

# Pollen-based temperature and precipitation changes in the Ohrid Basin (western Balkans) between 160 and 70 ka

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15 **Abstract.** Our study aims to reconstruct climate changes that occurred at Lake Ohrid (south-western Balkan Peninsula), the oldest extant lake in Europe, between 160 and 70 ka (covering part of Marine Isotope Stage – “MIS” – 6, ~~and~~ all of MIS 5 and the beginning of MIS 4). A multi-method approach, including the “Modern Analogues Technique” and the “Weighted Averaging Partial Least-Squares Regression”, is applied to the high-resolution pollen sequence of the DEEP site, collected from the central part of Lake Ohrid, to provide quantitative estimates of climate and bioclimate parameters. This allows us to document climatic change during the key periods of MIS 6 and MIS 5 in South Europe, a region where accurate climate reconstructions are still lacking for this time interval.

Our results for the penultimate glacial show cold and dry conditions, while the onset of the Last Interglacial is characterized by wet and warm conditions, with temperatures higher than today (by ca. 2°C). The Eemian shows also in the Balkans the well-known was not a stable phase and a climatic tri-partition, with an initial pre-temperate phase of abrupt warming (128-121 ka), a central temperate phase with decreasing temperatures associated to wet conditions (121-118 ka), followed by a post-temperate phase of progressive change towards cold and dry conditions (118-112 ka), is evident.

After the Eemian, an alternation of four warm/wet periods with cold/dry ones, likely related to the succession of Greenland stadials and cold events known from the North Atlantic, occurred. The observed pattern is also consistent with hydrological and isotopic data from the central Mediterranean.

25 The Lake Ohrid climate reconstruction shows greater similarity with climate patterns inferred from northern European pollen records than with southern European ones, which is probably due to its intermediate position and the mountainous setting. However, this hypothesis needs further testing as very few climate reconstructions are available for southern Europe for this key time period.

## 1 Introduction

Since the Mid Pleistocene, the Quaternary is characterized by high-amplitude glacial-interglacial climate variability, occurring cyclically with a 100 ka (kiloanni) periodicity (e.g. Raymo et al., 1989; Tzedakis et al., 1997). The marine isotope stages - “MIS” - 6 (penultimate glacial) and MIS 5 (interglacial-glacial Last Interglacial Complex - LIC) are defined by marine oxygen isotope records ( $\delta^{18}\text{O}$ ; Lisiecki and Raymo, 2005). MIS 6 is also named the penultimate glacial (~~or~~ Riss Glaciation in the alpine area, Late Saale/Saalian Complex in northern and central Europe) and can be roughly dated from ca. 190 to ca. 130 ka, while MIS 5 ~~is termed the Last Interglacial Complex (LIC) and~~ lasts from ca. 130 to ca. 80 ka (Govin et al., 2015; Railsback et al., 2015 and references therein). The penultimate glacial is characterized by ~~a~~ millennial-scale climate variability (Martrat et al., 2004), and ~~the end of MIS 6 is characterized~~ ends by several abrupt events, which are probably related to the iceberg-rafted debris (IRD) deposition intervals in the Northeast Atlantic (McManus et al., 1999). In contrast, the LIC includes the Last Interglacial (roughly equivalent to MIS 5e, or Eemian), followed by a period named “Early Last Glacial” characterized by a succession of stadial (cold/dry conditions) and interstadial (warm/wet conditions) periods (MIS 5d to 5a). These stadials and interstadials correlate to glacial advances/retreats that are documented by ice-rafted debris in North Atlantic sediments (e.g. Bond events and Heinrich events: Bond et al., 1992; Bond and Lotti, 1995) and by changes in oxygen isotope composition in Greenland ice cores (Dansgaard-Oeschger cycles: Dansgaard et al., 1993). Equivalent to the marine isotope stages, the ice core records distinguish Greenland stadials (GS) and Greenland interstadials (GI) where short-lived cold episodes are associated to surface ocean cooling (C events). Across the LIC, seven such cold events (C19-25) have been documented (McManus et al., 1994; Oppo, 2006; Rasmussen et al., 2014).

The Eemian (127-110 ka, Turner 2002, Shackleton et al., 2003) is of particular interest with regard to orbital parameters inducing a strong seasonal forcing of insolation, contrasted vegetation changes (Beaulieu and Reille, 1992; Zagwijn, 1996) and climatic conditions (Cheddadi et al., 1998; Sánchez-Goñi et al., 2012). Therefore, this period is also considered as a useful target for General Circulation Models (GCMs) data-model comparison (Kaspar et al., 2005; Otto-Bliesner et al., 2013). In the Northern Hemisphere, the Eemian was wetter (Fauquette et al., 1999; Guiot, 1990; Guiot et al., 1993; Klotz et al., 2003) and ~~warmer in summer~~ by up to 1-2 °C warmer in summer than the Holocene (Kaspar et al., 2005; Otto-Bliesner et al., 2013; Overpeck et al., 2006;), while sea level was ca. 6 - 9 meters higher (e.g., Kopp et al., 2009). The Eemian thus allows to study climate dynamics and ecosystem response in a warmer than present Northern Hemisphere without the influence of anthropogenic activity, thereby contributing to assessments of the future impact of the current anthropogenic climate change. Earlier studies of the Eemian considered it a stable, uninterrupted warm period (e.g. Guiot et al., 1993; McManus et al., 1994; Pons et al., 1992; Zagwijn, 1996), with climatic oscillations only recorded in the final part, at the transition with the following glacial, i.e. the Weichselian of central and northern Europe, named Early Würm in the alpine region (Beaulieu and Reille, 1984, 1989; Field et al., 1994; Litt et al., 1996). However, more recent studies suggest that ~~low-low~~ low-amplitude climatic fluctuations did occur during the Eemian (e.g. Brewer et al., 2008; Sánchez-Goñi et al., 2005; Sirocko et al., 2005) and in North GRIP ice core isotope records (NGRIP Members, 2004). A pronounced short-lived climatic fluctuation, the intra-Eemian cold event, occurred around 122 ka (Maslin and Tzedakis, 1996). Climate changes across the penultimate glacial and the Eemian ~~are~~ is documented by numerous pollen records from marine and terrestrial archives (e.g. Govin et al., 2015; Kaspar et

al., 2005; Otto-Bliesner et al., 2013). Some of these records have been used for the reconstruction of climatic parameters with a quantitative approach synthesized in Brewer et al. (2008). However, most of these have been carried out using pollen data from European sites located north of 45°N, while only few reconstructions were carried out in southern Europe. Two are based on pollen continental records, Lago Grande di Monticchio in southern Italy (Allen et al., 2000) and Ioannina in north-western Greece (Tzedakis, 1994) and two on marine pollen records, MD 99-2331 and MD 99-2042 on the Iberian margin (Sánchez-Goñi et al., 2005, Brewer et al., 2008). A first North-South comparison suggests that the two regions may have experienced a somewhat different climatic pattern during the Eemian (Brewer et al., 2008). While both regions experienced an early temperature optimum followed by a cooling trend, towards the end of the Eemian, temperatures and precipitation decreased more strongly in northern Europe compared to southern Europe (Brewer et al., 2008; Sánchez-Goñi, 2007 and references therein). Given that this comparison is based on 13 North European sites and on only 4 South European sites there is a need to provide more reliable quantitative climate reconstructions in southern Europe for the penultimate glacial, for the Eemian and for the entire Last Interglacial Complex LIC in order to improve our understanding of the climate response during high-amplitude glacial interglacial cycles to climate changes.

The Balkan Peninsula is unambiguously a key region at the confluence of central European and Mediterranean climate influences. The area is rich in extant Quaternary lakes and palaeolakes, with sediment records providing essential information on past vegetation and climate changes going back hundreds of thousands years, such as Lake Ohrid (Albania/F.Y.R.O.M.: e.g. Lézine et al., 2010; Sinopoli et al., 2018; Wagner et al., 2017), Lake Prespa (Albania/F.Y.R.O.M./Greece: Panagiotopoulos et al., 2014), Ioannina (West Greece: Tzedakis et al., 2003), Tenaghi Philippon (North-East Greece: Milner et al., 2016), and Kopais (South-East Greece: Tzedakis, 1999; Okuda et al., 2001). Despite the richness in long palaeoenvironmental archives, quantitative palaeoclimatic reconstructions have been rarely attempted or cover relatively short periods.

In this study, we use a multi-method approach to reconstruct climate parameters between the end of the penultimate glacial (160 to 128 ka) and the Last Interglacial Complex LIC (128-70 ka) inferred from the exceptionally long palynological record (569 m) of the Ohrid Basin in the Western Balkans (Sadori et al., 2016). The high-resolution palynological data has been acquired from a sediment core from the center of the lake (DEEP site: Sinopoli et al., 2018). The MIS 6 to MIS 5 transition at Lake Ohrid has been the subject of accurate chronological alignments and synchronizations (Zanchetta et al., 2016) which yield resulting in an offset of 2 ka compared to with other records (e.g. Govin et al., 2015; Railsback et al., 2015). The approach for paleoclimate reconstruction applied herein includes two methods frequently used in palaeoclimate reconstructions: the Modern Analogs Technique (MAT: Guiot, 1990) and the Weighted Averaging Partial Least-Squares Regression (WAPLS: Ter Braak and Juggins, 1993). In order to test the reliability of our numerical approach, we compare the results to independent climate proxies from the Ohrid Basin such as biomarkers (Holtvoeth et al., 2017) and total inorganic carbon (TIC) concentrations, which largely represent authigenic calcite precipitation (Vogel et al., 2010; Francke et al., 2016). To discuss the climate signal at a more global scale, we compare our results to available pollen-based reconstructions from northern Europe and the Mediterranean, and to marine and terrestrial proxies from the Mediterranean and the Northern Hemisphere (e.g., De Abreu et al., 2003; Drysdale et al., 2005; NGRIP Members, 2004; Lisiecki and Raymo, 2005; Martrat et al., 2004; Regattieri et al. 2014, 2017; Sánchez-Goñi et al., 1999; Wang et al., 2010).

## 2 Site description

~~A complete list of supporting literature can be found in Saderi et al., 2016, Sinopoli et al., 2018, and Wagner et al., 2017.~~ Lake Ohrid is located on the Balkan Peninsula at the border between the Former Yugoslav Republic of Macedonia (F.Y.R.O.M.) and Albania (Fig. 1). It is probably the oldest lake of Europe, with an estimated age of  $\geq 1.2$  Ma. The lake has a tectonic origin, as its catchment is located in a graben that formed during the Alpine orogenesis between ca. 10-2 Ma ago. Today, Lake Ohrid has a surface area of 360 km<sup>2</sup> (30 km long, 15 km wide, 693 m a.s.l.), an average depth of 164 m and a maximum depth of 293 m. The basin is bordered ~~to~~ the West by the Mokra Mountains (1514 m a.s.l.) and ~~to~~ the East by the Galičica Mountains (2265 m a.s.l.). The latter separate the watersheds of Lake Ohrid and adjacent Lake Prespa (849 m a.s.l.), which is located ca. 10 km to the East, although the two lakes are connected via a karst aquifer system. Apart of inflow from Lake Prespa ~~via the karst aquifers~~, Lake Ohrid is supplied with water from surface run-off via small streams, ~~and~~ rivers and by direct precipitation. Modern climate in the Ohrid region is Mediterranean with continental influences. The thermal capacity of the lake as well as its proximity to the Adriatic Sea and the local topography affect the local climate. The mean annual temperature recorded in the Ohrid region averages at 11.5 °C; temperatures range between ca. 2 and 6 °C in winter (minimum in January) and between 10 and 22 °C in summer (maximum in July). The morphology of the catchment also affects the wind regime, with northerly winds prevailing during winter and south-~~erly and~~ southeasterly winds during spring and summer. The pluviometric regime is Mediterranean, with an average annual precipitation of 878 mm (Fig.1).

Lake Ohrid has a rich macrophytic flora (more than 124 species) distributed into ~~four different~~ zones dominated by *Lemna trisulca* L., *Phragmites australis* (Cav.) Trin. ex Steud., *Potamogeton* L., Characeae, *Ceratophyllum* L., *Myriophyllum* L. and the colonial alga *Cladophora* spp. The present vegetation around Lake Ohrid belongs to the sub-mediterranean type, in which mediterranean and Balkan elements dominate together with central European ones. The vegetation is sequenced in altitudinal belts, starting from lake level (693 m a.s.l.) to the top of the mountains (ca. 2200 m a.s.l.). Riparian forest (dominated by *Salix alba* L.), with elements of mediterranean vegetation (*Fraxinus ornus* L., *Pistacia terebinthus* L. and *Phyllirea latifolia* L.), is present from the altitude of the lake level to lower elevations together with *Buxus sempervirens* L., *Quercus trojana* Webb, *Carpinus orientalis* L. and *Ostrya carpinifolia* Scop. Otherwise, forests are characterized by mixed deciduous elements and are mainly composed of *Quercus cerris* L., *Q. frainetto* Ten., *Q. petraea* (Matt.) Liebl., *Q. pubescens* Willd. up to 1600 m a.s.l., followed by montane and mesophilous forests (from 1600 to 1800 m a.s.l.) dominated by *Fagus sylvatica* L. in association with *Carpinus betulus* L., *Corylus colurna* L. and *Acer obtusatum* (*Acer opalus* subsp. *obtusatum* (Waldst. & Kit. ex Willd.) Gams). *Abies alba* Mill. and *A. borisii-regis* Matt. mixed forests grow below 1900 m a.s.l., at the upper limit of the forested area, while sub-alpine grassland and shrubland with *Juniperus excelsa* (subsp. *polycarpus* (K. Koch) Takhtajan) are found above the tree-line in mountains situated at south-east of the lake. Towards the East, *Pinus peuce* Griseb., is present at high elevation, associated with *Pteridium aquilinum* (L.) Kuhnor, *Vaccinium myrtillus* L. Sparse population of *Pinus* species considered to be Tertiary relics are present in the wider area.

