Earth and Planetary Science Letters 457 (2017) 302–312

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The modern and Last Glacial Maximum hydrological cycles of the Eastern Mediterranean and the Levant from a water isotope perspective

Y. Goldsmith [a,*], P.J. Polissar [a], A. Ayalon [b], M. Bar-Matthews [b], P.B. deMenocal [a], W.S. Broecker [a]

[a] Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY, USA
[b] Geological Survey of Israel, 30 Malchei Israel Street, Jerusalem 95501, Israel

ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form 6 October 2016
Accepted 8 October 2016
Available online 2 November 2016
Editor: D. Vance

Keywords:
stable isotopes
speleothem
Rayleigh distillation
Last Glacial Maximum
Israel
Mediterranean

ABSTRACT

The isotopic composition of precipitation (δ_P) is one of the most widely used and informative terrestrial paleoclimate proxies. δ_P integrates a series of hydrological processes; therefore, any interpretation of paleohydrology using δ_P requires a thorough understanding and quantification of the full hydrological cycle. In this paper, we use modern data to analytically model the full isotopic hydrological cycle of the Eastern Mediterranean and the Southern Levant, including oceanic evaporation, distillation during transport and precipitation over land. This model allows us to determine the important factors controlling this system. The model results underscore the significance of the isotopic distillation process driven by the land–sea temperature gradient as a significant factor controlling the long-term average isotopic composition of precipitation across Israel. Based on the understanding of the processes that govern the modern system, we model the isotopic composition of precipitation from the Last Glacial Maximum (LGM) using published data for speleothem oxygen isotopes in calcite, oxygen and hydrogen isotopes in fluid inclusions and clumped isotope values from Soreq Cave and the isotopic composition of East Mediterranean planktonic foraminifera *G. ruber*. The data and model results indicate two plausible scenarios for the LGM that entail changes in the magnitude of distillation over Israel, in normalized humidity over the Mediterranean and possible shifts of the moisture trajectories over the Mediterranean. The results presented in the paper illustrate the importance of understanding the full local hydrological cycle when reconstructing and interpreting the isotopic composition of precipitation.

1. Introduction

The isotopic composition of precipitation is widely used to constrain modern hydrological process and past terrestrial climate. The isotopic signal is acquired through a sequential series of hydrological steps, which require quantification in order to produce reliable climatic interpretations based on the isotopic composition of precipitation. In prior work, the contributions of moisture sourcing (e.g. Pausata et al., 2011) and the isotopic composition of vapor (e.g. Good et al., 2015) to the isotopic composition of precipitation have been established. These realizations must thus be incorporated into paleoclimate interpretations of isotope records. In this paper, we present a methodology for analyzing and interpreting modern and paleo-rainfall isotopic data. We first investigate the modern hydrological cycle and show that it is possible to derive from first principles the major factors controlling the system. We then use these principles to reinterpret isotopic records from the Last Glacial Maximum (LGM). The investigation is focused on the Eastern Mediterranean (EM) because of the wealth of modern and paleo-isotopic data that exists in this region, which enable identification of the major processes controlling the isotopic composition of precipitation.

The isotopic composition of modern precipitation in the EM and the Levant has gained much attention in the past four decades due to its uniquely high d-excess (defined as d-excess $= \delta D - 8 \times \delta^{18}O$, Dansgaard, 1964) in respect to the global isotope composition of precipitation (e.g. Gat and Dansgaard, 1972; Gat and Carmi, 1970, 1987; Gat et al., 2003; Ayalon et al., 2004; Angert et al., 2008) and due to its paleoclimate utility as a climate recorder in speleothems (e.g., Ayalon et al., 1998, 2013; Bar-Matthews et al, 1997, 1999, 2003; Frumkin et al., 1999; Orland et al., 2014) and lacustrine environments (Kolodny et al., 2005). Previous re-

* Corresponding author.
E-mail address: yonig@ldeo.columbia.edu (Y. Goldsmith).

http://dx.doi.org/10.1016/j.epsl.2016.10.017
0012-821X/

search conducted on the modern conditions in this region span short time periods (e.g. Gat and Carmi, 1970, 1987), are centered in specific sub-regions in Israel (e.g. Angert et al., 2008; Ayalon et al., 2013) or pertain to specific parts of the hydrological cycle (e.g. Gat et al., 2003). Although general models have been presented that describe how the unique composition of modern precipitation (e.g. Gat et al., 1996; and Gat and Carmi, 1970, 1987) and the paleohydrology of the EM (Gat and Dansgaard, 1972; Gat and Carmi, 1987; McGarry et al., 2004) were acquired, they are based on limited aspects of the hydrological cycle (i.e. vapor, precipitation etc.) and do not encompass the full hydrological cycle, which is composed of sea surface water, vapor, distillation, precipitation and evaporation. Here we analyze data from long-term monitoring of the isotopic composition of precipitation from 14 sites distributed across Israel and water and vapor data from the Mediterranean. Together, these data allow us to quantify the major processes that control the hydrological cycle of the Eastern Mediterranean and evaluate the processes that control the long-term average isotopic composition of precipitation in Israel.

1.1. Modern climatology of Israel

Rainfall in Israel occurs almost exclusively between Oct and Apr, with most of the rainfall falling between Dec and Feb. During the rainy season, cold-core, upper-level, low-pressure troughs propagate from west to east over southern Europe and the Mediterranean (Ziv et al., 2006). When dry air from Europe passes over the mountainous regions to the north of the Mediterranean it encounters the warm Mediterranean sea surface and forms the Cyprus Low, a cyclonic surface low-pressure system, which lifts the moistened marine air to produce clouds and precipitation (Fig. 1). These systems migrate eastward and deliver precipitation over Israel (Ziv et al., 2006) (Fig. 1).

