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# Holocene paleoclimate inferred from salinity histories of adjacent lakes in southwestern Sicily (Italy)

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ABSTRACT

Marked uncertainties persist regarding the climatic evolution of the Mediterranean region during the Holocene. For instance, whether moisture availability gradually decreased, remained relatively constant, or increased during the last 7000 years remains a matter of debate. To assess Holocene limnology, hydrology and moisture dynamics, the coastal lakes Lago Preola and Gorgo Basso, located in southwestern Sicily, were investigated through several stratigraphic analyses of ostracodes, including multivariate analyses of assemblages, transfer functions of salinity, and biochemical analyses of valves (Sr/Ca, $\delta^{18}O$ and $\delta^{13}C$). During the early Holocene, the Gorgo Basso and Lago Preola ostracode records are similar. After an initial period of moderate salinity (1690–6100 mg/l from ca. 10,000–8190 cal yr BP), syndepositional or diagenetic dissolution of ostracode valves suggests that salinity declined to <250 mg/L from ca. 8190 to 7000 cal yr BP at both sites. After ca. 6250 cal yr BP, the ostracode records are strikingly different. Lago Preola became much more saline, with paleosalinity values that ranged from 2270 to about 24,420 mg/L. We suggest that Lago Preola's change from a freshwater to mesosaline lake at about 6250 cal yr BP was related to sea level rise and resulting intrusion of seawater-influenced groundwater. In contrast, Gorgo Basso remained a freshwater lake. The salinity of Gorgo Basso declined somewhat after 6250 cal yr BP, in comparison to the early Holocene, ranging from about 550 to 1680 mg/L. *Cypria ophtalmica*, a species capable of rapid swimming and flourishing in waters with low dissolved oxygen levels, became dominant at approximately the time when Greek civilization took root in Sicily (2600 cal yr BP), and it completely dominates the record during Roman occupation (roughly 2100 to 1700 cal yr BP). These freshwater conditions at Gorgo Basso suggest high effective moisture when evergreen olive-oak forests collapsed in response to increased Greco-Roman land use and fire. Ostracode valve geochemistry (Sr/Ca, $\delta^{18}O$) suggests significant changes in early vs. late Holocene hydrochemistry, either as changes in salinity or in the seasonality of precipitation. Harmonizing the autecological and geochemical data from Gorgo Basso suggests the latter was more likely, with relatively more late Holocene precipitation falling during the spring, summer, and fall, than winter compared to the early Holocene. Our ostracode-inferred paleosalinity data indicate that moisture availability did not decline during the late Holocene in the central Mediterranean region. Instead, moisture availability was lowest during the early Holocene, and most abundant during the late Holocene.



## 1. Introduction

Understanding the causes of environmental change between the early and late Holocene is a dominant theme in

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paleoenvironmental research from the Mediterranean region (Magny et al., 2003, 2011b; Roberts et al., 2011). Apparent contrasts in regional climate and hydrology have emerged. Paleohydrological studies from the central Mediterranean (bound by longitude 6–18°), including lake level reconstructions and stable isotope records, generally infer the highest lake levels and effective moisture (i.e. precipitation minus evaporation) south of 40° N from about 10,000 to 5000 cal yr BP, and lowest after 5000 cal yr BP (Magny et al., 2013). The opposite pattern was reconstructed for sites north of 40° N. Hydrological changes south of 40° N are generally ascribed to a wet early Holocene, followed by the development of an increasingly summer-dry climate during the late Holocene (Roberts et al., 2008; Magny et al., 2013). In contrast, in the cooler and moister northern Mediterranean, rising lake levels and advancing glaciers during the late Holocene are attributed to a combination of increasing summer precipitation and/or declining evaporation as summer temperatures declined. This interpretation for the northern Mediterranean is consistent with climatic changes in Central and Northern Europe (Magny et al., 2003; Giraudi et al., 2011).

Many paleoecological studies also applied the climatic framework proposed for south of 40° N to interpret Holocene vegetation change. Under the "aridification" hypothesis, forests expanded when lake levels were high during a moist early Holocene, and the widespread opening of forests, expansion of broadleaved evergreen vegetation, and declining lake levels during the mid-late Holocene resulted from declining summer moisture availability (Sadori and Narcisi, 2001; Jalut et al., 2009; Sadori et al., 2011; Peyron et al., 2013). However, new records from the warmest and driest regions of Mediterranean Europe challenge these assumptions. Forests were absent during the early Holocene in Malta and along the south coast of Sicily. Subsequent expansion by evergreen forests of *Olea europaea* and *Quercus ilex* in Sicily, and *Pistacia lentiscus* shrublands in Malta after 7000 cal yr BP (Noti et al., 2009; Tinner et al., 2009; Calò et al., 2012; Djamali et al., 2013) support an alternative hypothesis that attributes hydrological and vegetational changes to the seasonality of precipitation, and the intensification of human impacts. Specifically, lake levels were high during the early-mid Holocene due to abundant cool season precipitation, and declined during the mid-late Holocene due to a reduction in winter precipitation, not a drying summer climate (Giraudi et al., 2011; Calò et al., 2012). In contrast to lake levels, forests are more sensitive to the duration of summer drought than the abundance of winter precipitation (Allard et al., 2008; Misson et al., 2011; Nijland et al., 2011). Thus arboreal expansion after 7000 cal yr BP, may indicate increasing moisture availability south of 40° N after a dry early Holocene (Tinner et al., 2009; Vannière et al., 2011; Calò et al., 2012; Djamali et al., 2013). In Sicily, evergreen forests persisted until the last 2000 years, and forest collapse is associated with evidence of increasing human disturbance (e.g. fire, land clearance for agriculture, intensified crop production and husbandry) not long-term hydrological changes, suggesting that summer moisture could have remained adequate after lake levels declined (Tinner et al., 2009; Bisculm et al., 2012; Calò et al., 2012; Tinner et al., 2016.).