### 3. Materials and Methods

#### 3.1 Pollen data from the DEEP core

A drilling campaign ~~mainly funded~~within the scope of by the International Continental Scientific Drilling Program (ICDP) was carried out as part of the project Scientific Collaboration On Past Speciation Conditions in ~~lake-Lake~~ Ohrid (SCOPSCO) in 2013. Six parallel cores were recovered from the depocenter of the lake at 243 m water depth (DEEP site). A composite sequence representing an overall sediment depth of 569 spanning at least the last 1.2 million years has been obtained (Wagner et al., 2017). According to the age model, the uppermost 247.8 m of the DEEP core cover the last 637 ka (Francke et al., 2016). Palynological data has been published for the upper 200 m of the DEEP pollen record, covering the last 500 ka, with a time resolution of ca. 1600 years (Bertini et al., 2016; Sadori et al., 2016). Results have shown an alternation of forested and non-forested periods that are ascribed to five glacial-interglacial cycles. The study presented herein is based on ~~new-~~“higher-resolution” pollen data (one sample every ca. 400 years, Sinopoli et al., 2018, in the following named “high-resolution”) summarised in Figure 2.

#### 3.2 Quantitative reconstruction of temperature and precipitation

We adopted two different methods in order to improve the error assessment of our approach (e.g., Klotz et al., 2003; Kühl et al., 2010; Peyron et al., 2005, 2011, 2013). It has been demonstrated by several studies that reconstructions based on just one method can have limitations, depending on the time interval and on the methods chosen (Birks et al., 2010; Brewer et al., 2008). Here, we have selected the Best Analogs Approach or Modern Analog Technique (MAT: Guiot, 1990) and the Weighted Average Partial Least-Squares Regression (WAPLS: Ter Braak and Juggins, 1993), two classical methods already used to reconstruct climate changes in the Mediterranean during the Holocene and other time periods (e.g. Brewer et al., 2008, Mauri et al., 2015; Peyron et al., 2011, 2013). Both methods are based on the assumption that climate change strongly influences the distribution and composition of vegetation as every plant species tolerates distinct ranges of temperature and humidity. The MAT is based on the comparison between fossil pollen assemblages and modern ones. The MAT determines the degree of dissimilarity (in terms of taxa abundance and composition) between modern pollen data (associated to known climatic parameters) and the fossil data for which the climatic parameters are to be estimated. For each fossil pollen assemblage, a number of modern pollen assemblages are selected (based on a chord distance calculation) as the closest ones or “analogues”. The number of analogues used may affect the quality of the reconstructions. In the present paper, the most robust reconstructions are obtained using 6 analogues. This is the optimal number of analogues (determined using the lowest root-mean-square error of prediction) in order to minimize the chances of falsely determining two modern samples to be analogues or considering two analogous samples not to be analogues. The method uses the present-day climate data associated to the selected modern analogues to infer the past climate values (Guiot, 1990). In contrast to the MAT, the WAPLS method is a transfer function, which uses a real statistical calibration between climate parameters and modern pollen data. The method is based on unimodal relationships between pollen percentages and climate. In WAPLS, several components are calculated based on weighted averaging algorithms that successively explain more variance in the data; this means that taxa, which better define

a climate parameter are weighted more than the other ones (Ter Braak and van Dam, 1989). A cross-validation has been done for determining the right number of components (Ter Braak and Juggins, 1993). For both methods, we have used a modern pollen dataset containing more than 3088 samples from European and Mediterranean regions (Peyron et al., 2013). From this dataset, we have excluded those pollen samples collected in warm to hot steppes in order to improve the climate reconstruction during steppic phases (Tarasov et al., 1998). Moreover, *Pinus* has been excluded due to its overwhelming presence in the DEEP record that potentially masks climatically controlled environmental signals from other taxa. The differences between the two methods probably depend on the lack of present-day European analogues for some glacial vegetation formations.

Five climate parameters have been reconstructed for the DEEP pollen record excluding *Pinus* (Fig. 3, for the reconstruction with *Pinus* see Fig. A in supplementary materials) with each method: 1) the mean temperature of the coldest month (MTCO), 2) the mean temperature of the warmest month (MTWA), 3) the mean annual temperature (TANN), 4) the mean annual precipitation (PANN) and 5) the growing degree days above 5°C (GDD5) (Peyron et al., 1998). The analysis was carried out with the software package R program, a system for statistical computation and graphics (R Foundation, <https://www.r-project.org/>), by using the Package ‘rioja’ (Juggins, 2016). Error bars have been calculated but are not shown in the figure for graphic clarity. They are available as supplementary material (Fig. BA). Fig. CB (supplementary material) indicate the reliability of the analogues selected by reporting the squared-chord distance between the first and the last analogue for a chosen climate parameter (TANN) calculated by MAT method. The first(last) analogue corresponds to the closest analogue with the low(high) chord distance.

#### 4. Results

Previous low-resolution data show that MIS 6 was characterized by prevalence of *Artemisia*, *Amaranthaceae* and *Asteroidae* since 160 ka (Sadori et al., 2016). During the LIC, high-high-resolution data provides evidence for forested periods (interglacial and interstadials) alternating with periods of a more open environment (stadials). The pollen analysis revealed that the surroundings of Lake Ohrid during the Eemian were characterized by mesophilous communities prevailing on montane ones (Fig. 2). Forests were mainly featured by expansion of *Quercus robur* type and *Q. cerris* type together with *Pinus* and *Abies* (Sinopoli et al., 2018). Trees never completely disappear, being also recorded during stadial periods, albeit at low percentages. Here we adopt the terminology used by Woillard (1978) for La Grande Pile pollen record to enhance comparability (see Tab. 1). We are aware that the marine stratigraphy does not always precisely match the terrestrial one (e.g. Sánchez-Goñi et al., 2007).

Our climate reconstruction suggests cold and dry conditions during MIS 6 and, in MIS\_5, an alternation of warm and wet conditions during the Eemian and St. Germain I and II interstadials with cooler and dryer ones occurring during stadials (Fig. 3).

#### 4.1 The late part of the Penultimate glacial (MIS 6, 160-128 ka)

The ~~late and long-lasting~~ second part of MIS 6 was very cold and dry (Fig. 3) as suggested by the results from both MAT and WAPLS. This portion of the glacial period can be divided into a first part, between 160 and 143 ka, which is characterized by cold and dry climate conditions (mean annual temperature below 6 °C and annual precipitation mainly between 350 and 600 mm/yr), and a second part, lasting from 143 to 128 ka, when several short-term high-amplitude oscillations are reconstructed, especially from 140 to 135 ka. These abrupt changes involve all the climate parameters. These oscillations represent significant shifts in mean annual temperature (TANN) and precipitation (PANN), ranging from 2.7 °C to 10°C and from 120 mm/yr to 600 mm/yr respectively. The GDD5 (growing degrees days over 5 °C, annual accumulated temperature over 5 °C) pattern is strongly linked to the MTWA (mean temperature of the warmest month) pattern. The pronounced peak in temperature around 138 ka is probably linked to the high percentages of mesophilous taxa; however, this increase seems overestimated with the MAT. Notably, this oscillation and also the other lower-amplitude oscillations between 143 to 128 ka are more marked in the reconstruction inferred from the MAT (Fig. 3). These values are probably overestimated as the MAT is more sensitive than WAPLS and other methods such as PDF (Brewer et al., 2008; Köhl et al., 2010). Brewer et al. (2008) demonstrated that a wider spread of estimates is found during colder periods and that the analogue methods seem to give a larger variability in time than the other methods, especially during the cold periods.

#### 4.2 The Last Interglacial Complex -LIG- (MIS 5, 128-70ka)

##### 4.2.1 The last interglacial (128-112 ka) or Eemian

~~At 128 ka,~~ the transition to the last interglacial, dated at 128 ka, is marked by a rapid rise in temperature and in precipitation, being very close to modern values. The so-called thermal optimum-maximum of the Eemian, occurring at Lake Ohrid between 128 and 121 ka, is characterized by TANN between 10 and 12 °C, the highest of the investigated period, 2 °C warmer than the present day (Figs 3, 5, 6). Winter temperatures were also warmer than today, while summer ~~ones~~ temperatures were close to modern values and precipitation 100 mm lower than present day (Figs 3, 5). A cool event is suggested between 121 and 118 ka, while precipitation reaches the highest values of the Eemian at around 119.4 ka. After this cool phase, during the last part of the last interglacial (118-112 ka), we reconstruct a progressive cooling and a decrease in precipitation until the end of the Eemian at 112 ka.

##### 4.2.2 The Early Last Glacial (112-70 ka)

The Early Last Glacial (Table 1) is characterized by an alternation of short cold/dry periods with longer warm/ wet ones:

- warm and wet interstadial periods: St. Germain I (108-90.289.8 ka), St. Germain II (85.7-78.8), Ognon I (76.677.6-75.475 ka), Ognon II (73.4-69.9 ka).
- cool and dry stadial periods: Melisey I (112-108 ka), Montaignu (105.2-104 ka), Melisey II (90.289.8-85.7 ka), stadial I (78.8-77.6 ka), stadial II (75.475-73.4 ka)

#### 4.2.2.1 Interstadials: warm and wet conditions

The first interstadial following the Eemian (Fig. 3) corresponds to the St. Germain I (108-~~90.2~~ ~~89.8~~ka) which can be divided (Tab. 1) in three parts, two of which, St. Germain Ia (108-105.2 ka) and St. Germain Ic (104-~~90.2~~ ~~89.8~~ ka), are warm and wet, while the other, Melisey II (105.2-104 ka), is cold and dry. During St. Germain Ia, both TANN and PANN increase, suggesting that the St. Germain I was warm and wet, but still to a lower extent less than the Eemian. In contrast, the St. Germain Ic appears to be wetter and overall warmer than St. Germain Ia (Fig. 3). The precipitation increases strongly and reaches values between ca. 600 and 900 mm/yr which i-s the wettest period between 160 and 70 ka. A pronounced dry event is centered at 95.3 ka. The second interstadial (85.7-78.8 ka) corresponding to St. Germain II is characterized by temperate conditions comparable to those of St. Germain Ic (104-~~90.2~~ ~~89.8~~ ka) even if it seems drier. The following two interstadials corresponding to the Ognon I and II (77.6-~~75.4~~ ~~75~~ and 73.4-69.9 ka) show climate conditions comparable to those occurring during the second interstadial (Fig. 3).

#### 4.2.2.2 Stadials: cold and dry conditions

The temperate conditions of the last interglacial are interrupted by a first cooling event corresponding to the stadial Melisey I (112-108 ka) characterized by cold and dry conditions (Fig. 3). A second abrupt event is recorded between 105.2 and 104 ka, namely during the Montaigu cooling (St. Germain Ib) that divides the St. Germain I into two “interstadials”. During this event, precipitation reaches values similar to those of the previous stadial (Melisey I). Temperature and precipitation follow the same pattern with a strong decrease at 104.6 ka. Melisey II (~~89.8~~ ~~90.2~~-85.7 ka) appears as the coldest and driest event of the early last glacial (Fig. 3), with a strong temperature and precipitation decrease evidenced by both methods. As during the end of MIS 6, the cooling reconstructed with the MAT is probably overestimated given that the analogue method provides a large variability during the cold periods. However, the climate was certainly very cold during Melisey II, particularly in winter as illustrated by the WAPLS. Precipitation reaches extremely low values, dropping to ca. 100 mm/yr, which is even lower than in MIS 6 but here too the drying seems overestimated with the MAT for the same reasons as temperatures. The following two stadials (78.8-77.6 ka and ~~75.4~~ ~~75~~-73.4 ka) should indicate a pattern very similar to Melisey II, with an abrupt decrease of temperature and precipitation followed by a likewise abrupt increase at the end of each phase (Fig. 3).

