ABSTRACT

The response of continental climate to the well-documented climate oscillations during the last glacial period has been a subject of intense interest, yet much less is known about the influence on regional continental climates than in the marine or polar realms of Earth. The detailed lake-level history of the closed Lake Lisan (paleo–Dead Sea) in the Middle East has been reconstructed from shoreline indications and high-resolution U-Th and 14C chronologies, thus providing data on the response of the lake's catchment area to the climate changes during the corresponding period. We present a correlation between the newly developed Lake Lisan level curve for the past 55 k.y. and the North Atlantic Heinrich events. The correlation indicates a closely connected climate response between these North Atlantic events and the hydrological conditions that prevailed in the Eastern Mediterranean. Our findings show that although the generally cooler conditions that prevailed during the last glaciation favored high levels of the lake, catastrophic events in the North Atlantic, which are associated with maximum cooling, have been responsible for droughts in the Eastern Mediterranean. We infer that cold-water input to the Mediterranean originating in the collapse of the North Atlantic Deep Water circulation caused the reduction of evaporation and less precipitation in the Eastern Mediterranean.

Keywords: Lake Lisan, lake levels, Heinrich events, paleoclimate, Eastern Mediterranean.

INTRODUCTION

The late Pleistocene is characterized by rapid changes in global climatic conditions as reflected in the growth and retreat of large ice sheets, sea-level changes, and isotopic compositions of polar ice and deep-sea cores (Chappell and Shackleton, 1986; Dansgaard et al., 1993; Yokoyama et al., 2000; Johnsen et al., 1992). Analyses of deep-sea cores and polar ice revealed the important effects of abrupt Dansgaard-Oeschger warmings and Heinrich events (Bond and Lotti, 1995; Broecker, 1994) on North Atlantic climate during the last glacial period. Although the climatic consequences are assumed to affect large areas on Earth, there is a lack of well-dated evidence of the impact of such events on continental regions.

Paleo–lake-level studies are important for reconstructing the past continental climatic record because they provide a sensitive means to evaluate water balance (Street-Perrott and Harrison, 1985). They can be used for monitoring the magnitude of hydrological changes. In combination with high-resolution lake-level chronologies, the relationship between timing of global events and regional hydrological records can be established. Such coupling is potentially a powerful means for understanding mechanisms of transferring climate signals over the globe and elucidating their imprint on continental climates (e.g., Allen et al., 1999).

REGионаl settingS

Past lakes in the Dead Sea basin (Fig. 1) were sensitive to water input, and changes in their levels reflect variability in regional hydrology and climate (Neev and Emery, 1967; Stein, 2001; Bartov et al., 2002). Here we report a high-resolution lake-level curve for Lake Lisan (ca. 70–15 ka), which is based on determination of shore indicators and their ages (Schramm, 1997; Schramm et al., 2000; Barton et al., 2002).

The Lake Lisan sediments are mainly laminated aragonite and detrital silts, occurring at near-annual resolution, plus nearshore clastic layers. The aragonite, which directly precipitated from the lake, occurs in pure, well-defined laminae and thus is appropriate for U-series and 14C age dating (Kaufman, 1971; Schramm, 1997; Schramm et al., 2000; Barton et al., 2002). The identification of numerous indicators of buried ancient shorelines within the exposed Lake Lisan deposits (Machlus et al., 2000; Barton et al., 2002) allowed the physical correlation in the field between paleo–shore environments and the dated aragonite (Fig. 2).

The limnological behavior of Lake Lisan reflects intervals of extensive input of freshwater, resulting in lake-level rise, a (density) layered structure, and precipitation of aragonite (Stein et al., 1997). Evaluation of Lake Lisan deposits, along with U-series ages of the aragonites, shows that during the last glacial period, the colder marine isotope stage (MIS) 2 and 4 times were major wet periods, whereas the warmer MIS 3 was relatively drier (Stein, 2001). Here we show that occurrences of gypsum precipitates, depositional hiatuses, and thick clastic sequences mark arid conditions in the Lisan drainage area and are correlated with short-term variations observed in the North Atlantic ice-core record (Schramm, 1997). The gypsum-forming overturn events and deposition of thick clastic sequences have been found to be associated with Heinrich events (Schramm, 1997). The establishment of the independent lake-level curve allows for a direct comparison between the hydrologic response of the lake and North Atlantic climate changes.