The topography of Israel can be divided into three areas from West to East: the low coastal plain, a North-South mountainous region and the Dead Sea Valley (Fig. 1). Precipitation amount generally correlates with temperature and altitude, where greater precipitation falls at higher and colder elevations (Fig. 1). In addition, temperatures decrease and rainfall increases from South to North (Fig. 1). The southern part of Israel lies in the global desert belt and the northern part has a Mediterranean climate. The Dead Sea Valley is a local rain–shadow desert.

The climatic regime in Israel is, in many ways, ideal for isotopic study. As rainfall only occurs during winter there are no complications due to seasonality of precipitation. In addition, the cold temperatures during winter reduce evaporation from the base of the cloud and thus reduce the variability of the isotopic composition. The distance from the sea, elevation, temperature and latitude are all correlated, all driving the isotopic composition in the same direction. In addition, the short transport distance (<100 km) prevents significant moisture recycling.

1.2. Definitions and isotope notations

During phase changes in the hydrological cycle, fractionation occurs between the heavy and light isotopes of oxygen and hydrogen due to differences in their vibrational energy and thus their affinity for higher (e.g. gas) or lower (e.g. water) energy states. Therefore, the ratio of the heavy to light isotopes records the magnitude of these phase changes (Gat, 1996). The isotopic compositions of oxygen and hydrogen (δ) are reported in the delta notation:

$$\delta = \left(\frac{R_{(sample)}}{R_{(VSMOW)}} \right) - 1 \tag{1}$$

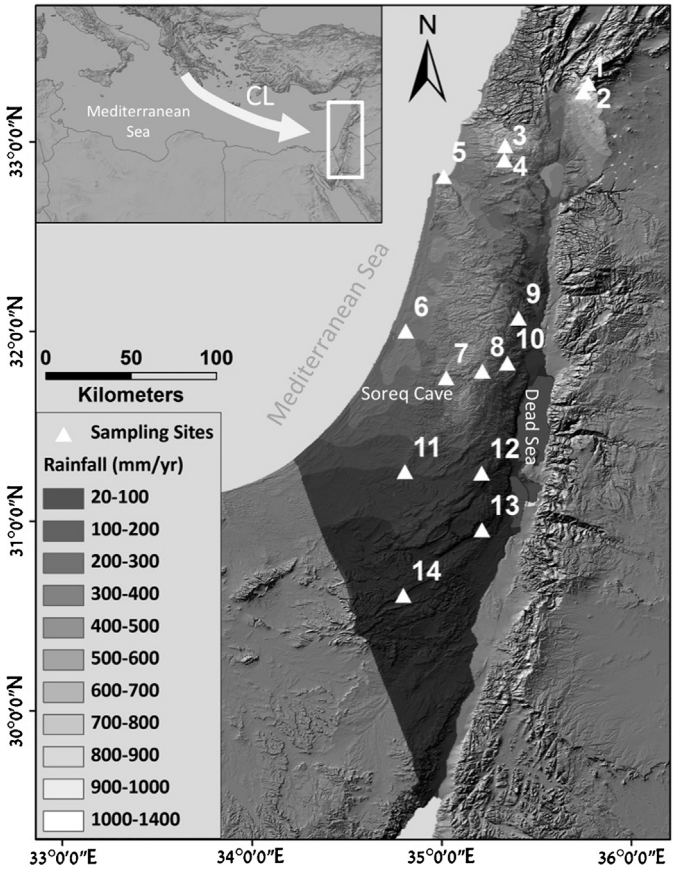

Fig. 1. An annual rainfall map of Israel (gray scale) superimposed on a shaded relief map, showing the rainfall sampling sites (white triangles) and locations mentioned in the text. The site numbers correspond to Table 1. The map at the top left shows the general location and direction of the modern Cyprus Low (CL) – the prominent path of moisture reaching Israel.

where R is the ratio of the heavy to light isotopes and VSMOW is the standard used. The calculations are performed using the abundance ratios, but for convenience the isotope data in the plots and tables are multiplied by 10^3 and presented in per-mil units (‰).

The equilibrium fractionation factor ($\alpha_{l-v(T)}$), which is a function of the temperature, is defined as:

$$\alpha_{l-v(T)} = \frac{R_l}{R_v} \tag{2}$$

where R_l and R_v are the isotopic ratios in liquid and vapor, respectively. Majoube (1971) empirically calculated the fractionation factor as:

$$\ln \alpha^{18O}_{l-v} = \frac{1137}{T^2} - \frac{0.4156}{T} - 0.00207 \tag{3}$$

and

$$\ln \alpha^{D}_{l-v} = \frac{24844}{T^2} - \frac{76.248}{T} + 0.05261 \tag{4}$$

where T is the temperature in Kelvin.

During equilibrium processes, the relative magnitude of fractionation of oxygen and hydrogen $(\alpha_D - 1)/(\alpha_{18O} - 1)$ cause hydrogen to fractionate $\sim\times 8$ that of oxygen. Therefore, the isotopic composition of global precipitation falls on a slope of 8 when plotted on a $\delta^{18}O$ vs. δD plot (Gat, 1996). The kinetic fractionation factor of oxygen is larger than that of hydrogen relative to equilibrium fractionation. Therefore, during kinetic fractionation, which predominantly occurs during evaporation at the moisture source (Merlivat and Jouzel, 1979), oxygen fractionates to a larger degree