### 5. Discussion

#### 5.1 Differences between MAT and WAPLS and reliability of the methods

The temperature reconstructions from both methods are reasonably coherent (trends and values) during the interglacial and interstadials, but a wider spread of estimates is found during colder periods (Fig. 3) for which the analogues method suggests higher-amplitude oscillations and lower values than those inferred by the transfer function (Fig. 3). More precisely, during ~~the first part of MIS 6~~ (ca. 160-143 ka), both methods produce low-amplitude oscillations in temperatures, but the values determined by MAT appear to be around 4 °C lower than those determined by WAPLS. Even if the precipitation curves



produced by both methods show the same trend, reconstructed values by MAT are roughly 300 mm lower than those resulting from WAPLS. After 143 ka, the differences between the two methods are more ~~marked-pronounced~~ (Fig. 3). It ~~i~~'s worth to be mentioned that WAPLS precipitation values are inside the errors bars (Fig. A, supplementary materials). Discrepancies between the methods may be related to several factors that either depend on the method itself or on the composition of past pollen assemblages. ~~A-s mentioned in section 3.2 m-~~Modern analogues methods are very sensitive to minor variations in the pollen assemblages, especially during glacial periods (Brewer et al., 2008). Similar discrepancies associated with MAT also occur in the reconstruction of La Grande Pile; strong cold ~~and dry~~ oscillations are evidenced (and probably overestimated) after the Eemian thermal optimum by Brewer et al (2008). MAT is frequently used to reconstruct the climate of the Lateglacial and Holocene (e.g. Mauri et al., 2015; Peyron et al., 2005) but, as demonstrated by Guiot et al. (1993), ambiguous outcomes may occur particularly for past glacial and cold intervals (stadials). The major problem appears to be the lack of modern analogues or only limited similarity with past glacial vegetation (Guiot et al., 1993; Peyron et al., 1998). Indeed, as reported in several studies (Guiot, 1987; Guiot et al., 1993; Klotz et al., 2003), glacial steppe vegetation dominated by high percentages of *Amaranthaceae* (as at Lake Ohrid, Fig. 2) has no present-day analogue in Europe. For this reason, we have used modern samples from cold steppe principally from the Tibetan Plateau and from Russia as “potential” analogues for glacial periods (Peyron et al., 1998, 2005). Squared-chord distance has been used to determine the degree of dissimilarity (Fig. A, supplementary materials), revealing that our reconstruction can be judged reliable and without a no-analogs situation occurring. The differences between the two methods for cool/cold periods may also be ascribed to the quasi-continuous presence of arboreal taxa in steppic assemblages. During the period between 143 and 128 ka, the major oscillations are probably overestimated and likely linked to the presence of arboreal mesophilous (temperate) taxa in steppic pollen assemblages. Mesophilous taxa amount to 10-30 %, with prevalence of deciduous and semi-deciduous oaks, while pioneer shrubs are between 5-10 %, with prevalence of *Juniperus* (Fig. 2). This discrepancy attests to the specific local hydroclimatic features of the Ohrid Basin and its fundamental role as a refugium for many arboreal taxa. Considering the very high sensitivity of the MAT, WAPLS seems to be a better method to reconstruct the climatic changes during cold events in refuge areas.

## 5.2 Climate changes at Lake Ohrid: comparison with independent proxies and other climate reconstructions

Our data are in agreement with climate signals depicted in ~~pollen and~~ geochemical data from the DEEP site (Francke et al., 2016, Wagner et al., 2017) and other Lake Ohrid cores (core JO2004 from the south of the lake, Bordon, 2008; core Co1202 from the north-east, Holtvoeth et al., 2017; see Fig. 1; [Vogel et al., 2010](#)). When comparing our results to the Eemian climate reconstruction of JO2004 (Bordon, 2008), the trends are similar, while some differences in temperature and precipitation values should be pointed out. They probably result from differences in pollen assemblages due to the different positions of the analysed cores. Core JO2004 was retrieved from the southern part of the lake, closer to the lake shoreline. Therefore, its pollen assemblages show increased values of local taxa and of those not dispersed over long distances; in contrast, these taxa are found in lower abundance or not at all in the central part of the basin from where the DEEP core was retrieved. Due to the central position of the DEEP and the morphology of the territory around the lake (vegetation organized in altitudinal belts) we ~~think-assume~~ that our climate reconstruction integrates the palynological signal of the surrounding mountain ranges and,

consequently, our data accounts for a regional and not a local climate reconstruction. In Figure 4, the temperature and precipitation (PANN and TANN) signals are compared to the total inorganic carbon (TIC) and the total organic carbon (TOC) records from the DEEP core and to the TIC and Tetra Ether index of archaeal lipids (TEX<sub>86</sub>) from core Co1202. For more information about these proxies see Francke et al. (2016), Vogel et al. (2010), Holtvoeth et al. (2017) and references therein.

5 All proxies reported in Figure 4 are used as indicators for environmental and climatic change. Concerning proxies from the DEEP core, PANN and TANN resemble TIC and TOC. TIC concentrations and precipitation of mainly authigenic carbonate is controlled by water temperature and productivity, but also by ion concentrations in the lake, which depend on precipitation and the activity of the karst aquifer system (Vogel et al. 2010, Francke et al., 2016). Minima in TOC that correspond to minima in TANN indicate that these minima are the result of restricted productivity combined with increased decomposition of organic matter due to the prolonged winter season and enhanced mixing of the water column (Francke et al., 2016). However, TOC reflects autochthonous and allochthonous organic matter input, i.e. supply of biomass from both the lake as well as the surrounding land (Francke et al. 2016, Holtvoeth et al., 2017, [Zanchetta et al., 2018](#)). The productivity of the terrestrial vegetation and ~~export~~ supply of terrestrial organic matter to the lake seem to be largely controlled by precipitation rather than temperature, thus, explaining similarities with the PANN record. While TIC and TOC may co-vary at times they are not generally causally related. During MIS 6, TIC is mostly very low, suggesting cold and dry climate conditions (Francke et al., 2016), in agreement with the pollen-inferred mean annual temperature and precipitation (Fig. 4). At the transition toward MIS 5, TIC and TEX<sub>86</sub> values increase together, indicating a warming and augmentation of humidity, consistent with the increase in PANN and TANN inferred from pollen. The distinct high-amplitude fluctuations inferred from pollen during the final part of MIS 6, could at least partly be due to lake-level changes as the water table during this period was generally on the rise (Lindhorst et al., 2010, Holtvoeth et al., 2017; Wagner et al., 2017). As mentioned before, the (modern) lake basin and parts of the lake floor show a pronounced terraced morphology. The relatively rapid flooding of extended, nearly horizontal surfaces, in particular at the northern and southern ends of the lake, may thus have diminished sizeable parts of (flat) terrestrial habitat in short periods of time. ~~These lake-level fluctuations could be responsible of the oscillations seen in PANN and TANN of DEEP core between 136 and 130 ka.~~ The impact of ~~lake-lake~~ lake-level change on the low-lying terrestrial habitats could be clearly seen in the biomarker and pollen records of the proximal core Co1202 (Holtvoeth et al., 2017). While localised processes are likely averaged out by the longer-distance transport of material towards the distal DEEP site, a basin-wide effect of lake-level change and the associated distribution of low-lying biomes in the north, northeast and south of the basin might have to be considered in order to explain the observed fluctuations in the ~~pollen record~~ PANN and TANN records of the DEEP core between 136 and 130 ka. Precipitation-controlled lake-level change may have affected the surface area of low-lying terrestrial habitats on terrace surfaces before the temperature threshold for the precipitation of authigenic carbonate (TIC) was crossed, leading to the 2000/3000 years offset in the beginning of the high-amplitude fluctuations in pollen-derived PANN and TANN records and the rise in TIC.

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The beginning of the Last Interglacial is almost synchronous as indicated by the records of TIC (DEEP), carbonate and TEX<sub>86</sub> (Co1202, Figure 4). However, according to the TIC and TEX<sub>86</sub> records of Co1202 the thermal ~~optimum~~ maximum, characterized by stable conditions ~~and warm temperature~~, occurs between 126.5 ka and 124 ka; in contrast to our reconstructed

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temperature that increases earlier, at 127 ka. This slight discrepancy is probably due to differences in the chronology established independently for the two cores. An explanation for the delay of TIC values takes into account the time needed for the dissolution of calcite from the surrounding rocks and/or dissolution of endogenic calcite after deposition (see Francke et al., 2016). At long time scales, calcite precipitation occurs during periods of high precipitation such as interglacials and interstadials when supply of calcium and carbonate ions from calcite dissolution into the lake increases, and/or elevated temperature and high evaporation occur. Biogenic calcite formation is hampered during dry and cold periods (glacial and stadials) due to decreased precipitation and associated nutrient supply, and to reduced terrestrial calcite dissolution and inflow of dissolved carbonate from the karst system (Lézine et al., 2010). Soon aAfter the “climate optimum thermal maximum” (128-121 ka), from 120 ka and culminating at 119.4 ka, TIC values decrease together with mean annual temperature, by contrast, in the same time precipitation rises. The low TIC content can be explained by lower water temperature, which hampers calcite precipitation. Slight pProgressive drying occurs from 121 ka until the end of Eemian at 112 ka. This trend is more or less followed by TIC and the pollen inferred climate trends at Lake Ohrid, corroborating the climate reconstruction based on core JO2004 (Bordon, 2008). This trend also and confirms the assumption that the Last Interglacial was not a uniform wet and warm phase in western Europe (e.g. Cheddadi et al., 1998; Guiot et al., 1993; Klotz et al., 2004; Köhl and Litt, 2003; Rousseau et al., 2006; Sánchez-Goñi et al., 2005) and that successive cool/dry events occur at ca. 110 and 105 ka.

### 5.3 Comparison with European climate reconstructions inferred from pollen records

Lake Ohrid’s chronology is well established for MIS 5 due to the high number of tephra layers (Francke et al., 2016; Leicher et al., 2016), in particular, for the transition between the Riss glaciation and the Eemian, for which a further correlation with geo-chemical and pollen data from Lake Ohrid and other proxies from Mediterranean sequences was carried out by Zanchetta et al. (2016). For other European pollen records such chronological constraints are not available and, thus, the chronologies are probably less precise. Keeping in mind the existing chronological uncertainties, a comparison of precipitation and temperature anomalies is carried out, with the values inferred from three other long pollen records (Fig. 5) spanning the interval between 140 and 70 ka: Les Echets, Le Bouchet and La Grande Pile (Fig. 1). Lake Ohrid, despite being considered as “a southern site”, shows past climate trends similar to the French records (Fig. 5). This similarity is probably due to its high elevation, causing enhanced precipitation in relative to the rest of southern Europe and making it similar to regions directly subjected to the North-Atlantic circulation. In order to discuss Lake Ohrid’s climate record more in depth on a European scale, a further comparison is shown in Figure 6. Here, Lake Ohrid climate anomalies are plotted with the ones estimated by Brewer et al. (2008) for southern and central-northern European sites, using a pollen-inferred multi-method approach which take into account the various sources of errors in paleoclimate reconstructions. The investigated interval is in this case limited to the period 135-105 ka, which includes the whole Eemian (ca. MIS 5e-d according to Sánchez-Goñi et al., 2007). During the final part of MIS 6 (Fig. 3, 6), climate seems to have been particularly harsh at Lake Ohrid, with highly reduced precipitation both compared to other European sites (Brewer et al., 2008) or to present. However, the precipitation anomaly values are comparable to those of the French sites (Fig. 5). For the latter, we have to consider that the same methods have been applied, which could have resulted in the more consistent values. There are opposite trends, difficult to interpret, in the anomalies at the end of MIS

6 in the considered records. La Grande Pile, Les Echets and Le Bouchet reconstructions show a “~~climate optimum~~thermal maximum”, the so-called climate optimum, from 127 to 118 ka followed by an abrupt cooling around 117 ka (fig. 6 and Brewer et al., 2008). The signal reconstructed for northern Europe is different from the French sites, Brewer et al. (2008) had identified a climate tri-partition during the Eemian, already evidenced by Tzedakis 2007 (and references therein): early optimum, followed by slight cooling, followed by a sharp drop in temperatures and precipitation. This set of changes appears restricted to the north, with a very different set of changes in south. In southern Europe, the Eemian climate appears to have remained warm with stable conditions over a long period between 126-105 ka (Fig. 6). Lake Ohrid is located in a central position on the Balkans Peninsula, at the confluence of central European and Mediterranean climate. The Lake Ohrid climate reconstruction also shows a “~~climate optimum~~” in the early part of the Eemian and then a progressive cooling without a sharp drop in temperatures and precipitation (Fig. 6); this suggests an intermediate climate signal, more similar to the French sites (Fig. 5) than to the northern or southern European ones (Fig. 6). Brewer et al. (2008) show that climate changes during this period were heterogeneous, with greater winter warming in the center and north-east of Europe than in the west and north-west. Other studies of the spatial distribution of temperature changes during this period have shown similar trends in temperature, with the largest positive anomalies in central and northern Europe, and negative anomalies in south-eastern Europe (Kaspar et al., 2005; Turney and Jones, 2010; Otto-Bliesner et al., 2013). Furthermore, one remaining question is whether the climate of this period was very close to modern values or warmer and wetter than the present-day as suggested by existing studies (Guiot et al., 1989). The time series of anomalies presented here (Fig. 5) suggest a positive anomaly of 1 to 2°C for the Ohrid Basin, strongly depending on the method used (~~Fig. 5~~). Melisey I is the first cooling event, with a significant reduction in temperatures and precipitation, although less pronounced than at the French sites (Fig. 5). At Lake Ohrid, a surprising positive anomaly in the middle of Melisey I is suggested and is potentially due to the persistence of trees during stadials, highlighting the important role of the Ohrid Basin as a refugium for arboreal taxa. According to several studies carried out in central and northern Europe (Guiot et al., 1993; Klotz et al., 2004; Rioual et al., 2001), the Melisey I event is characterized by an abrupt decline in temperatures first, followed by increasing continental conditions, with a subsequent decline in winter temperatures and an increase in summer temperatures. Other pollen records from Lake Ohrid also strongly suggest that climatic conditions remained favorable to grow mesophilous taxa (Bordon, 2008; Holtvoeth et al., 2017; Lézine et al., 2010). St. Germain Ia (Figs. 3 and 5) is drier than St. Germain Ic at Lake Ohrid, with the latter showing annual precipitation up to ca. 400 mm/yr higher than during the former. The values are consistent with the data obtained by Klotz et al. (2004) for central Europe, more specifically, in the northern Alpine foreland. The same trend is also recorded in the French sites presented here (Fig. 5). Melisey II appears as the most extreme stadial of the LIC, coinciding with the maximum extension of ice sheets during the Early Weichselian. However, the cooling reconstructed at Ohrid is probably overestimated with the MAT for the same reasons as during MIS 6. If we consider the WAPLS reconstruction, the anomalies estimated at Ohrid during Melisey II are 2 °C higher than for the French sites (Figs 3 and 5). During St. Germain II, temperature and precipitation values for Lake Ohrid are similar to those of St. Germain Ia (Figs 3 and 5). This pattern is corroborated by other studies for the North Atlantic, using marine  $\delta^{18}\text{O}$  data (Keigwin et al., 1994), for North Europe (e.g., Guiot et al., 1989) and for the Iberian Margin (Sánchez-Goñi et al., 2000). At the end of the interstadial, a trend towards low temperatures and an increase in precipitation is recorded at Lake

Ohrid, in agreement with the climate reconstruction of Guiot et al. (1989) for the French pollen records (Fig. 5). The most striking feature of Lake Ohrid, recorded at the top of the studied sequence, is the presence of two interstadials following St. Germain II, namely Ognon I and Ognon II. These interstadials are anyway visible, even if less marked in other eastern Mediterranean records (Tenaghi Philippon: Müller et al., 2011; Lake Van: Pickarski et al., 2015) and could be correlated with the Dansgaard-Oeschger events DO 19 and 20 (Dansgaard et al., 1993).