The lake curve for the period 55–17 ka is presented in Figure 3. Between 55 and 30 ka (corresponding to MIS 3), the lake level, although punctuated by excursions, stood generally at 280–290 m below mean sea level (bmsl), ~125 m above the present Dead Sea level. During MIS 2, Lake Lisan rose to its maximum level, reaching the elevation of ~165 m bmsl. At this time the lake expanded over the entire Dead Sea–Jordan Valley and joined the northern water body of the ancient Sea of Galilee (Hazan, 2002). It remained at this level for ~2 k.y., dropping at 24 ka to ~220 m bmsl. Between 22 and 17 ka,
Figure 1. Lake Lisan location map. Extent of Lake Lisan along Dead Sea–Jordan Valley during several phases of lake’s history. Highest lake stand, at 165 m below mean sea level (bmsl), reaches the Sea of Galilee (Bartov et al., 2002; Hazan, 2002). Normal lake level at ~280 m bmsl occurred during MIS 3, and lowest level corresponds to Heinrich event 4 with an ~40% reduction from area of normal levels. Inset shows regional setting. LGM is Last Glacial Maximum.

during the Last Glacial Maximum, lake level rose again, reaching the elevation of 190 m bmsl, and then dropped rapidly, resulting in the deposition of a thick gypsum sequence at the top of the Lisan deposits (Schramm, 1997; Stein et al., 1997; Bartov et al., 2002). The lake-level drops that punctuate the history of Lake Lisan are effectively instantaneous within the available time resolution and show a remarkable correlation with the timing, based on previous evaluations, of North Atlantic Heinrich events.

CORRELATION WITH HEINRICH EVENTS

The ages of Heinrich events have been determined by 14C method in the Deep Sea cores (e.g., DSDP 609, NA 87-22), where the ice-rafted debris was identified and comparisons were drawn between paleoceanographic proxies and Greenland ice (Bond et al., 1992, 1993; Bond and Lotti 1995; Vidal et al., 1997; Clark et al., 1999; Chapman et al., 2000; Elliot et al., 2001). Then, the 14C ages of the Heinrich (H) events were transformed to the Greenland Ice Core Project (GRIP) and Greenland Ice Sheet Project 2 (GISP2) ice-core chronologies (Bond et al., 1993; Bond and Lotti, 1995). In the following section we compare the calendar ages of the Lisan level falls to the GISP2 chronology.

The H1 event (16 ± 1 ka) coincides with the deposition of the thick gypsum sequence at the top of the Lisan Formation and the lake level’s drop toward Dead Sea levels. The H2 event (23.8 ± 1.0 ka) coincides with a lake-level drop of ~50 m. This drop is well documented in both the Dead Sea (this study) and the Sea of Galilee areas (Hazan, 2002). The H3 event (30 ± 1.0 ka) has a weaker expression in the Lisan curve, but nevertheless is associated with a minimum decline of 20 m (Fig. 3). The H4 event (38.0 ± 1.0 ka) coincides with a rapid, 50 m level drop from the “normal” MIS 3 lake level of ~280 m bmsl and was followed by an abrupt recovery to the normal level. The age of H5 is a matter of debate (Vidal et al., 1997; Clark et al., 1999; Chapman et al., 2000; Elliot et al., 2001); nevertheless, it is reasonable to place this event just prior to interstadial 12 in GISP2, implying an age of 46.5 ± 1.0 ka in the GISP2 chronology (Clark et al., 1999). It is associated with a longer-term lake-level drop of ~70 m between 48 and 42 ka (Schramm, 1997; Schramm et al., 2000; Machlus et al., 2000; Bartov et al., 2002). Although the age uncertainties associated with Lake Lisan stratigraphy and Heinrich events do not allow us to distinguish leads and lags, all of the lake-level declines except the one associated with H5 have a duration similar to that of the Heinrich events, indicating that the lake-level drops and the Heinrich events are probably coeval.

DISCUSSION

The correlation of the Heinrich events with major lake-level declines at first appears paradoxical. Over the long term, high and low levels in the Dead Sea–Lake Lisan basin occurred in conjunction with colder (MIS 2 and 4) and warmer (MIS 1 and 3) global climate intervals, respectively. Heinrich events occurred during periods of maximal cooling. The addition of freshwater to the North Atlantic would inhibit formation of North Atlantic Deep Water, further inhibiting northward transport of heat from the tropics and thus reinforcing these cooling episodes. Thus, it might be expected that the Heinrich events would be associated with higher levels in Lake Lisan, contrary to the observation of lake-level declines.