The continuing uncertainty in a fundamental aspect of Mediterranean climate history, whether moisture availability increased, decreased, or remained stable during the Holocene, limits understanding of the drivers of Holocene vegetation, disturbance, and hydrology, and therefore potential impacts of future climate change scenarios (Henne et al., 2015). Resolving these conflicting interpretations of Holocene climate change requires additional proxies for changes in moisture availability, particularly for important changes in growing season moisture that constrain vegetation, agriculture, and fire regimes.

Here we present paleohydrological reconstructions of Lago Preola and Gorgo Basso, karst lakes located in southwestern Sicily (Fig. 1), based on the biogeochemistry and autecology of freshwater and brackish ostracodes. Although ostracode analyses are available from other Mediterranean areas (e.g. Anadón et al., 1994; Belis et al., 1999, 2008; Kaltenrieder et al., 2009; Marco-Barba et al., 2013a,b), this is the first such study from Sicily. Our new records complement existing investigations of lake level change at Lago Preola (Magny et al., 2011a), and of pollen and charcoal at Lago Preola (Calò et al., 2012) and Gorgo Basso (Tinner et al., 2009). Our study addresses mid-late Holocene moisture balance in the central Mediterranean from a fresh perspective: site specific hydrology and paleosalinity through the examination of ostracodes. At long time scales involving major climatic shifts (glacial-interglacial cycles), changes in ostracode assemblages are primarily temperature dependent, but within these cycles, ostracodes are more sensitive to changes in hydrochemistry, especially salinity (De Deckker and Forester, 1988; Curry and Baker, 2000; Curry, 2003).

The Mediterranean climate of Sicily features precipitation exceeding evaporation only during the cool rainy season, typically September-April (Fig. 2). Therefore, groundwater recharge that feeds our karst lakes derives almost entirely from cool season precipitation (Ducci and Tranfaglia, 2008; Fiorillo and Guadagno, 2010). Summer evaporation is also an important constraint on the water balance and chemical composition of Mediterranean lakes (Jones and Imbers, 2010). Past research from Lago Preola indicated high lake levels from about 10,000–6500 cal yr BP, highly variable conditions from 6500 to 4500 cal yr BP, and low levels from 4500 cal yr BP to the present (Magny et al., 2011a). We propose that if the early Holocene summers were wet, and summer moisture declined and temperatures increased during the mid-late Holocene (i.e. the "aridification" hypothesis), then the salinity of our lakes would be expected to be lowest during an early Holocene wet period, and highest during a dry late Holocene, due to increasing evaporative concentration of dissolved ions. Alternatively, if precipitation seasonality was more intense during the early Holocene (i.e. more winter and less summer precipitation), and summer moisture availability increased toward the late Holocene, as in most of Europe, we would expect salinity to be highest during the early Holocene, and lowest during the late Holocene.

We test these competing hypotheses using new ostracode paleosalinity, isotope, and ecology records from Gorgo Basso and Lago Preola. Our new records use the geochemistry of ostracode valves (Sr/Ca, $\delta^{18}O$ and $\delta^{13}C$) to infer the ancient chemistry of the host water (De Deckker et al., 1988; Holmes, 1996; Anadón et al., 2002; Boomer and Eisenhauer, 2002; Frenzel and Boomer, 2005; Viehberg et al., 2008; Holmes and De Deckker, 2012; Decrouy, 2012; Marco-Barba et al., 2012, 2013a,b). We use transfer functions for salinity to assess changes in water level and permanence, effective moisture, and water residence time (e.g. Mezquita et al., 1999, 2005; Reed et al., 2012; Marco-Barba et al., 2012). We also use ordination of stratigraphic assemblages to investigate limnological changes (Curry, 2003; Mezquita et al., 2005; Belis et al., 2008) and compare our new ostracode records to pollen, charcoal, and lake-level reconstructions from the same sediments to provide an integrative interpretation of changing climate, hydrology, and vegetation.

## 2. Site and methods

### 2.1. Study area

Lago Preola (LP; 37.621°N, 12.638°W; 33 ha; when full, maximum depth = 2 m) and Gorgo Basso (GB; 37.609°N, 12.655°; 3 ha; maximum depth = 8 m) are located in the *Riserva Naturale*