#### 5.4 Comparison with other European and North Atlantic proxy records

In order to discuss the Ohrid climate signal at a wider scale, Figure 7 shows the correlation of the reconstructed climate parameters with marine and continental proxies from Mediterranean and North Atlantic regions (Fig. 1).

In speleothem and lake sediment records,  $\delta^{18}\text{O}$  is mostly seen as an indicator of the “amount of precipitation”, lower/higher values are related to increasing/decreasing humidity (Bard et al., 2002; Drysdale et al., 2005, 2009; Regattieri et al., 2014; Zanchetta et al., 2007, 2016). The Ohrid precipitation trend shows similarities with the oxygen isotope records reported in Figure 7, suggesting a generally good agreement with the variations in Mediterranean rainfall detected in Italy in speleothems from Antro del Corchia and Tana che Urla (Drysdale et al., 2005; Regattieri et al., 2014) and in the lake record of Sulmona (Regattieri et al., 2017). According to Drysdale et al. (2009), there is a pause-break in the decrease of  $\delta^{18}\text{O}$  in continental and marine values prior to the beginning of the Eemian at ca. 129 ka, which can be related to Heinrich event 11 (H11, Shackleton et al., 2003). During this event, the North Atlantic thermohaline circulation and the North Atlantic deep-water formation shut down with a consequent phase of cooler and drier conditions for mid-latitude Western Europe (Genty et al., 2003). At Lake Ohrid (Fig. 7), H11 is clearly detected, for the first time in a climate reconstruction, and in the TIC records of the DEEP core and Col202 core (Figs 4, 7).

~~The climatic changes evidenced at Lake Ohrid during the Eemian (at ca. 126 ka, 122 ka, 119 ka and 114 ka, Fig. 7) are particularly consistent with speleothems and  $\delta^{18}\text{O}$  Sulmona records (see Fig. 7). Important changes during the LI have also been detected, besides at Lake Ohrid, also in the alkenone-based sea surface temperature (SST) reconstruction of the ODP-976 and ODP-977 sediment core (Alboran Basin, Martrat et al., 2004), in  $\delta^{18}\text{O}$  records of the Iberian Margin (MD95-2042 and MD95-2040, Sánchez Goñi et al., 1999, 2005; De Abreu et al., 2003) and from Greenland (Fig. 7), in line with other studies on speleothems and on Mediterranean and North Atlantic marine records (e.g. De Abreu et al., 2003; Demény et al., 2017; Drysdale et al., 2009; Lisiecki and Raymo, 2005; Martrat et al., 2007, 2014; McManus, et al., 1994; Mokeddem et al., 2014; NGRIP Members, 2004; Oppo et al., 2006; Sánchez Goñi et al., 1999, 2005; Wang et al., 2010). Based on the ODP-976 and ODP-977 alkenone data (Martrat et al., 2004, 2014), warm SSTs occurred during interstadial periods, while cold SSTs persisted during stadials Melisey I and II. SST changes are associated to large shifts in mean annual air temperature and moisture content as reflected in vegetation changes inferred from pollen analysis in European and Mediterranean records (Martrat et al., 2004; Tzedakis et al., 2003). The event centered at ca. 115 ka is of particular interest (Fig. 7). According to Müller and Kukla (2004), this SST drop in the Nordic Seas marked a southward displacement of the North Atlantic Current. This event was associated with a substantial cooling in North Europe and drier conditions in Mediterranean regions, marking the end of the Eemian in northern and central Europe (Müller and Kukla, 2004; Tzedakis et al., 2003), while in the south it~~

correlated with a reduction in mesophilous trees. This event is also recorded at Lake Ohrid (Fig. 7) with a simultaneous drop in temperature and precipitation values, and is associated to the GIS26 stadial of the Greenland ice core record (NGRIP, 2004) and to the C25 cold event in the North Atlantic (McManus et al., 1994; Mokeddem et al., 2014). This connection between Lake Ohrid and the North Atlantic (Fig. 7), ~~is also~~ ~~is also~~ highlighted by the evidence of the Melisey I stadial, which corresponds to North Atlantic event C24 (and to GS25), the Montaigu event, corresponding to C23 (and GS24), and the Melisey II stadial, which corresponds to C21 (and GS22). Besides this event, the final part of MIS 5 at the transition ~~with to~~ MIS 4 at Lake Ohrid is characterized by a series of abrupt climate changes (Ognon I and II phases), composed of two interstadials and two stadials. The latter correspond to the North Atlantic cold events C20 (GS21) and C19 (GS20), respectively (Fig. 7). A similar pattern can be depicted in the SST record of ODP\_977 (Fig. 7), with two abrupt warming events, preceded by a strong cooling after a long period of stability (Martrat et al., 2014).

## 6. Conclusions

We provide a quantitative reconstruction of climate parameters based on the pollen record from Lake Ohrid (DEEP site), using two complementary approaches for the period between 160 and 70 ka. This period covers the last part of the ~~Riss-penultimate~~ ~~g~~Glaciation, equivalent to MIS 6 (160-128 ka), and the Last Interglacial Complex (LIC, 128 to 70 ka), equivalent to MIS 5, as well as the first part of MIS 4.

Our results for the LIC show an alternation of warm and wet periods (128-112 ka, 108-~~89.890.2~~ ka, 85.7-78.8 ka, 77.6-~~75.475~~ ka, 73.4-70 ka) with cold and dry ones (112-108 ka, 105.2-104 ka, ~~89.890.2~~-85.7 ka, 78.8-77.6 ka and ~~75.475~~-73.4 ka) attributable to the well-known succession of climatic events occurring during MIS 6 and 5.

With regard to the last interglacial, our results provide evidence that the Eemian was not as stable ~~as previously thought~~, confirming existing studies. The climate reconstruction led to distinguish three periods: a climatic optimum (128-121 ka), followed by progressive cooling in conjunction with an increase in precipitation (121-118 ka), and, finally, a period characterized by a decrease in both temperatures and precipitation (118-112 ka).

The early last glacial (from 112 to 70 ka) is characterized by a succession of cold and warm periods (stadials and interstadials) in which cold ones show an increase in seasonality and dry conditions. This climatic trend can be correlated to the succession of Greenland stadials and of North Atlantic cold events (Dansgaard et al., 1993; GRIP Members, 1993), illustrating the teleconnections between the North Atlantic realm and the Mediterranean region. The same succession of cold and dry events at Lake Ohrid is also coherent with hydrological and isotopic data from the central Mediterranean.

At a wider scale, our results showed a great similarity between Lake Ohrid and climate reconstructions of French and central European records rather than the stacked curve of four southern European records. Lake Ohrid shows intermediate features between these two areas; our curves are in line with those of other southern European climate proxies (e.g. central Italian speleothems). Future climate reconstructions and independent proxies are needed for the southern Mediterranean to resolve the complex regional expressions of past climate changes.

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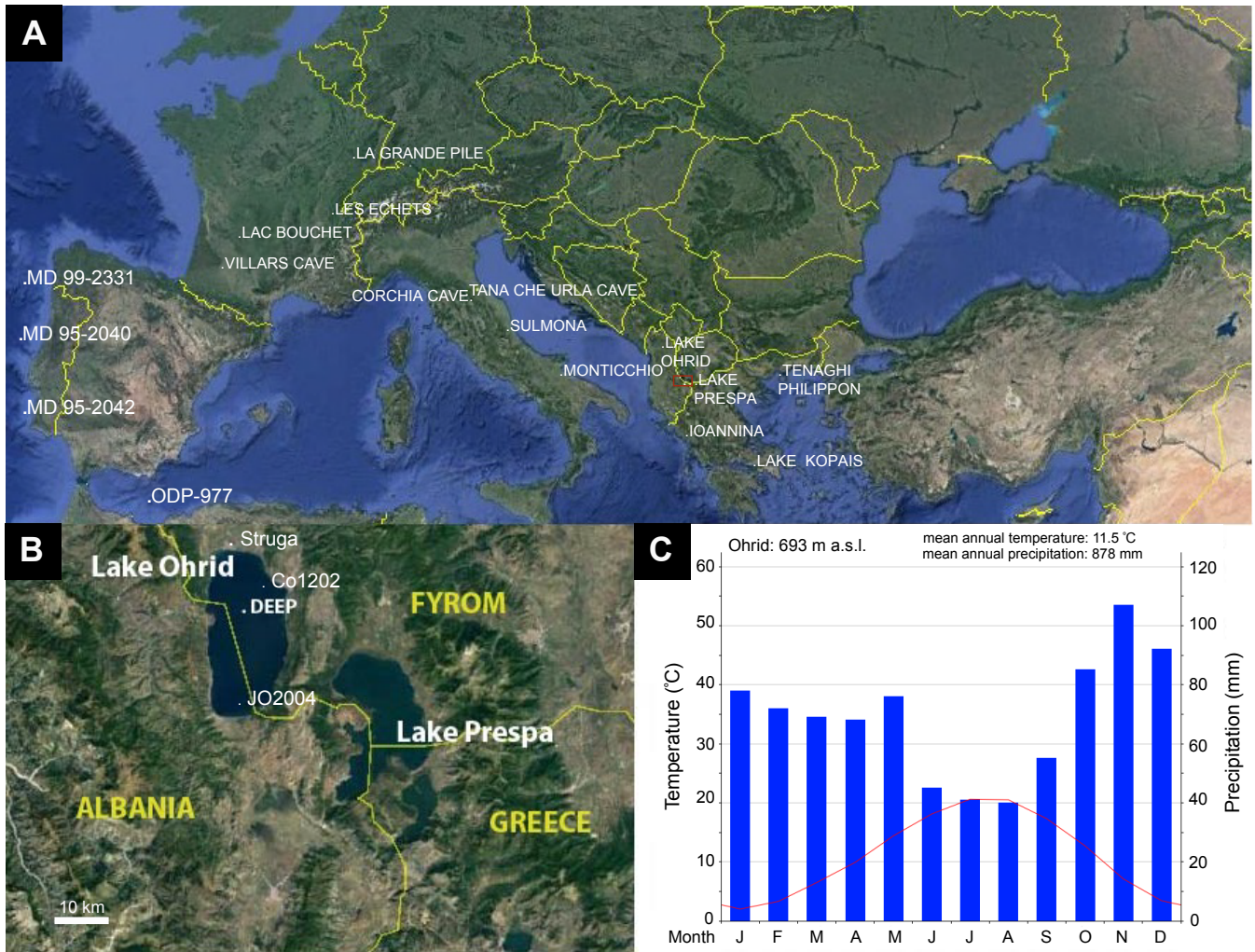
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**Table**

<u>MARINE STRATIGRAPHY</u>		<u>COMMON NAME</u>	<u>LA GRANDE PILE</u>	<u>LAKE OHRID LIMIT (years ka)</u>
<u>MIS 4</u>			<u>Ognon II</u>	<u>73.4-69.9</u>
			<u>Stadial II</u>	<u>75-73.4</u>
<u>MIS 5</u>	<u>5a</u>	<u>Early Last Glacial</u>	<u>Ognon I</u>	<u>77.6-75</u>
			<u>Stadial I</u>	<u>78.8-77.6</u>
			<u>St. Germain II</u>	<u>85.7-78.8</u>
	<u>5b</u>		<u>Melisey II</u>	<u>90.2-85.7</u>
	<u>5c</u>		<u>St. Germain Ic</u>	<u>104-90.2</u>
			<u>St. Germain Ib (Montaigu event)</u>	<u>105.2-104</u>
		<u>St. Germain Ia</u>	<u>108-105.2</u>	
	<u>5d</u>		<u>Melisey I</u>	<u>112-108</u>
	<u>5e</u>	<u>Last Interglacial</u>	<u>Eemian</u>	<u>128-112</u>
<u>MIS 6</u>		<u>Riss Glaciation</u>		<u>160-128</u>

**Table 1** Correlation of nomenclature defined by Woillard (1978) for La Grande Pile (NE France) with common terrestrial nomenclature and the Marine Isotope Stages (MIS, Lisiecki and Raymo, 2005). This is just a scheme and a precise correspondence between MIS5 substages and the terrestrial phases defined by Woillard (1978) is not yet precisely established.

Figure



5 Fig. 1 A) Location map of the Mediterranean record cited in this paper. B) Location map of Lake Ohrid and its surroundings (US Dept. of State Geographer © 2017 Google Image Landstat/ Copernicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO) C). Ombrothermic diagram of Struga meteorological station (<http://en.climate-data.org/location/29778/>).



