrate that cold episodes were instead associated with Lake Lisan highstands on multi-centennial to millennial timescales, reaching up to 200 m or more above the modern Dead Sea level. Intervals corresponding to Heinrich events appear to have deviated from that pattern, with dry conditions and relative lowstands in Lake Lisan (although still 60–120 m above the present-day Dead Sea level; Bartov et al., 2003; Torfstein et al., 2013a).

The previous work generally argued that Lake Lisan highstands represent climatically wet episodes. To date, however, such interpretations have remained largely phenomenological, did not really account for variability in the (large) evaporative loss term, and were expressed in qualitative or semi-quantitative terms only. The present study builds on this previous work and on modelling of recent changes in the region (Salhotra et al., 1985; Stanhill, 1994; Alpert et al., 1997; Asmar and Ergenzinger, 2002a,b,c,d; 2003; Lensky et al., 2005), to advance a quantitatively coherent understanding of relationships between the various observed aspects of regional climate variability over the last glacial cycle. A basic model is developed in which lake level depends on changes in evaporation from the variable Lake Lisan surface area, and on mean net precipitation over the wider catchment area. I then evaluate – for observed timings and amplitudes of lake-level variations – realistic precipitation ranges over the wider catchment, given values (with uncertainties) of evaporation fluctuations that are based on realistic ranges of variability in key climatological parameters. The solutions provide internally consistent suites of potential variability in the regional climate (precipitation, evaporation, wind speed) and lake level over the last glacial cycle. The model is not exhaustive and lacks details that are included in the aforementioned studies of recent changes, which is deliberate to make it applicable to the long timescales and large uncertainties (shortage of direct measurements) associated with geological studies. Despite these simplifications, the results provide indicative, internally consistent, first-order estimates of regional environmental variability.

2. Method

As with any lake, fluctuations in the level of Lake Lisan (H) reflect the integration over time of mean net precipitation (Ψ) over the lake's wider catchment area (A_{catch}), and evaporation (E) from the lake's surface area (A). The lake's surface area varies with its level; as lake level rises, the lake occupies more of the rift valley, and its surface area increases (Fig. 1). This variation of surface area with lake level is important, because the rate of evaporation, which affects the lake surface area, is high in this region. Currently, the rate of evaporation from fresh water (often referred to as 'pan evaporation') is of the order of -3 m y^{-1} in this region (Alpert et al., 1997). Due to the influences of high salinity (around $S = 276$), however, the rate of evaporation from the sea itself is near to -1.3 m y^{-1} (note, these are pre-1951 values that pre-date extensive anthropogenic diversion of the Jordan River) (Salhotra et al., 1985; Stanhill, 1994; Alpert et al., 1997). In contrast to A, the size of A_{catch} (which receives the precipitation that feeds the lake) is determined by the larger-scale regional topographic configuration, which is assumed to have remained constant throughout the last glacial cycle (Fig. 1).

Today, A_{catch} is roughly 40 times larger than the Dead Sea surface area (e.g., Waldmann et al., 2010; Frumkin et al., 2011) (Fig. 1). To maintain the Dead Sea at steady state, water gain from mean net precipitation (Ψ_{mod}) over the catchment must balance the evaporative water loss (-1.3 m y^{-1}) over the Dead Sea surface area ($A_{DS_{mod}}$). Rapid responses of the Dead Sea level to modern droughts demonstrate that this steady state response is not greatly delayed by groundwater inertia (Enzel et al., 2003), which agrees with experiments that reveal high groundwater flow rates (Magal et al., 2010). Hence, Ψ_{mod} over A_{catch} in this steady state scenario needs to be of the order of 1.3/40 m per year; i.e., 33 mm y^{-1}. Using the approximation given in Frumkin et al. (2011) for modern mean gross precipitation (P_{mod}), which is $P_{mod} = \Psi_{mod}/0.3$, P_{mod} is estimated at 110 mm y^{-1}, where the difference between P_{mod} and Ψ_{mod} is due to evaporation and evapotranspiration. The value of 110 mm y^{-1} determined here for mean annual precipitation over the lake's catchment area compares well with the rainfall distribution compilations of Enzel et al. (2003, 2008), Waldmann et al. (2010) and Frumkin et al. (2011) (Fig. 1).

Evaporation from a freshwater body predominantly depends on surface-water and air temperature (and, therefore, on the lake-air temperature difference), relative humidity, and wind stress. Here I adapt the calculations of Rohling (1999) to the Dead Sea/Lake Lisan configuration. In that formulation, evaporation from low-salinity waters (in m y^{-1}) is given by:

$$E_{lowS} = -\rho_a LCV(q_s - rq_a)1.26 \times 10^{-2} \quad (1)$$

where ρ_a is the air density at mean lake-level pressure (set to 1012 mbar); $L = (2500.83 - 2.34T_s) \times 10^3$ is the latent heat of vapourisation in J kg^{-1} at surface-water temperature T_s in °C (Abbott and Tabony, 1985); $C = 1.15 \times 10^{-3}$ is an exchange