It would also be expected that the North Atlantic modulation of the short-term declines in Lake Lisan level should find expression in other climatic records. Indeed, sea-surface temperatures (SSTs) of the Alboran Sea, from alkenones, indicate a correlation between episodes of abrupt SST cooling and the Heinrich events (Cacho et al., 1999). The cooling peaks are superimposed on a rather smooth SST curve of the Western Mediterranean during most of the last glacial period. The abrupt cooling of the Alboran Sea (Rohling et al., 1998; Cacho et al.,...
Figure 2. Reconstruction of paleoshorelines. A: Reconstruction of lake level curve is based on identification of paleoshorelines, determination of their absolute elevation relative to mean sea level (msl) and their ages. Paleoshorelines are marked by beach ridges (black circles), which are identified in stratigraphical section. Ages are determined by \(^{14}C\) age measurements on organic material found within shoreline deposits or by U-series on aragonite laminae (black squares) that directly overlie beach deposits (B). Figure illustrates reconstruction of the level curve of Lake Lisan between 55 and 40 ka by describing two sections: left—located close to a fan delta that entered lake, right—located in deeper water environment. When lake level dropped, an erosional channel developed in left section while a depositional hiatus is identified in right section. Maximum lake level during time of hiatus (indicated by arrows) is determined by minimum level of hiatus at ~370 m bmsl (Bartov et al., 2002). B: Beach deposit covered by aragonite laminae of Lisan Formation (left) and beach deposit on Dead Sea shores serving as analog for past environment (right).

1999; Sanchez Goni et al., 2002) has been explained by climate models (Paillard and Cortijo, 1999; Ganopolski and Rahmstorf, 2001), which suggest that the lack of sinking of the surface cold water into the deep North Atlantic during the Heinrich events enabled colder water to reach such low latitudes in the subtropical North Atlantic and flow into the Mediterranean.

The lowering of the Western Mediterranean SSTs during Heinrich events, as shown also by oxygen isotopes of speleothems and D/H ratios in their fluid inclusions (Bar-Matthews et al., 1999; Matthews et al., 2000), could also have been caused by cold air masses that reduced evaporation. The presence of cold air masses would have caused a dramatic reduction in the strength and the frequency of storms that are normally fed by moisture uptake from the relatively warmer Mediterranean surface water. Fewer and less intense storms, in turn, would have resulted in a significant decrease in precipitation over the Eastern Mediterranean region. Thus, it appears that the dramatic lowering of the Mediterranean SSTs caused changes in the storm track responsible for the normal heavy precipitation and relatively high levels of the lake. We suggest that even a short-term shutdown of the storms (Florineth and Schluchter, 2000) could account for the abrupt drops in lake level. When SSTs returned to their normal glacial range, once again moisture-laden storms affected the Dead Sea drainage basin, causing the lake level to recover.

In summary, Lake Lisan provides a high-resolution chronology of wetness in the Eastern Mediterranean that is intimately linked to the North Atlantic climatic record. This finding shows that short-term perturbations in the glaciated North Atlantic region can impose an immediate catastrophic response in far-away continental areas, thus demonstrating the effectiveness of the transfer of the climatic signal over the globe.

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Figure 3. Correlation between levels of Lake Lisan and Heinrich events. Lake level curve was constructed by using shore indicators (circles) determined by radiometric (U-series and radiocarbon) ages on aragonite sediments (squares). Dashed lines of lake-level curve represent segments with no direct shore indications. For example, between 67 and 57 ka, dashed line marks a minimum lake level. U-series dating and radiocarbon calibration are given in Schramm et al. (2000) and Bartov et al. (2002). Sample isotopic ages and measured elevations define amplitude of lake-level changes associated with level indicators such as beach deposits. Local maxima shown in curve are determined by minimum elevation of lacustrine sediment and its age (for details see Bartov et al., 2002). During period 55–30 ka, corresponding to marine isotope stage (MIS) 3, lake level was stable at 280–290 m below mean sea level (bmsl), interrupted by three level drops. During MIS 2, Lake Lisan rose to its maximum elevation, reaching 165 m bmsl at 26–25 ka. It remained at this level for ~2 k.y., then dropped to 24 ka. At 22–17 ka, during Last Glacial Maximum (LGM), lake level rose to 190 m bmsl. At end of LGM, lake level dropped rapidly. The five level drops in Lake Lisan coincide with Heinrich events in Greenland Ice Sheet Project 2 (GISP2) chronology (see text for further explanation).