## Lake Ohrid - DEEP core

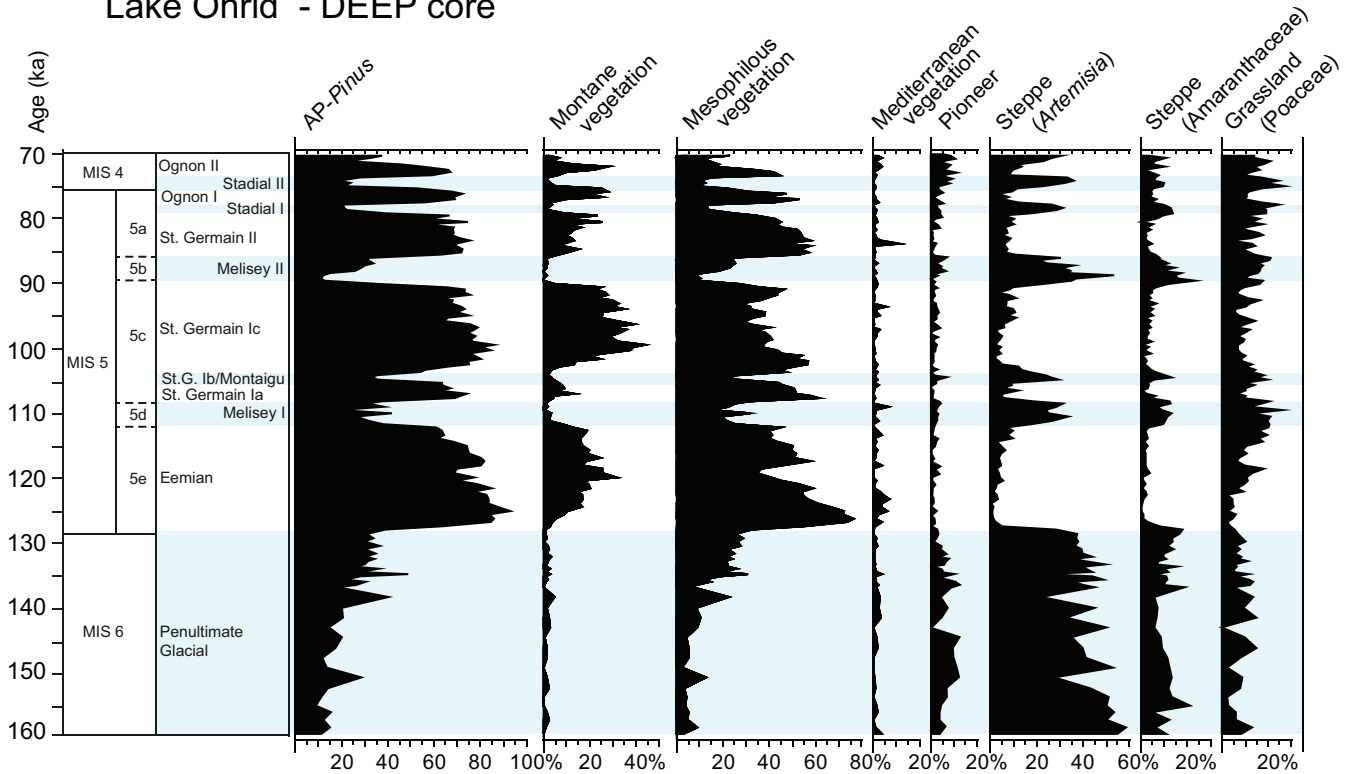
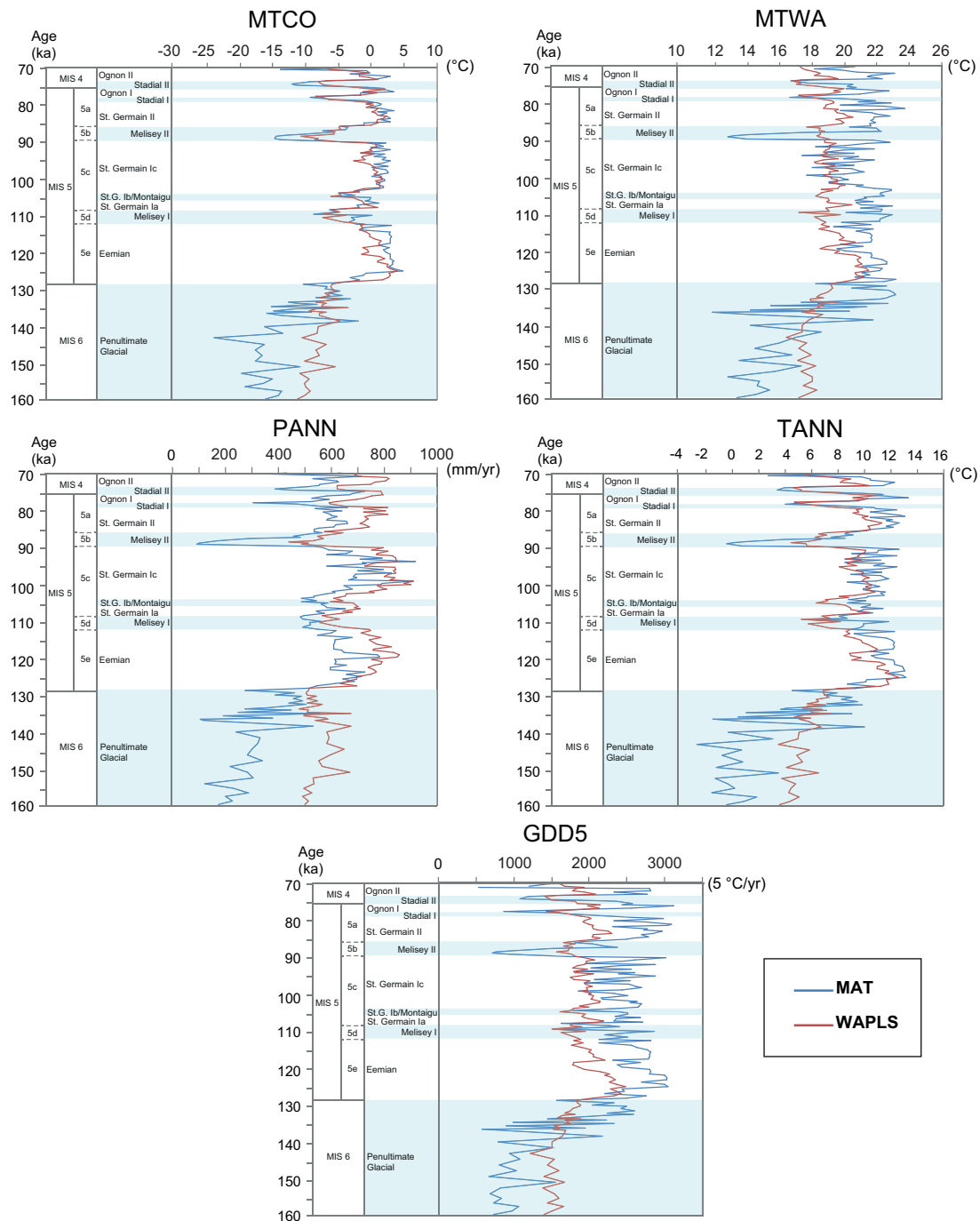


Fig. 2 Lake Ohrid (FYROM/ Albania) - DEEP core - Pollen percentage diagram of selected taxa and ecological groups, against age (ka). Montane **vegetation+rees**: *Abies*, *Betula*, *Fagus*, *Ilex*, *Picea*; mesophilous **vegetation+rees**: *Acer*, *Buxus*, *Carpinus betulus*, *Castanea*, *Celtis*, *Corylus*, *Fraxinus excelsior/oxycarpa*, *Ostrya/Carpinus orientalis*, *Hedera*, *Quercus robur* type, *Quercus cerris* type, *Tilia*, *Ulmus*, *Zelkova*; mediterranean **vegetation+rees**: *Cistus*, *Fraxinus ornus*, *Olea*, *Phillyrea*, *Pistacia*, *Quercus ilex* type, *Rhamnus*; steppe: *Artemisia*, *Amaranthaceae*, *Chicoriodeae* and *Asteroideae* and grassland: *Poaceae* and *Cyperaceae*. Data from Sadori et al. (2016) and Sinopoli et al. (2018).



5 Fig. 3 Climate reconstruction inferred from Lake Ohrid pollen data (Sadori et al., 2016; Sinopoli et al., 2018). Climate parameters obtained with the MAT method (black-blue line) and the WAPLS method (red line): MTCO (mean temperature of the coldest month), MTWA (mean temperature of the warmest month), PANN (mean annual precipitation), TANN (mean annual temperature) and GDD5 (growing degrees days over 5° C). Climate parameter values are plotted against age (ka); they are not expressed in anomalies (past climate value minus the modern measured value). Blue shading indicates cold periods (~~Riss~~ penultimate glacial and ~~Early-early Würm~~ last glacial stadials). ~~Blue shading indicates cold periods (Riss glacial and Early Würmian glacial stadials).~~

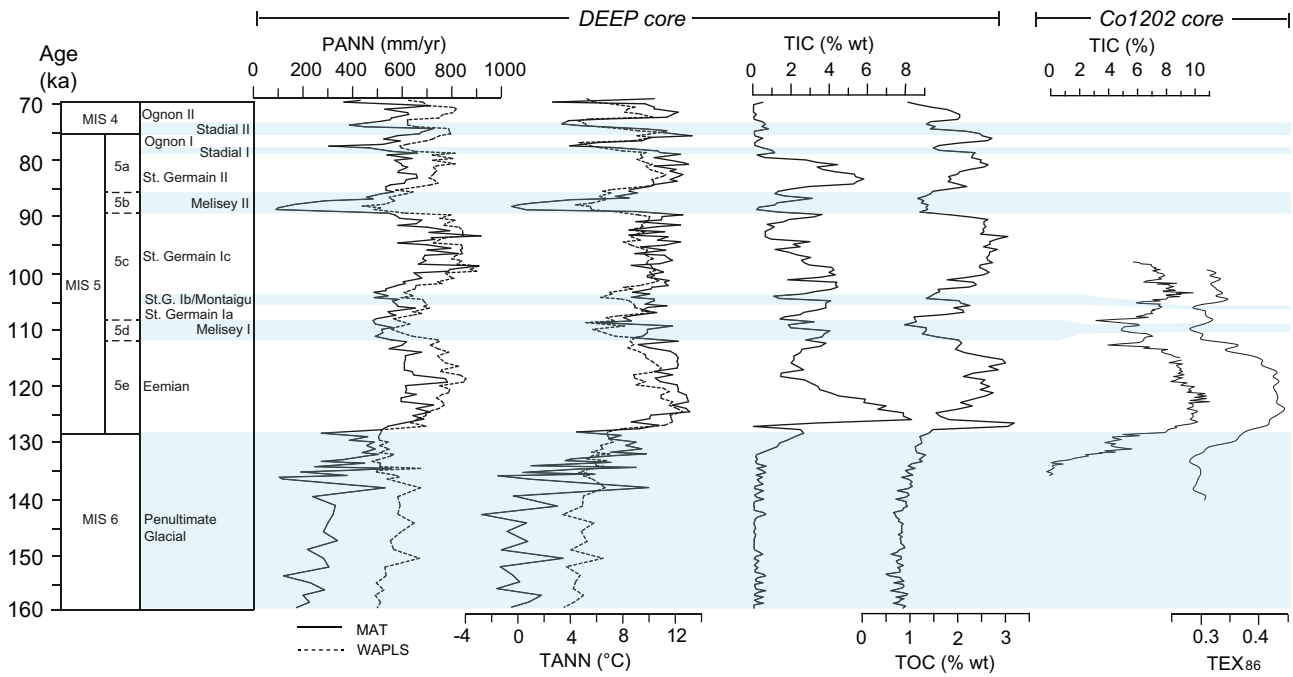
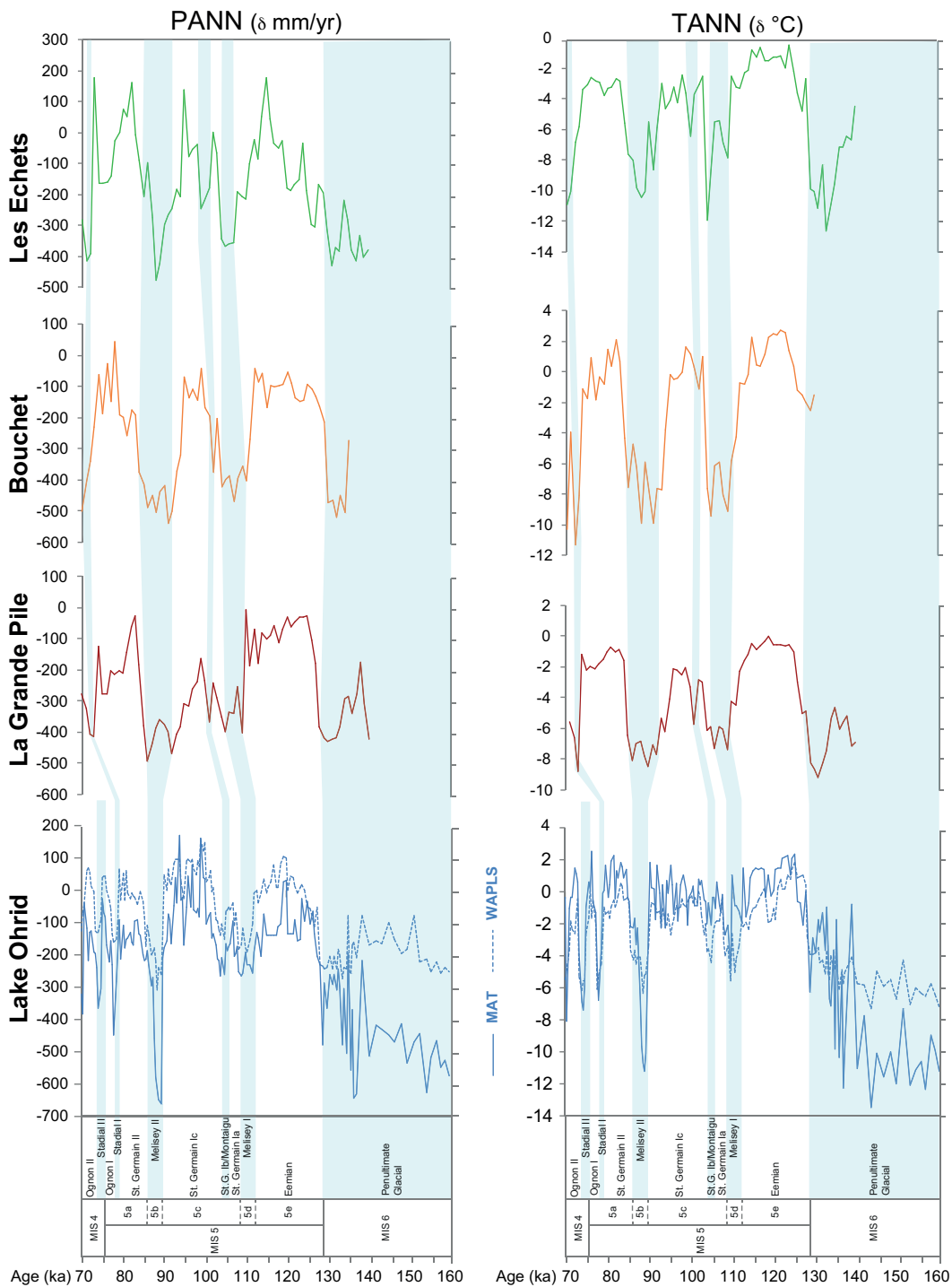


