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Climate proxies for the last 17.3 ka from Lake Hazar (Eastern Anatolia), extracted by independent component analysis of μ-XRF data

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ABSTRACT

The elemental composition of lake sediment cores is often the result of several independent processes. In this study we attempt to extract statistically independent climate related signals from μ-XRF multi element data of a core drilled from Lake Hazar in Eastern Anatolia, using the independent component analysis (ICA) method. In addition, we analysed ostracod shells for oxygen and carbon isotopes. The ICA method has advantages over traditional dimension reduction methods, such as principal component analysis or factor analysis, because it is based on maximal statistical independence rather than uncorrelatedness, where independence is a stronger property.

The Hz11-P03 core, which represents the last 17.3 ka, was recovered from Lake Hazar which, at times, formed the headwaters of the Tigris. Applying the ICA method, we selected two out of six independent components by measuring distance correlation similarity. We propose that one of the selected components can be read as a proxy for temperature and the other for precipitation in this region.

Our results indicate that the region was relatively cold and wet during the late glacial, between 17.3 and 14.8 ka BP, and wet and warm during Bølling-Allerød. The lake level dropped below today's level during the Younger Dryas stadial (12.49 and 11.76 ka BP), forming a marked hiatus in the core's stratigraphic record. During the beginning of the Holocene, while precipitation values were high, the temperature gradually increased until 8 ka BP. Between 8 and 5 ka BP, the region was warm but extremely dry. After 5 ka BP, around 3.5 ka BP temperatures suddenly fell, and three abrupt dry phases are observed around 3.5 ka and 2.8 ka and 1.8 ka BP.

1. Introduction

Geochemical proxies are the most widely used indicators of Quaternary paleoclimates. In particular, the geochemical "archives" contained in lacustrine sediments provide long and high-resolution proxies of terrestrial records. However, such geochemical proxies, especially those gathered from the lakes, can only be indirect indicators of past climates (Roberts et al., 2008) and may be influenced, to different degrees, by several independent factors. In order to overcome this indirectness, multi-proxy methods are widely used. However, it may be complicated and misleading to interpret multi-proxy data qualitatively in order to form a single composite impression about the past dynamics that govern those proxies. Part of this shortcoming is due to the fact that, commonly used data reduction techniques, such as principal component analysis (PCA) and factor analysis (FA), are not capable of imposing certain probabilistic constraints on the problem exposed by the multi-proxy data. The orthogonal transformation of PCA and FA point out the directions of maximal variance. However, maximal variance may not be the researcher's main aim, unless it is aimed to find for the orthogonal directions ordered in maximal changes through the data. On the other hand, the resultant sediment geochemistry can be assumed to be a linear combination of statistically independent processes. In this study, instead of the widely used data reduction methods which depend on uncorelatedness (here by

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uncorrelatedness of two random variables, as defined in probability theory, two random variables are uncorrelated, if their covariance is equal to zero) of the resulting vectors, we apply the method of independent component analysis (ICA) with the aim of extracting the statistical independent/quasi-independent processes of the past climate causing the variability in the proxy data sets.

Micro-X-ray fluorescence (μ-XRF) of elemental profiles can be used as proxies for different processes in lakes with differing environmental settings (cf. Davies et al. (2015)). The statistical dependence of μ-XRF elemental profiles of a core is widely recognized by the research community. For example, instead of elemental profiles, it is a standard practice to use elemental ratio profiles to normalize the effects of some process-related factors and possible systematic errors (cf. Croudace and Rothwell (2015)). The elemental profiles of lake cores are the results of physical/statistical independent or quasi-independent processes and parameters, such as precipitation, organic production, temperature, water level and redox conditions in the lake or in its drainage basin.

In previous studies, PCA and FA are the most widely used statistical transformation methods applied to extract the underlying components of proxy data. PCA and FA give useful results if the observed time series are normally distributed and are linear mixtures of the source series (Aires et al., 2000). However, even modern climate variables rarely obey Gaussian distribution (Perron and Sura, 2012; Sura and Hannachi, 2014), and shifts, trends and abrupt events increase the degree of past climate variables' non-Gaussianity and non-linearity. It is unreasonable to expect the data to be in the form of linear mixtures when one considers the highly dynamic environments from which they are sampled. The FA method does not actually extract components, rather it explains the governing factors of the system and the constituents of each factor, in the second order statistical sense. The components extracted by PCA are uncorrelated and the method tries to find the components that explain the maximal variance. Since the extracted components with maximum variances are not separated sources, instead they are mixtures of the true signals (Stone, 2004), the objective of PCA is questionable in the sense of source separation. This low-order nature is due to the fact that the backbone of both FA and PCA methodologies are the variance-covariance matrices.

