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Centennial-scale vegetation dynamics and climate variability in SE Europe during Marine Isotope Stage 11 based on a pollen record from Lake Ohrid

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ABSTRACT

To better understand climate variability during Marine Isotope Stage (MIS) 11, we here present a new, centennial-scale-resolution pollen record from Lake Ohrid (Balkan Peninsula) derived from sediment cores retrieved during an International Continental Scientific Drilling Program (ICDP) campaign. Our palynological data, augmented by quantitative pollen-based climate reconstructions, provide insight into the vegetation dynamics and thus also climate variability in SE Europe during one of the best orbital analogues for the Holocene. Comparison of our palynological results with other proxy data from Lake Ohrid as well as with regional and global climate records shows that the vegetation in SE Europe responded sensitively both to long- and short-term climate change during MIS 11. The chronology of our palynological record is based on orbital tuning, and is further supported by the detection of a new tephra from the Vico volcano, central Italy, dated to 410 ± 2 ka. Our study indicates that MIS 11c (~424–398 ka) was the warmest interval of MIS 11. The younger part of the interglacial (i.e., MIS 11b–11a; ~398–367 ka) exhibits a gradual cooling trend passing over into MIS 10. It is characterized by considerable millennial-scale variability as inferred by six abrupt forest-contraction events. Interestingly, the first forest contraction occurred during full interglacial conditions of MIS 11c; this event lasted for ~1.7 kyrs (406.2–404.5 ka) and was characterized by substantial reductions in winter temperature and annual precipitation. Most notably, it occurred ~7 ka before the end of MIS 11c and ~15 ka before the first strong ice-rafted debris event in the North Atlantic. Our findings suggest that millennial-scale climate variability during MIS 11 was established in Southern Europe already during MIS 11c, which is earlier than in the North Atlantic where it is registered only from MIS 11b onwards.

1. Introduction

In light of present anthropogenic climate change, the study of past interglacials provides a promising avenue towards improved predictions of future climate change and its consequences for the biotic and abiotic environment (e.g., Past Interglacials Working Group of PAGES, 2016). Marine Isotope Stage (MIS) 11 has received special attention in these efforts because it represents one of the best orbital analogues for present climate based on the low eccentricity and muted influence of precession (Loutre and Berger, 2003; Müller and Pross, 2007; Ruddiman, 2005; Yin and Berger, 2015). Ice-core data from Antarctica (e.g., Jouzel et al., 2007; Pol et al., 2011) as well as marine (e.g., Barker et al., 2015; Martrat et al., 2007; McManus et al., 2003; Oppo et al., 1998; Voelker et al., 2010) and terrestrial proxy records (e.g., de Vernal and Hillaire-Marcel, 2008; Melles et al., 2012; Prokopenko et al., 2002) suggest that MIS 11 was characterized by exceptionally

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long-lasting (~30 kyrs) warm conditions that spanned two insolation peaks. Compared to other Quaternary interglacials, MIS 11 is the only one during which high CO_2 (270–285 p.p.m.v.; Lüthi et al., 2008) and CH_4 (600–700 p. p.b.v.; Loulergue et al., 2008) concentrations prevailed for more than 20 kyrs.

Terrestrial climate-proxy data for MIS 11 suggest a prevalence of exceptionally warm and wet conditions in the high latitudes of the Northern Hemisphere; for instance, pollen data document the presence of boreal forests in the Siberian Arctic (Melles et al., 2012) and on southern Greenland (de Vernal and Hillaire-Marcel, 2008). The higher number of terrestrial climate-proxy records available for the mid-latitudes allows identification of a considerable spatial complexity. Whereas warm and wet conditions prevailed across Europe (see reviews by Candy et al., 2014, and de Beaulieu et al., 2001), extreme droughts occurred in the southern part of North America (e.g., Valles Caldera, New Mexico – Fawcett et al., 2011). Pronounced climate instability during MIS 11 on both centennial (Koutsodendris et al., 2010; Prokopenko et al., 2010; Tye et al., 2016) and millennial (Oliveira et al., 2016; Tzedakis et al., 2009) timescales has been documented in several terrestrial records from Eurasia, further suggesting that MIS 11 climate was also temporally highly complex (Kleinen et al., 2014). The origin of these climate instabilities has been related to the weakening of the Atlantic Meridional Overturning Circulation (AMOC; e.g., Barker et al., 2015; McManus et al., 2003; Oppo et al., 1998) and associated ocean-atmosphere interactions (e.g., Billups et al., 2004; Oliveira et al., 2016).