Fig. 4 Lake Ohrid: Comparison between DEEP core annual temperature (TANN), precipitations (PANN) and TIC (Francke et al., 2016) with TIC and TEX<sub>86</sub> (Co1202 core, Holtvoeth et al., 2017). Blue shading indicates cold periods (~~Riss~~ penultimate glacial and early ~~Würm~~ last glacial stadials).

5



**Fig. 5 Comparison between Lake Ohrid climate parameters with available climate reconstructions: Les Echets (265 m a.s.l.), Le Bouchet (1200 m a.s.l.), and La Grande Pile (330 m a.s.l.) from Guiot et al. (1989, 1990, 1993). TANN (mean annual temperature) and PANN (mean annual precipitation) are plotted against age (ka). Values represent anomalies (past climate value minus the modern measured value). Blue shading indicates cold periods (Riss-penultimate glacial and early last glacial stadials).**

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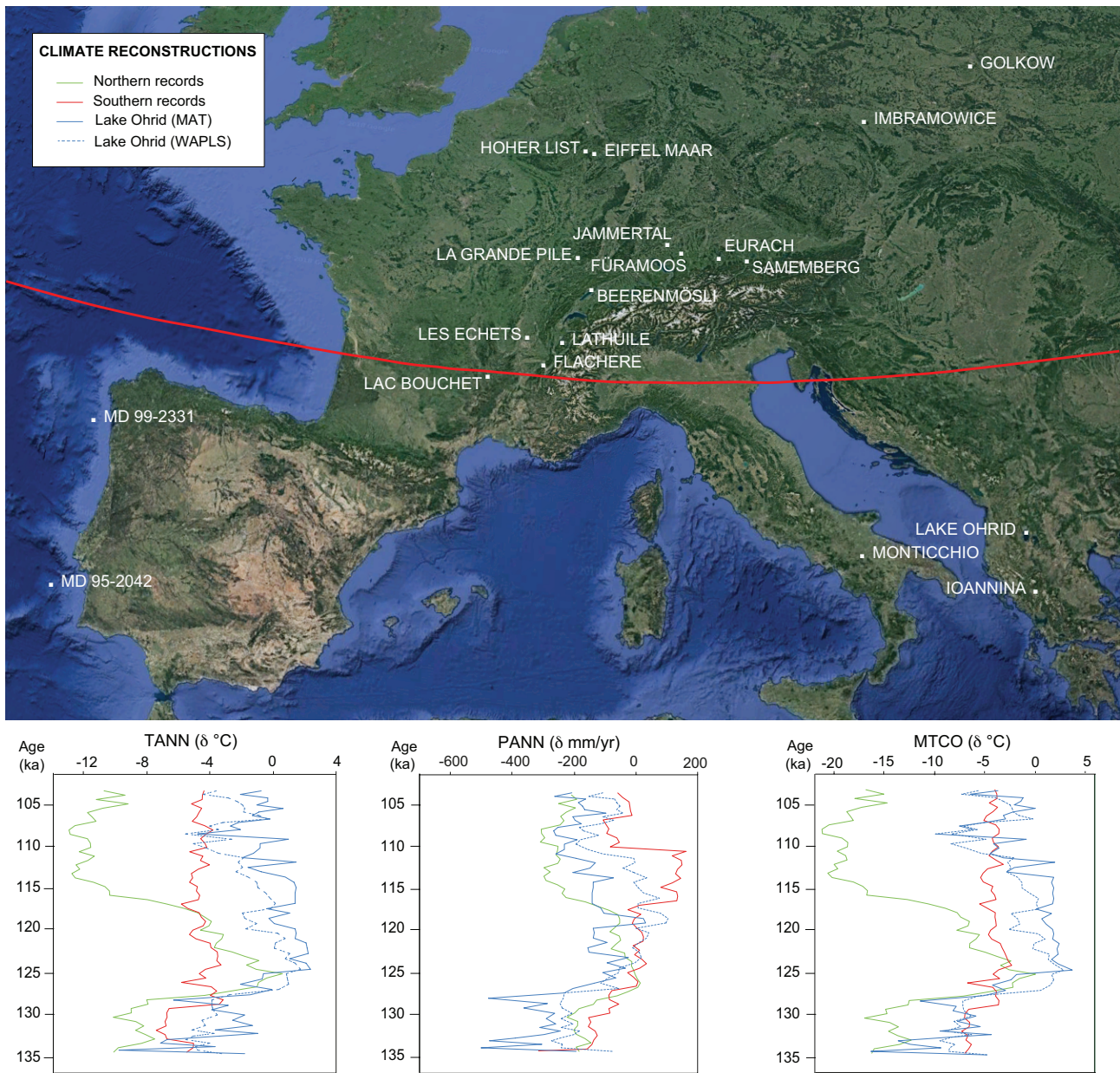


Fig. 6 Comparison between the Lake Ohrid climate reconstruction and the climate reconstruction performed by Brewer et al., (2008) for North and South Europe; TANN (mean annual temperature), PREC (mean annual precipitation) and MTCO (mean temperature of the coldest month) are plotted against chronology (ka). Values represent anomalies (past climate value minus the modern measured value).

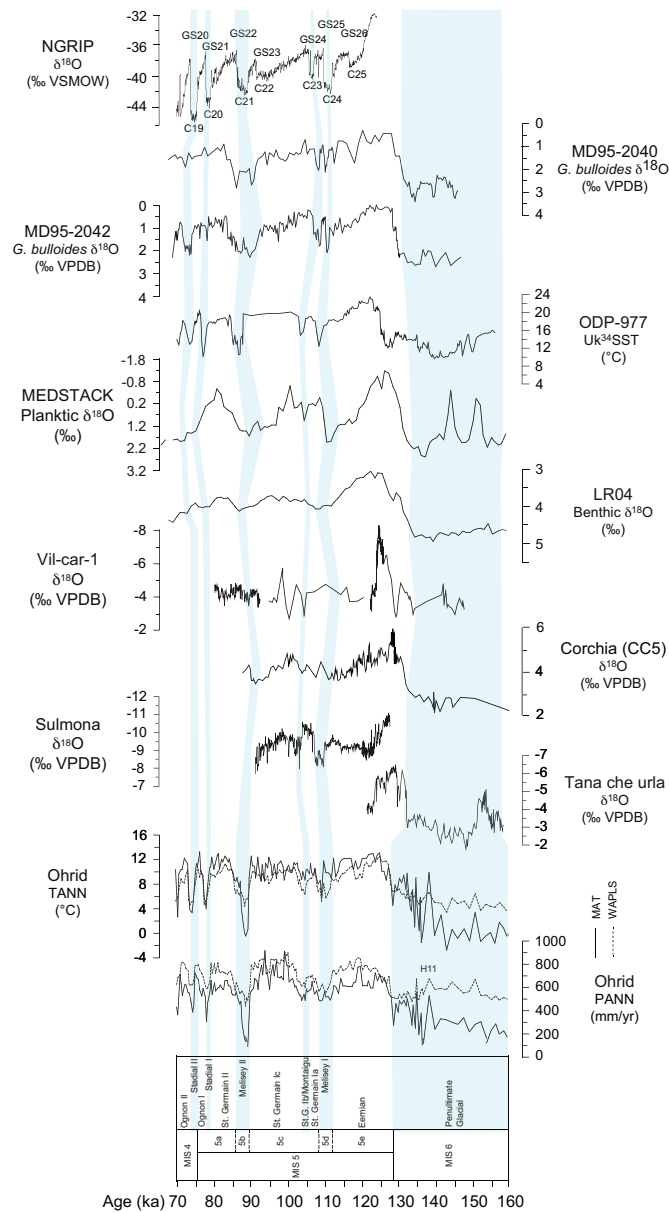
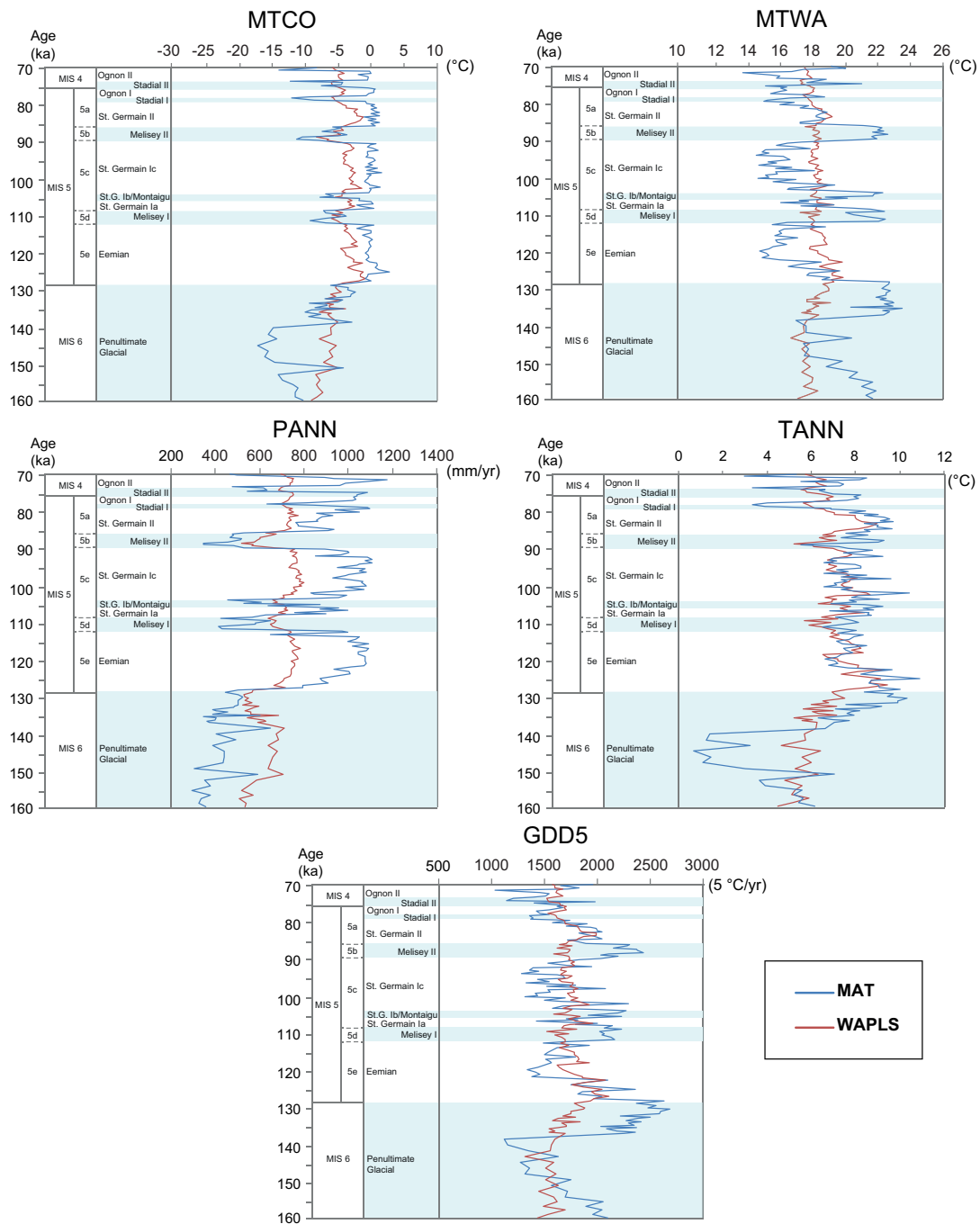
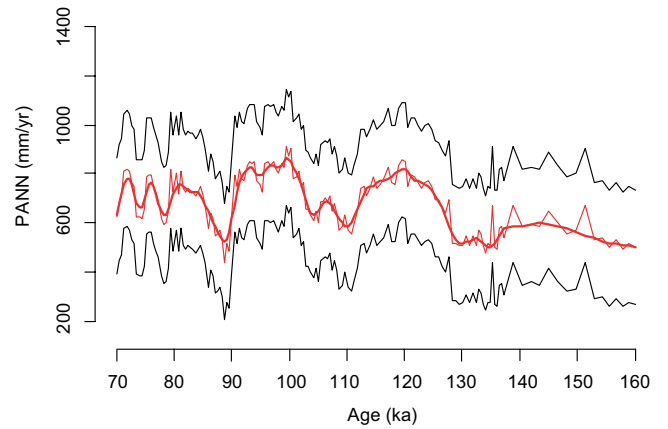
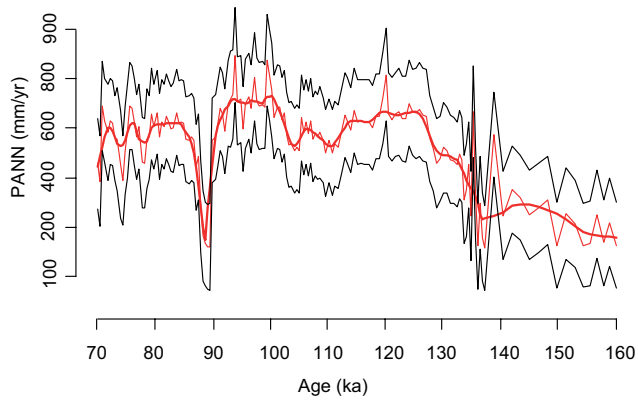
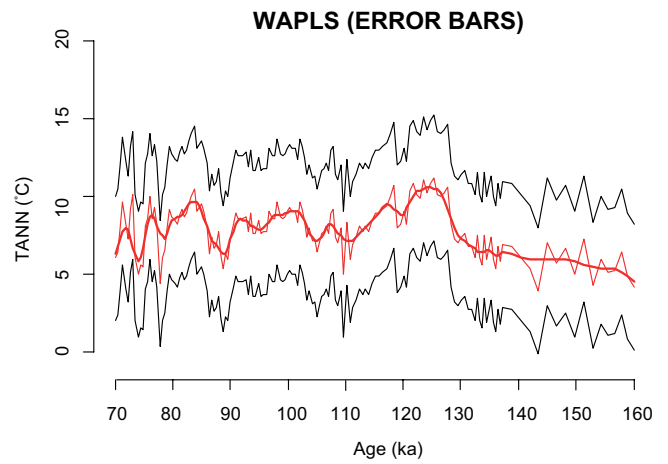
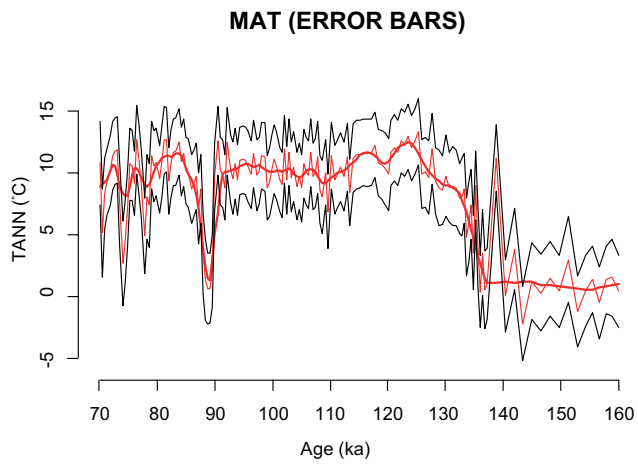


