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Relationships between lake-level changes and water and salt budgets in the Dead Sea during extreme aridities in the Eastern Mediterranean

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ABSTRACT

Thick halite intervals recovered by the Dead Sea Deep Drilling Project cores show evidence for severely arid climatic conditions in the eastern Mediterranean during the last three interglacials. In particular, the core interval corresponding to the peak of the last interglacial (Marine Isotope Stage 5e or MIS 5e) contains ~30 m of salt over 85 m of core length, making this the driest known period in that region during the late Quaternary. This study reconstructs Dead Sea lake levels during the salt deposition intervals, based on water and salt budgets derived from the Dead Sea brine composition and the amount of salt in the core. Modern water and salt budgets indicate that halite precipitates only during declining lake levels, while the amount of dissolved Na^+ and Cl^- accumulates during wetter intervals. Based on the compositions of Dead Sea brines from pore waters and halite fluid inclusions, we estimate that ~12–16 cm of halite precipitated per meter of lake-level drop. During periods of halite precipitation, the Mg^{2+} concentration increases and the Na^+/Cl^- ratio decreases in the lake. Our calculations indicate major lake-level drops of ~170 m from lake levels of 320 and 310 m below sea level (mbsl) down to lake levels of ~490 and ~480 mbsl, during MIS 5e and the Holocene, respectively. These lake levels are much lower than typical interglacial lake levels of around 400 mbsl. These lake-level drops occurred as a result of major decreases in average fresh water runoff, to ~40% of the modern value (pre-1964, before major fresh water diversions), reflecting severe droughts during which annual precipitation in Jerusalem was lower than 350 mm/y, compared to ~600 mm/y today. Nevertheless, even during salt intervals, the changes in halite facies and the occurrence of alternating periods of halite and detritus in the Dead Sea core stratigraphy reflect fluctuations between drier and wetter conditions around our estimated average. The halite intervals include periods that are richer and poorer in halite, indicating (based on the sedimentation rate) that severe dry conditions with water availability as low as ~20% of the present day, continued for periods of decades to centuries, and fluctuated with wetter conditions that spanned centuries to millennia when water availability was ~50–100% of the present day. These conclusions have potential implications for the coming decades, as climate models predict greater aridity in the region.

1. Introduction

In many regions of the world droughts are a major concern, affecting agriculture, industry and everyday life. In drought sensitive regions, such as the Middle East, water scarcity impacts political stability. Climate models and observations show a drying trend in the lands around the Mediterranean, reflecting both natural variability and increased anthropogenic greenhouse gas concentrations and predict up to 20% decreases in water availability by the end of the 21st century (Kelley et al., 2012; Lelieveld et al., 2012; Mariotti et al., 2008; Seager et al., 2014). While aridification of the Mediterranean region might be explained by poleward expansion of the Hadley circulation and associated widening of the subtropical dry zone (Frierson et al., 2007), the mechanism and strength of the Mediterranean climate response to increasing greenhouse

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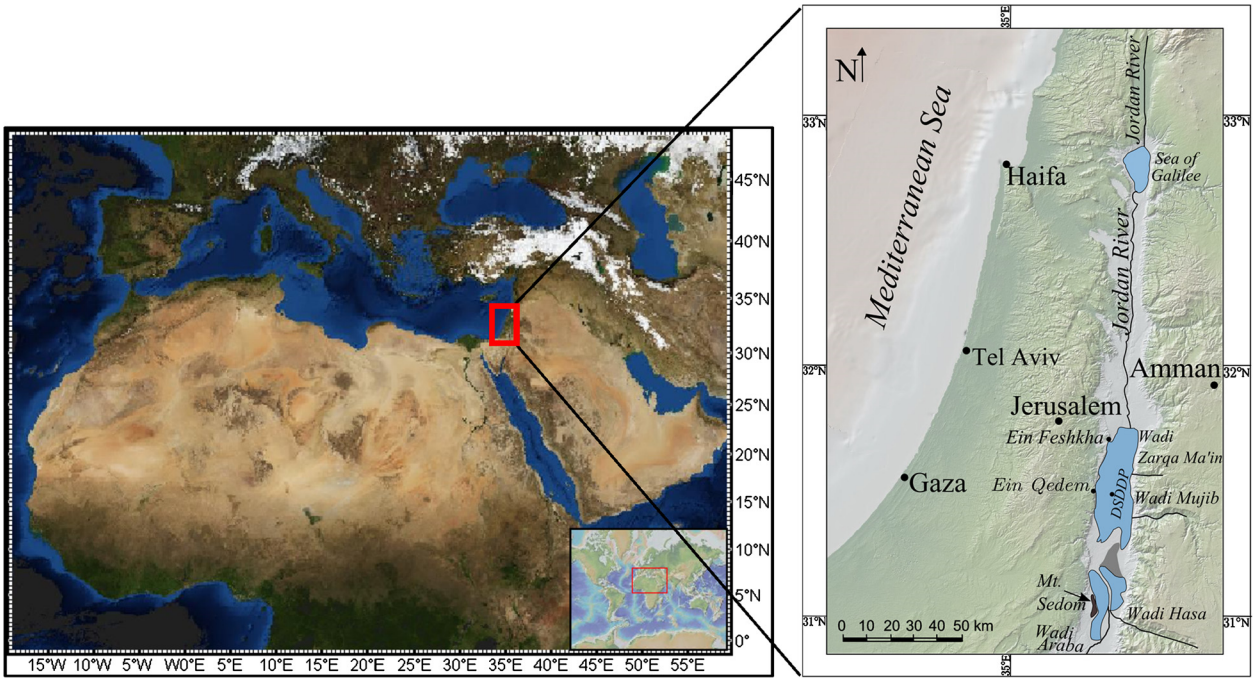