The response of terrestrial ecosystems to climate forcing during MIS 11 has remained insufficiently constrained despite the emergence of new terrestrial records over the past years. In particular, the impact of short-term climate variability on terrestrial ecosystems (and, by extension, the dynamics of short-term terrestrial climate variability itself) during MIS 11 is yet poorly understood due to the low spatial coverage of continuous, high-resolution pollen records. The pollen records for MIS 11 in Central and NW Europe (e.g., Lake Ossowka – Nitychoruk et al., 2005; Dethlingen – Koutsodendris et al., 2010; Marks Tey – Tye et al., 2016) cover only parts of the interglacial owing to the obliteration of the respective archives by advancing glaciers. Moreover, plant migration lags complicate the reconstruction of short-term climate change in Western and Central Europe under boundary conditions other than during full interglacials (Koutsodendris et al., 2012; Müller et al., 2003). In contrast, pollen records from the Mediterranean region can provide high-fidelity information on short-term climate change throughout the Quaternary because glacial advances did not affect the respective archives. At the same time, they were also located within or in close proximity to glacial tree refugia (Medail and Diadema, 2009), which minimizes the time lag between climatic forcing and vegetation response as it may result from taxon-specific migration times. However, the yet available MIS 11 pollen records from southern Europe, such as from Greece (Tenaghi Philippon – Pross et al., 2015, and references therein; Wijmstra and Smit, 1976; Ioannina – Tzedakis et al., 2001; Kopais – Okuda et al., 2001; Megalopolis – Okuda et al., 2002), France (Praclaux; Reille et al., 2000), and Asia Minor (Lake Van; Litt et al., 2014) are of relatively low temporal resolution and therefore can only provide limited insight into short-term climate and ecosystem change. Crucial information on terrestrial climate and vegetation dynamics during MIS 11 has become available from the Iberian margin off Portugal, i.e., core MD01-2447 (Desprat et al., 2005), core MD01-2443 (Tzedakis et al., 2009), and IODP Site U1385 (Oliveira et al., 2016). However, the pollen records from the former two sites do not span the MIS 12/11 transition, and the temporal resolution of the pollen record from the latter site is compromised by low sedimentation rates across the MIS 12/11 transition and during the early part of MIS 11c. Therefore, these records do not cover the full range of climate variability connected to MIS 11.

Because continuous, highly resolved records that cover the onset, course and termination of MIS 11 are required in order to fully appreciate the evolution of this critical interval of the Quaternary, we have palynologically analyzed new core material covering MIS 11 from Lake Ohrid (SW Balkan Peninsula; Fig. 1). The cores were retrieved within an International Continental Scientific Drilling Program (ICDP) campaign in 2013 (Wagner et al., 2017). Previous studies have demonstrated the sensitive response of both the aquatic ecosystems of Lake Ohrid and the terrestrial ecosystems in the catchment area of the lake to climate change on sub-orbital (e.g., Lézine et al., 2010; Vogel et al., 2010; Wagner et al., 2010) and orbital timescales (Francke et al., 2016; Just et al., 2016; Sadori et al., 2016).

For the purpose of this study, we have used core material from the DEEP site that extends continuously back to at least 1.3 Ma (Wagner et al., 2017) and hence also covers MIS 11. To unravel the terrestrial ecosystem response to abrupt climate change and to reconstruct the magnitude of climate change at Lake Ohrid during MIS 11, we have increased the temporal resolution of previously published pollen information spanning this interval (Bertini et al., 2016; Sadori et al., 2016) by four times and generated quantitative pollen-based climate estimates from our data. We integrate our new centennial-scale-resolution pollen record with previously published sedimentological and oxygen-isotope data from the DEEP Site (Francke et al., 2016; Lacey et al., 2016). Finally, we compare our results with (supra)regional proxy records both from the marine and terrestrial realms in order to shed light on the character and timing of short-term climate change during MIS 11.

2. Regional setting

Located in a N-S-trending tectonic graben on the southwestern Balkan Peninsula, Lake Ohrid is surrounded by the Mokra mountains to the west (maximum altitude: 1514 m above sea level [a.s.l.]) and the Galičica mountains to the east (2265 m a.s.l.). The lake is situated at an altitude of 693 m a.s.l. and is up to 289 m deep (Wagner et al., 2017). It has a surface area of 358 km^2, a water volume of ~50.7 km^3 (Matzinger et al., 2007), and a direct catchment area of 1310 km^2 (Wagner et al., 2010).

Climatically, the Lake Ohrid region is influenced predominantly by high- and mid-latitude climate systems of the Northern Hemisphere (i.e., Westerlies, Siberian High; Fig. 1). It is characterized by typical Mediterranean climate conditions, marked by wet and cold winters (with the occurrence of frost), and dry and warm summers (Lionello et al., 2006, and references therein). During winter, moisture delivery is mainly linked to increased convective precipitation (Bosmans et al., 2015) and the penetration of westerly storm tracks across the Mediterranean region (e.g., Xoplaki et al., 2004); cold spells are related to southward outbreaks of polar air masses from the Russian/Siberian High (e.g., Saaroni et al., 1996). Meteorological data acquired during the 1961–1990 period from the meteorological stations at the towns of Ohrid and Resen (about 20 km east of Lake Ohrid) have yielded a mean annual precipitation between 698 and 1194 mm yr^{-1} (average: 907 mm yr^{-1}). The mean annual air temperature is 11.1 °C, with minimum and maximum temperatures of −5.7 and 31.5 °C, respectively (Popovska and Bonacci, 2007).

Today, Lake Ohrid is surrounded by forest vegetation that consists predominantly of Mediterranean and Balkan elements, while several central European taxa are also present (Čarni and Matevski, 2015; Matevski et al., 2011; Panagiotopoulos et al., 2013). The riparian forests around Lake Ohrid are dominated by *Salix alba*. Deciduous and semi-deciduous oaks (e.g., *Quercus cerris, Q. frainetto,*