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Spatially interpolated time series of δ^{18}O in Eastern Mediterranean precipitation

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ABSTRACT

The water cycle is one of the key parameters that determine the climatic character of a region. Stable isotopes have long been established as a valuable tracer in the study of the origin, dynamics and interactions between the various components of the hydrologic cycle, both of the present and of the past. Even though significant efforts have been made, the spatial and temporal coverages of the available water isotope data are far from satisfactory. Statistical modeling and interpolation of existing measurements is a possible answer to this problem. This work is based on the experience gained by several recent studies in order to generate $0.5° \times 0.5°$ gridded monthly time series of δ^{18}O in the precipitation of the Eastern Mediterranean. The empirical model incorporates geographical and topographical data in order to capture the main modes of the spatial variability of the isotopic composition of precipitation, while the incorporation of meteorological data time series provides the necessary temporal variability. Overall, despite the rather coarse spatial resolution of the existing isotopic data, the applied methodology provides a satisfactory reproduction of the measurements.

1. Introduction

Stable isotopes have been long identified as ideal tracers of the origin and interactions of water since they are integral parts of the water molecules. Changes in the isotopic composition of a water mass within the hydrological cycle can be traced and modeled, providing a means to relate this water to the different phases of the cycle.

The largest variations in the isotopic composition of a water vapour mass are associated with the evaporation and condensation of atmospheric moisture and precipitation (Gat, 2001). Air temperature and relative humidity are the governing factors of isotopic fractionation during the evaporation–condensation process (Craig and Gordon, 1965; Gat, 1996), whereas local factors, such as topography, may also prove significant under a non-equilibrium (kinetic) fractionation regime (Poage and Chamberlain, 2001; Liotta et al., 2006). The formation of raindrops is initiated by condensation controlled by the temperature of the air mass, and by exchange of water vapour between the cloud and the raindrop until it leaves the cloud. This water vapour exchange is considered to be an equilibrium fractionation procedure controlled by local air temperature. The cloud base temperature defines the isotopic content of the raindrop leaving the cloud and allows its correlation to surface air temperature (Gat, 1996). Molecular kinetics suggests that higher air temperatures at the cloud base result in raindrops enriched in heavier isotopes (Gat, 2001). The amount of water precipitated during an event, also has a distinct effect on the isotopic composition of raindrops. In the lower mid-latitudes, light rains are usually associated with enhanced evaporation of raindrops below the cloud leading to isotopic enrichment. Heavy rains on the other hand may manifest the effect of Rayleigh distillation, resulting in a gradual depletion of the isotopic content of the raindrops similar to that observed during the gradual rainout of an air mass over the continents (Gat, 2001).

During infiltration and underground water migration stable isotopes behave conservatively under ambient temperatures thus they can be used as proxies of the climatic conditions pertinent to the time passed after the water mass has left the surface (de Vries, 2000). The isotopic signature of water is preserved in the form of paleorecords such as old groundwater, minerals, fossils, lake sediments, ice cores, tree-rings, and coral skeletons, and can be used in order to reconstruct the past climatic conditions (Rozanski, 1985; Evans et al., 2002; Cane et al., 2006; Jones et al., 2005; Robinson et al., 2006). The deduction of past climate from proxy paleorecords is possible by the transcription of the changes in the isotopic composition of proxies into changes in the isotopic composition of precipitation and therefore changes in the climatic variables. This approach is based on the present day relationships between the various components involved at a given location, but these may not be directly applicable to past eras simply because the climatic conditions may have changed. Therefore, the effect of climate change has to be taken into account.

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The emerging significance of the stable isotopes of water led several national and international organizations to establish measurement networks, among which the Isotope Hydrology Information System (ISOHIS) managed by the International Atomic Energy Agency (IAEA) and the Global Network of Isotopes in Precipitation (GNIP) jointly managed by IAEA and the World Meteorological Organization (WMO) (IAEA, 2005; IAEA/WMO, 2005). Nevertheless, extended records are available only for a small number of stations around the globe, while the spatial coverage is far from being acceptable. Improving the spatial coverage and temporal extent of the isotopic measurement networks requires significant budget and even in this case the results will only be available after several years. Statistical and modeling methods are immediate alternatives.

Numerical modeling has evolved from simple simulations of Rayleigh-type distillation processes into modules incorporated in many major atmospheric general circulation models (AGCM's). These modules are quite successful in capturing the main characteristics of the isotopic patterns across the globe, under the restriction of the resolution of each model (typically between $5°\times5°$ and $1°\times1°$) (Hoffmann et al., 2000; Mathieu et al., 2002; Noone and Simmonds, 2002; Kurita et al., 2005). Regional circulation models (RCMs) incorporating isotopic modules with a finer resolution (about $0.5°\times0.5°$) have also appeared, providing results significantly improved over mountainous areas due to their better representation of topography (Sturm et al., 2005).

A simpler approach to obtain isotopic data for a location where no data is available would be to interpolate existing data from other neighboring locations. Despite its lack of the physical basis that a numerical model provides, interpolation has been frequently used in environmental sciences, especially when an overview of the spatial distribution of the data is required. Isotopic hydrology literature has several examples to offer, utilizing a large variety of interpolation methods (e.g. Evans et al., 2002; Darling, 2004; Kendall and Coplen, 2001; Birks et al., 2002; Longinelli and Selmo, 2003; Gibson et al., 2005). All these methods are able to produce high-resolution gridded isotopic data sets as well as an estimate of the associated uncertainty.