ICA is a more robust statistical transformation method, developed for signal separation, and provides an alternative to PCA (Comon, 1994). ICA's fundamental assumption is that the source time series are statistically independent for each point in time (Hyvärinen and Oja, 2000) and aims to identify a rotation matrix that in practice maximizes the independence of each source component. The main difference between the aims of PCA/FA and ICA is that the former aims to find uncorrelated components, whereas the latter aims to extract independent ones. Since, independency of random variables implies uncorrelatedness, the assumption of being independent is more powerful than being uncorrelated.

ICA has proven its explanatory power in different subjects (see reviews of Acharya and Panda (2008) and Naik and Kumar (2011)), such as feature extraction, signal processing, image processing, telecommunications, financial time series, etc. There are also, some examples in climate research which use ICA as an exploratory tool. By using ICA, Aires et al. (2000) claim to reveal the geographical variability of El Niño Southern Oscillation and its links with Atlantic Ocean. Basak et al. (2004), Mori et al. (2006) and Hannachi et al. (2009) extracted teleconnection patterns from sea level pressure field via ICA. Tatlı et al. (2004, 2005) offer ICA as a preprocessing method in order to reduce dimensions through the downscaling process of general circulation model outputs. However, ICA has never been applied to paleoclimate time series. Several different approaches to ICA exist, such as those based on the infomax or maximum likelihood methods (for an extended review see Choi et al. (2005)). We use the FastICA algorithm (Hyvärinen and Oja, 2000), because it is a rapid and computationally straightforward method.

In this study, by applying FastICA, we attempt to extract precipitation and temperature related components from the μ-XRF data of a 3.5 m long piston core (Hz11-P03) recovered from Lake Hazar (Eriş, 2013; Eriş et al., submitted). Hz11-P03 spans the last 17.3 cal ka, allowing us to understand past climate variability for the region throughout the last glacial-interglacial transition and the Holocene. Lake Hazar lies in the Eastern Anatolia region, feeds the headwaters of the major rivers of the Mesopotamia. Therefore, this study aims to give not only the climate variability of Lake Hazar and its catchment basin, also aims to give insight to the water variability in the so-called cradle of civilization.

There are some past climate studies in the region, such as geochemical and paleoecological data from Lake Nar and Eski Acıgöl (Roberts et al., 2001, 2016; Woldring and Bottema, 2003; Jones et al., 2006; Turner et al., 2008; Dean et al., 2015). There are also longer terrestrial records from Lake Van, which span the last 600 ka BP (see, Litt and Anselmetti (2014)). However, none of the aforementioned studies use statistical decomposition methods, except Stockhecke et al. (2016), which use PCA of Lake Van geochemistry data to reveal hydroclimate variability in Eastern Mediterranean for the last 360 ka BP.

2. Regional setting

Lake Hazar is located in south-eastern Anatolia at an altitude of 1255 m (Fig. 1). It is a 25 km long, 7 km wide intra-montane sedimentary basin with a surface area of 78.5 km^2 and a volume of 7.5×10^9 km^3. The maximum depth of the lake is 220 m. Lake Hazar is a tectonic lake, located in an active pull-apart basin along the East Anatolian Fault Zone (Hempton and Dunne, 1984; Garcia Moreno et al., 2011). Eastern Anatolia is the main water source for the major Mesopotamian rivers, Tigris and Euphrates. Lake Hazar lies on the upstream of a tributary of the Tigris river, which was previously an outlet of the lake (Çetin et al., 2003; Nicoll, 2010). Tectonic uplift of the south-eastern part of the lake and excessive use of for agricultural purposes has broken the connection between the lake and the Tigris. Today, it is a terminal lake and fed only by numerous small ephemeral streams.

The main water and sediment sources for the lake are the Kürkçayı and Zıkkım rivers which flow into the south-west and north-east of the lake, respectively. Maximum discharge occurs during the spring season as a result of snow melt and rainfall. The lake's catchment area is mostly covered by magmatic, metamorphic and ophiolitic rocks of the Mesozoic and Paleozoic Eras. The main bedrock along the southern cost of the lake, its most rugged area, also consists of Middle Eocene calcareous rocks and Late Jurassic magmatic rocks.

Lake Hazar is a monomictic, oligotrophic and alkaline lake (pH = 9.1±0.2) with high carbonate and bicarbonate concentrations. Complete mixing takes place during the autumn and early winter and incomplete mixing in the spring season. The lake is stratified between June and September, and the surface water temperature changes from 5 °C to 29 °C in the pelagic zone throughout the year (Koçer and Şen, 2012).

The climate of Eastern Anatolia has long been considered as being a transition between continental and Mediterranean climates and is described as a Continental Mediterranean climate (Türkeş and Tatlı, 2011) which is distinguished by excess precipitation in spring, rather than in winter (Erol, 2011). Precipitation in the

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