Fig. 1. Location map showing the main water sources into the Dead Sea, and the location of the DSDDP deep core.

gases is not well-understood (e.g. Seager et al., 2014). In the Eastern Mediterranean region, low lake levels in the Dead Sea have been shown to reflect increases in drought frequency that are also associated with higher annual temperatures and northward migrations of storm tracks (Enzel et al., 2003).

The climate during the Holocene and MIS 5e varied both spatially and temporally in the Mediterranean, Europe, North Africa and the Levant (Bar-Matthews, 2014; Damnati, 2000; deMenocal et al., 2000; Harrison et al., 1993; Kushnir and Stein, 2010; Mayewski et al., 2004). The Levant region, comprising Israel, Jordan, Palestine, Lebanon, and Syria, experienced much drier conditions than today, as indicated by halite precipitation in the Dead Sea (Kiro et al., 2016; Neugebauer et al., 2014; Torfstein et al., 2015). Yet, during the last interglacial peak (MIS 5e, ~130–115 ka), which was characterized by stronger insolation cycles, higher average global temperatures, higher sea levels and smaller continental ice sheets than the Holocene (Dutton and Lambeck, 2012; e.g. Felis et al., 2004; Govin et al., 2015; Kukla et al., 2002; Otto-Bliesner et al., 2013; Rohling et al., 2002), paleoclimate records from the eastern Mediterranean document extended intervals of relatively wet conditions, especially during the peak insolation interval of MIS 5e at around ~125 ka BP (Bar-Matthews, 2014; Bar-Matthews et al., 2003; Torfstein et al., 2015; Vaks et al., 2007). This wet interval was associated with the tropical northern hemisphere summer insolation peak, which forced intense African summer monsoon rainfall that resulted in increased Nile flow, and the formation of a major sapropel (S5) in the Eastern Mediterranean (Rohling et al., 2002; Rossignol-Strick, 1985; Torfstein et al., 2015; Vaks et al., 2007; Waldmann et al., 2010). Nevertheless, during the past 140 kyr in the Levant, the main source of precipitation moisture has primarily been the Mediterranean Sea (Kolodny et al., 2005; McGarry et al., 2004; Torfstein et al., 2015). Sorting out the hydrological variability in the Levant during the last interglacial and its relation to orbital and global climate variations remains a challenge.

The Dead Sea watershed straddles both the Mediterranean climate zone and the Sahara-Arabian desert belt, reflecting the interplay between these two climate belts. Considering that the effects of anthropogenic warming on the semi-arid and Mediterranean climate is a concern for the future, it is important to know what has occurred in the past, and sedimentary archives provide a means to learn about the severity, duration and frequency of past droughts. The ICDP Dead Sea Deep Drilling Project (DSDDP) recovered such a record from the deep floor of the Dead Sea (Fig. 1) during 2010–2011 (Neugebauer et al., 2014; Stein et al., 2011). The drill site was 297 m below the lake surface, and cores were recovered to a depth of 456 m below the lake floor (mblf), covering ~200 kyr (Fig. 2 and Torfstein et al., 2015), thus including the Holocene and MIS 5e.

The age model used in this study is constructed mainly after Torfstein et al. (2015), based on U-series dating of aragonite, the lithology of the core, and correlation of aragonite $\delta^{18}O$ in the DSDDP core with $\delta^{18}O$ in the Soreq cave (Bar-Matthews et al., 2003), the marine benthic $\delta^{18}O$ LR04 stack (Lisiecki and Raymo, 2005) and Mediterranean core records (e.g. Wang et al., 2010). For the last glacial maximum to the present-day, the age model is based on the ^{14}C data of Kitagawa et al. (2016). Torfstein et al. (2015) discussed the general paleohydrology of the region, based on the lithology of the core, and showed that the last interglacial was characterized by a high degree of climate variability, with a dry interval marked by halite precipitation during the MIS 6/5 transition, followed by wetter conditions during the peak of MIS 5e without halite precipitation, in turn followed by an extreme dry interval characterized by a thick accumulation of halite.

Here we develop a salt and water budget based on halite fluid inclusions and pore water chemical compositions, together with halite thicknesses from the DSDDP cores. Based on these considerations, we calculate the lake-level changes during the driest intervals in this region and estimate the discharge of water and the amount of precipitation. Our results show that the Levant has experienced severe dry conditions lasting up to a few thousand years during both the Holocene and MIS 5e.

2. Geological and hydrological settings

During the late Quaternary, the Dead Sea basin, the lowest elevation on the continents (the deepest Dead Sea lake floor is >720 mbsl, while the 2016 lake level is at 431 mbsl), was oc-

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