Fig. 7 Comparison of TANN, PANN values from Lake Ohrid with other hydrological and climate proxies from the Mediterranean and the North Atlantic:  $\delta^{18}\text{O}$  speleothem record from Tana che Urla Cave and  $\delta^{18}\text{O}$  of endogenic calcite from Sulmona Lake (Regattieri et al., 2017 and 2014 respectively);  $\delta^{18}\text{O}$  speleothem record from Corchia cave (CC5, Drysdale et al., 2005);  $\delta^{18}\text{O}$  benthic from LR04 stack (Lisiecki and Raymo, 2005); planktic  $\delta^{18}\text{O}$  from MEDSTACK data (Wang et al., 2010); Sea Surface Temperature (SST) from core ODP-977 (Western Mediterranean, Martrat et al., 2004); planktic  $\delta^{18}\text{O}$  from Iberian Margin (MD95-2042, Sánchez Goñi et al., 1999; Sánchez Goñi et al., 2005); planktic  $\delta^{18}\text{O}$  from Iberian Margin (MD95-2040, De Abreu et al., 2003); Greenland  $\delta^{18}\text{O}$  record (NGRIP Members, 2004). Numbers denote Greenland Stadials (GS), corresponding to North Atlantic cold events (C events, after McManus et al., 1994). Blue shading indicates cold periods (Riss-penultimate glacial and early last glacial stadials).



**Fig. A Climate reconstruction inferred from Lake Ohrid pollen data, Pinus included. Climate parameters obtained with the MAT method (blue line) and the WAPLS method (red line): MTCO (mean temperature of the coldest month), MTWA (mean temperature of the warmest month), PANN (mean annual precipitation), TANN (mean annual temperature) and GDD5 (growing degrees days over 5° C). Climate parameter values are plotted against age (ka); this figure can be compared with Fig. 2 (climate reconstruction, Pinus excluded)**



**Fig. BA** MAT and WAPLS error bars for PANN and TANN climate parameters. The last graph represents the squared-chord distance between the first and the last analogue for a chosen climate parameter (TANN) calculated by MAT method.



# SQUARE-CHORD DISTANCE

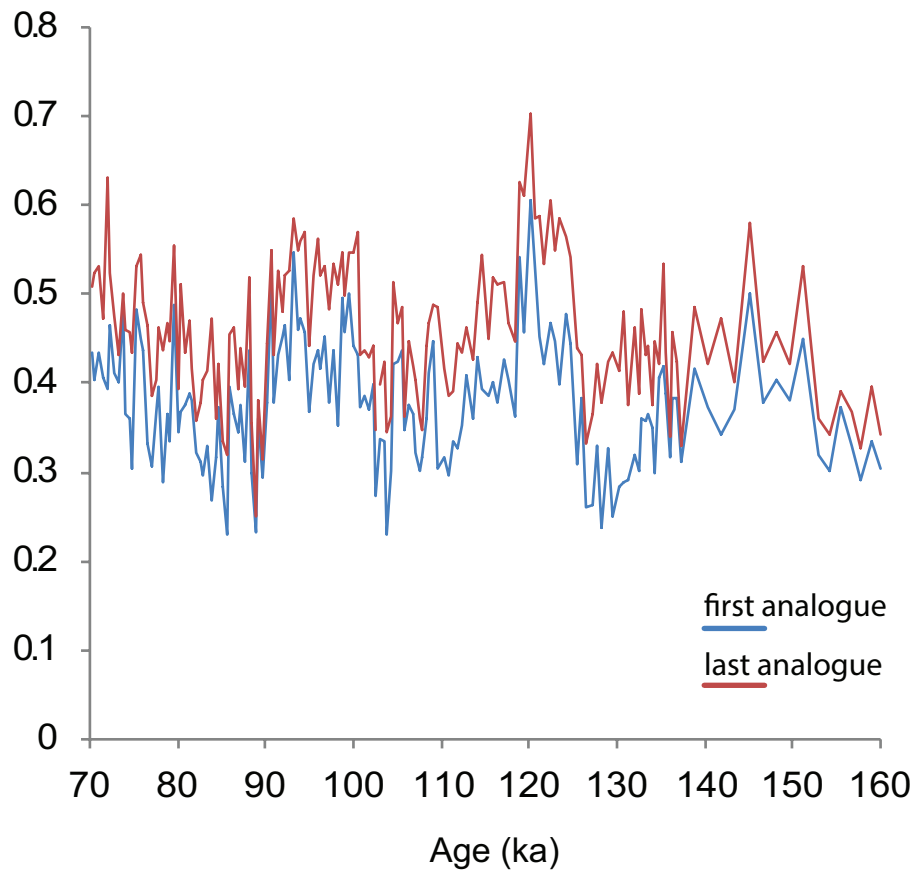


Fig. CB Squared-chord distance between the first and the last analogue for a chosen climate parameter (TANN) calculated by MAT method.

## REPLY TO EDITOR

Dear authors,

Thank you for your revised document. I have studied the corrections and see that a lot of the request of reviewers have been  
5 addressed in this version. Before accepting your manuscript, I request a few little amendments:

1 - You present the curve of ODP Site 977 for comparison with your data. Please take care of the typing of the name of this site in the text and in the figures. It is not correctly written everywhere. For example see Fig. 1 (in the draw) and Fig.7 (it is here corrected in the caption but not in the draw).

10 Authors: THANK YOU, WE CORRECTED THEM

in addition in the Figure 7, I think that it is not the right citation for the ODP 977 curve. In Martrat et al., 2014, the curve presented did not cover the whole interval showing here but only from 150kyr to 108 kyr. The paper from the same authors published in 2004 and 2008 are more appropriate here. Please, have a look on the best paper for the citation.

15 THE EDITOR IS RIGHT, WE CHANGE THE CITATION IN THE CAPTION AND IN THE TEXT

2- In table 1, is it possible to add some ages on the left to have some "tie-points" for the different events. Please do that.

WE ADDED THE LAKE OHRID LIMITS

20 3- I agree with the reviewer concerning the groups cited in the Fig. 2. Hedera is not a tree, same for Cistus. Even if it corresponds to groups published in another publication, I suggest to change that. One way may be to replace "trees" by "forest" or "vegetation" or "formation".

WE FOLLOWED THE EDITOR REQUEST

25 4- Please add for GDD5 (..... 5°C/yr) in fig.3

DONE

These changes do not take a lot of time to do. So I am waiting after your corrected manuscript to be able to conclude the review process quickly.

30 With my best regards

Nathalie Combourieu-Nebout

THANK YOU FOR IMPROVEMENTS AND CORRECTIONS

35

## REPLY TO REFEREE 1

5 After a debate among authors, we decide to reply more in detail to the referees clarify- ing how we intend to improve the manuscript. We would ask the editor and the referees to consider this version.

This is a very interesting paper worthy to be published and here are my suggestions for some improvements following the continuity of the text. Referee: P1, Line 25 (and p.14 lines 13-17). For me, the discussion on the stability of the Eemien rests on a misdefinition. Since Jessen, everybody know that an interglacial cycle includes a pe-  
10 riod of warming after the previous glacial, an optimum and finally a progressive cooling

leading to the next glacial. In this way the instability you mention is a truism! You could just mention that “The Eemian in the Balkans was characterized by an abrupt early warming during its anathermic phase followed a central phase . . .). Most of the authors, when dealing with “instability” or “stability” try to identify some short terms climate “oscillations” disturbing the classical interglacial trend on a warming followed by a cooling (as well discussed latter in your paper).

15

Authors: THE REFEREE IS RIGHT SAYING THAT THE “INSTABILITY” OF THE EEMIAN IS A WELL ASSESSED SUBJECT. WE CORRECTED IT.

P2, 1.30-35. Before Field et al. (1994), at least Beaulieu & Reille (1984,1889) already mentioned a period of transitional  
20 warming during the late Eemian.

## WE CONSIDERED THIS

P3, 1.2 and fig. 6: be careful with the coordinates. Les Echets: 45°52'36"N, 4°55'44"E and Lac du Bouchet: 44°54'31"N ,  
25 3°47'30" Lac du Bouchet is really transitional be- tween North and South according to your classification. As a matter of fact, this limit at 45°N is of interest as far as the Eemian is concerned, but during the Early Würm the story is more complex with the opposition between the “Odderade style” vegetation and climate successions and the “Grande Pile style” successions. It could be mentioned.

30 THANK YOU, WE CONSIDERED THIS

P3, 1.27. : I should prefer “higher resolution”, as an interval of 400 is not high resolution in terms of vegetation dynamics. Would you accept a pollen diagram covering the whole Holocene in only 28 spectra?

WE AGREE, IT'S "HIGHER RESOLUTION"

P4, the first sentence is not necessary as the following description is sufficient.

5 OK

P4, l.11: do not repeat "karst aquifers".

OK

10

P5, top: my copy is polluted by three lines in pseudo-latin.

WE DELETED THE ODD PHRASE

15 P5, l.34: could you develop and explain in more details your choice of 6 modern analogues?

TEXT WAS CHANGED

P6, l. 20: I suggest "pollen records " instead of "data" P6, l.35: again one line polluted with latin.

20

WE CHANGED INTO LOW-RESOLUTION DATA, THE POLLEN RECORD IS THE SAME

P9, l.5 and after: this interesting discussion could be included in the chapter "Materials and methods"?

25 WE DON'T AGREE: THIS SECTION TRY TO EXPLAIN THE DIFFERENCES IN THE RESULTS DUE TO THE DIFFERENT METHODS USED; SO IT'S REALLY BETTER TO KEEP IT IN THE DISCUSSION PART

P9, l.22: may-be a clumsy statement. If your climate reconstructions are derived from pollen spectra, it would be a great disaster for your results if they were not in agreement

30

WE DELETED POLLEN

P10, l. 24-29: Very interesting but I do not understand how the discussion is inferred from fig. 4: TIC and TOC do not change (slight increase in TOC) during the interval between 137 and 135 Ka marked by high amplitude changes in PAN and TAN??