Another approach is to develop empirical models for the prediction of the isotopic composition of water, based on existing data sets that have global coverage and adequate resolution. A refinement of this method proposed by Bowen and Wilkinson (2002), henceforth BW, was to introduce geostatistical methods in order to account for the empirical model residuals and minimize interpolation errors.

Global isotopic gridded data sets are available for ocean waters with a resolution of $1°\times1°$ (LeGrande and Schmidt, 2006) and for precipitation with resolutions ranging from $2.5°\times2.5°$ down to $5'\times5'$ (Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003; Hobson et al., 2004; Meehan et al., 2004; Bowen et al., 2005; Lykoudis and Argiriou, 2007). Most of these data sets were constructed according to the BW method that uses solely geographical and topographical regressors. On a country scale, Dutton et al. (2005) produced a $0.5°\times0.5°$ grid for river and precipitation waters across the USA, while Liebminger et al. (2006) showed that on a local scale, the inclusion of longitude as well as meteorological regressors improved the performance of the isotopic models. Including meteorological variables in an attempt to generate gridded isotopic data for the precipitation in Eastern and Central Mediterranean at a $10'\times10'$ resolution, was not an improvement over the simple BW model (Lykoudis and Argiriou, 2007).

All the gridded data sets mentioned above refer to long-term climatic means. In this work we attempt to generate a $0.5°\times0.5°$ gridded monthly time series of $\delta^{18}O$ in the precipitation over the Eastern Mediterranean covering the period from 1960 to 2002. Geographical and topographical regressors will account for the stationary characteristics of the spatial distribution of isotopes, while monthly time series of meteorological variables will be used to reproduce the observed temporal variation.

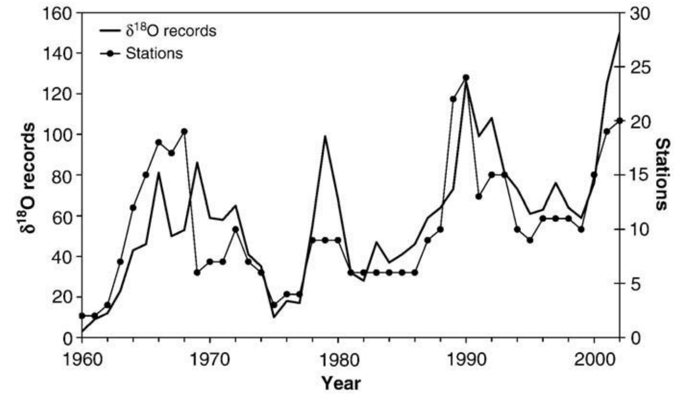

Fig. 1. Temporal distribution of the available isotopic data for the Eastern Mediterranean region (28°–43° N, 20°–40° E).

2. Data and methods

The area of interest extends between 28° N–43° N latitude and 20° E 40° E longitude. Stable isotopic composition of precipitation, air temperature, and precipitation amount was obtained from the ISOHIS and the GNIP databases (IAEA) (IAEA, 2005; IAEA/WMO, 2005). Data from the works of Payne et al. (1976), Leontiadis (1981), Kallergis and Leontiadis (1983), Leontiadis et al. (1984), Kita et al. (2004) and Stratikopoulos (2007) were also included. Meteorological data for some stations were also obtained from ECA. The database consisted of 2532 $\delta^{18}O$ records from 77 stations covering the period 1960–2002. The initial data were checked for consistency and 13 records were removed leaving 2519 records from 73 stations for the analysis. About 83% and 64% of the records also contained precipitation amount and air temperature respectively. The temporal and spatial densities of the data are far from being satisfactory as can be seen in Figs. 1 and 2 respectively.

Monthly gridded time series of precipitation and air temperature for the period 1960–2002, with a $0.5°\times0.5°$ resolution were obtained from the CRU TS 2.1 data set (Mitchell and Jones, 2005). Elevation data with an identical resolution was also obtained from the CRU. A second set of $0.5°\times0.5°$ gridded precipitation and air temperature was used, namely the E-obs data set from the ENSEMBLES project which also provided a matching elevation data set (Haylock et al., 2008). The locations for which isotopic data were available were referenced to the closest grid-cell center and were assigned the meteorological data corresponding to that grid cell. Based on the $\delta^{18}O$ locations, the two gridded sets have very similar temperatures, with the E-obs temperatures being slightly (about 2%) higher than those of the CRU TS 2.1. The discrepancies between the precipitation amounts reported

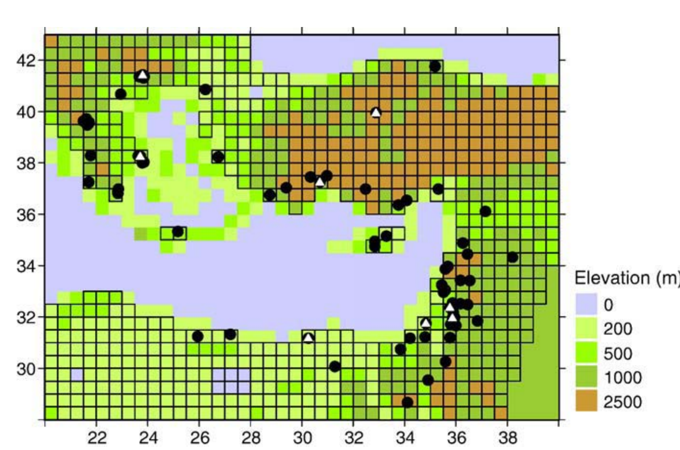

Fig. 2. Stations reporting isotopic data (dots) and locations used for the validation procedure (triangles). Grid cells with CRU (shaded) and E-obs (boxed) elevations.