35

WE ARE USING DATA FROM OTHER CORES AND OTHER PAPERS. GENERALLY, LAKE-LEVEL CHANGE RESPONDS TO PRECIPITATION CHANGE RATHER THAN TEMPERATURE AND MAY THEREFORE HAVE AFFECTED THE DISTRIBUTION OF LOWLYING TERRESTRIAL HABITATS ON FLAT TERRACE SURFACES BEFORE THE TEMPERATURE THRESHOLD WAS CROSSED THAT LED TO INCREASING IN LAKE TIC  
5 PRECIPITATION. TOC FROM COMBINED AQUATIC AND TERRESTRIAL SOURCES IS A MINOR FRACTION OF THE TOTAL SEDIMENT AND, AS SUCH, IS SUSCEPTIBLE TO DILUTION BY LITHOGENIC MATERIAL. THUS, IF PRECIPITATION INCREASED THE SUPPLY OF BOTH TERRESTRIAL OC AND LITHOGENIC (SILICICLASTIC) MATERIAL WOULD HAVE INCREASED. DEPENDING ON THE MAIN OC SOURCES THIS CAN LEAD TO BOTH AN INCREASE OR DECREASE IN TOC WITH INCREASING EROSION RATES, OR TOC MAY IN FACT REMAIN  
10 TEMPORARILY CONSTANT IF ITS MAIN SOURCE IS, E.G., SOIL OC (INCREASE OF OC AND SILICICLASTIC MATERIAL AT SAME RATE). THUS, WE DON'T NECESSARILY EXPECT TO SEE A COVARIATION OF PANN AND TANN WITH TIC AND TOC AT THIS TRANSITIONAL STAGE. WE WILL TRY TO MAKE IT MORE CLEAR

P10, l 34 : Not that slight??

15

SEE COMMENTS OF REFEREE 2, QUITE THE OPPOSITE

Chapter 5.4. : it would be of interest to take into account the climate reconstructions based on diatoms populations established by Rioual et al. (2007) at Ribains (see also Shemesh et al., 2001)

20

THANKS FOR THE SUGGESTION. HOWEVER IT'S NOT POSSIBLE TO ADD IT IN THE FIGURES (E.G. FIG. 5) BECAUSE IN THE RIOUAL ET AL (2007) PAPER, THE TEMPERATURE RECONSTRUCTION BASED ON THE DIATOMS IS NOT DIRECTLY COMPARABLE TO THE OHRID ONES. RIOUAL ET AL (2007) PLOTTED PDCA SAMPLE SCORES POLLEN DIATOMS AS A PROXY OF TEMPERATURE, NOT TEMPER- ATURE VALUES. IN THE  
25 PAPER OF RIOUAL ET AL (2001), THE CLIMATE RECONSTRUCTION BASED ON RIBAINS POLLEN DATA CANNOT BE ADDED HERE IN OUR FIGURE AS ITS PLOTTED AS FUNCTION OF DEPTH, NOT OF AGE. BUT, OF COURSE, THESE TWO PAPERS ARE CITED AND USED IT IN OUR INTERPRETATION

References Beaulieu J.-L. de & Reille M., 1984. A long upper Pleistocene pollen record from Les Echets near Lyon, France,  
30 Boreas, 13, p.111-132. Beaulieu J.-L. de & Reille M., 1989. The transition from temperate phases to stadials in the long Upper Pleistocene sequence from les Echets (France). Palaeogeography, Palaeoclimatology, Palaeoecology, 72, 147-159. Rioual P., Andrieu-Ponel V., Beaulieu J.-L. de, Reille M., Svobodova H. & Battarbee R. W., 2007. Diatom responses to limnological and climatic changes at Ribains maar (French Massif Central) during the Eemian and Early Würm. Quaternary Science Reviews, 26 (11-12), 1557-1609. Shemesh A., Rietti-Shati M., Rioual P., Battarbee R., Beaulieu J.-L. de, Reille M. and

Svobodova H., 2001. An Oxygen isotope record of lacustrine opal from a European Maar indicates climatic stability during the last interglacial. *Geophysical Research Letters*, 28 (12), 2305-2308.

5

## REPLY TO REFEREE 2

After a debate among authors, we decide to reply more in detail to the referees clarifying how we intend to improve the manuscript. We would ask the editor and the referees to consider this version.

Thank you for the opportunity to comment on this manuscript. The manuscript titled 'Pollen-based temperature and precipitation changes in the Ohrid Basin (western Balkans) between 160 and 70 ka' covers a sound data set of great value to the palaeoecological community as climate reconstruction for the last interglacial-glacial cycle from this sensitive area are scarce. Overall, I think the work is good and should be published in CP but there are a number of important details that need to be considered and corrected first. In many instances these are related to terminology, definition of terms and ambiguity or circularity in the phrasing. One important example of this is the use of different nomenclatures, e.g., from alpine region (Riss/Würm glacial), from northern/central Europe (Eemian interglacial), and the special nomenclature from France for interstadials/stadials. Regarding the last interglacial, be careful with the statement that the Eemian was not a stable phase in the Balkan region. The last interglacial at LO clearly shows a classical interglacial with an early warming at the beginning of MIS 5e, a climate optimum and a progressive cooling towards the end of the last interglacial. In general, I suggest to interpret the LO record with regard to further regional climate reconstructions (mentioned in the chapter 'Introduction', e.g., LGdM and Ioannina) and use it as a basis for discussing in more global scale with possible correlations to the France, speleothem records, MIS, etc. These important issues and more are detailed below along with some suggestions for grammatical corrections. Page, Line. Comment

Referee: P1, 17. The presented archive covers the period between 160 to 70ka. This includes not only MIS 6 and MIS 5, but also the early part of MIS 4. The authors mentioned it in the conclusion by themselves. (P14, 8).

25

Authors: OK

P1, 25-28. According to the anonymous referee #1. The last interglacial at Lake Ohrid shows a classical interglacial cycle with pre-temperate phase (early warming), temperate phase (climate optimum), and a post-temperate phase (progressive cooling), which is also well described by Tzedakis, 2007. Be careful with this general conclusion of an unstable last interglacial in the Balkan region!

WE ADJUSTED THE TEXT

P2, 3. Insert ‘...’MIS’ – 6 (penultimate glacial) and MIS 5 (last interglacial complex) are. . .’

OK

5 P2, 6. ‘. . .the penultimate glacial (or Riss Glaciation) . . .’ in comparison to P2, 12. ‘The Eemian. . .’ Please pay more attention to a uniform nomenclature. The term ‘Riss glaciation’ is normally used in the alpine area. In northern and central Europe, the penultimate glacial belongs to the ‘Late Saale/Saalian Complex’. If you want to continue with the term ‘Eemian’ for the last interglacial (MIS 5e), you should use the nomenclature of the northern and central Europe. Another example is the ‘(Early) Weichselian glacial’ instead of ‘Early Würm’ (P2, 34).

10

OK

P2, 7. Please pay more attention to uniformity. The LIC lasts from ca. 130-80 ka in the chapter ‘Introduction’, whereas the LIC covers the period from ca. 128-70 ka at page 3, 25. Please check the dates, there are several more discrepancies.

15

OK, WE MADE IT CLEARER. THE MIS 6 TO MIS 5 TRANSITION AT LAKE OHRID HAS BEEN THE SUBJECT OF AN ACCURATE ALIGNMENT AND SYNCHRONIZATION (ZANCHETTA ET AL., 2016) RESULTING IN AN OFFSET OF 2 KA WITH OTHER RECORDS (E.G. GOVIN ET AL., 2015; RAILSBACK ET AL., 2015).

20 P3, 2-4. The authors mentioned that Ioannina and LGdM have done climate reconstructions based on pollen data. Unfortunately, these two archives were not used for comparison (e.g. in Figure 5) or were not discussed in detail in the text (chapter 5.3), although these records are much closer to Lake Ohrid than the archives in France. Due to the fact that you mentioned in P3, line 15 that the Balkan Peninsula is a key region between the Mediterranean area and the Northern/Central Europe. It would be nice to see how these few southern European records differ from the northern European ones. What about  
25 the direct comparison with Lake Prespa, which covers the last 100 ka. I am not sure if they have done climate reconstructions, but are there any similarities or differences to your record?

THE IOANNINA AND MONTICCHIO CLIMATE RECONSTRUCTIONS HAVE BEEN DONE BY BREWER ET AL. (2008); WE HAVE NOT USED THEM FOR COMPARISON IN FIGURE 5 BECAUSE THIS STUDY ONLY FOCUSES  
30 ON THE EEMIAN PART, BUT WE HAVE USED THESE SITES IN FIGURE 6 (EEMIAN PART) FOR COMPARISON WITH OHRID (SOUTH EUROPE CLIMATE CURVE IS BASED ON IOANNINA, MONTICCHIO AND 2 MARINES CORES); SO, YES WE HAVE USED IOANNINA AND MONTICCHIO SYNTHETIC CLIMATE RECONSTRUCTIONS TO COMPARE OUR DATA WITH A MORE GENERAL SOUTH EUROPEAN CURVE (FIG 6). THERE IS NOT A QUANTITATIVE CLIMATE RECONSTRUCTION FOR LAKE PRESPA, AND THE CHRONOLOGY FOR BOTTOM  
35 CORE IS NOT WELL CONSTRAINED.

P3, 14. . . .glacial-interglacial cycle. (?)

OK

5

P4, 1-2. The first sentence is not necessary.

OK

10 P4, 11. Avoid the repetition of 'karst aquifers' at the end of line 11.

OK

P4, 12-13. Rephrase: ' . . .small streams, rivers, and by direct precipitation.'

15

OK

P4, 18. Rephrase: '...during winter and south-southeasterly (or southerly to south- easterly) winds during. . . .'

20 OK

P4, 21. This context is not clear – please rephrase. What are the four zones? Which species dominate which zone?

WE CORRECTED IT

25

P5, 1-3. Please check. This sentence is written in a different language.

WE DELETED IT

30 P5, 15. What is 'new' in the high-resolution pollen data, presented in this manuscript, when it is already published in Sinopoli et al., 2018? Did you analyse more 'new' samples for this manuscript, which are not shown in the Sinopoli et al. paper? Please clarify!

WE MADE IT CLEARER.

35 P5, 34. Which 'six modern analogues'? This subject should be further explained and clarified in the text.



SEE THE ANSWER TO REVIEW 1, WE CHANGED THE TEXT ACCORDINGLY.

P6, 18. It is not clear to me what do you mean with the ‘. . .first analogue and the last analogue. . .’? More details are needed.

5

THE FIRST ANALOGUE CORRESPONDS TO THE CLOSEST ANALOGUE, BASED ON THE CHORD DISTANCE CALCULATION; THE LAST ONE IS THE ANALOGUE WITH THE CHORD DISTANCE. WE WILL CORRECT IN THE TEXT AND IN FIGURE

10 P6, 35-36. Please check. This sentence is written in a different language.

WE DELETED IT

P7, 1. ‘. . .and annual precipitation between 350 and 600 mm/yr),. . .’ It depends on what method you looking at. For MAT, I  
15 can recognize a fluctuation from 100 to ca. 300 mm/yr in the mean annual precipitation. For WALPS, it fluctuates between 500 to 700 mm/yr. What is the explanation for this huge difference? Please clarify and add some more explanations.

THESE DIFFERENCES ARE DISCUSSED IN THE DISCUSSION PART: DURING THE FIRST PART OF MIS 6 (CA.  
160-143 KA), EVEN IF THE PRECIPITATION CURVES PRODUCED BY BOTH METHODS SHOW THE SAME  
20 TREND, RECONSTRUCTED VALUES BY MAT ARE ROUGHLY 300 MM LOWER THAN THOSE RESULTING FROM WAPLS. MODERN ANALOGUES METHODS ARE VERY SENSITIVE TO MINOR VARIATIONS IN THE POLLEN ASSEMBLAGES, ESPECIALLY DURING GLACIAL PERIODS (BREWER ET AL., 2008). SIMILAR DISCREPANCIES ASSOCIATED WITH MAT ALSO OCCUR IN THE RECONSTRUCTION OF LA GRANDE PILE AFTER THE EEMIAN THERMAL OPTIMUM BY BREWER ET AL (2008). AMBIGUOUS OUTCOMES MAY OCCUR  
25 PARTICULARLY FOR PAST GLACIAL AND COLD INTERVALS (STADIALS). THE MAJOR PROBLEM APPEARS TO BE THE LACK OF MODERN ANALOGUES OR ONLY LIMITED SIMILARITY WITH PAST GLACIAL VEGETATION (GUIOT ET AL., 1993; PEYRON ET AL., 1998). INDEED, AS REPORTED IN SEVERAL STUDIES (GUIOT, 1987; GUIOT ET AL., 1993; KLOTZ ET AL., 2003), GLACIAL STEPPE VEGETATION DOMINATED BY HIGH PERCENTAGES OF AMARANTHACEAE (AS AT LAKE OHRID, FIG. 2) HAS NO PRESENT-DAY ANALOGUE  
30 IN EUROPE. FOR THIS REASON, WE HAVE USED MODERN SAMPLES FROM COLD STEPPE, PRINCIPALLY FROM THE TIBETAN PLATEAU AND FROM RUSSIA AS “POTENTIAL” ANALOGUES FOR GLACIAL PERIODS (PEYRON ET AL., 1998, 2005) AND THESE SAMPLES ARE CHARACTERIZED BY LOW PRECIPITATIONS VALUES.

35 P7, 11 and 14. Which ‘other methods’? If necessary, add references.

WE ARE NOT SURE WE SHOULD LIST ALL OF THEM, AS WE REFER TO THE ORIGINAL PUBLICATIONS (BREWER ET AL, 2008 AND KUHL ET AL 2010 FOR MULTI-METHOD APPROACHES); WE ADDED THE PDF METHOD IN THE TEXT.

5

P7, 34-36. Which is the third part? Furthermore, an additional verb is missing. Please rephrase this sentence.

MELISEY II AS SHOWN IN TABLE 1, YES “ARE” IS MISSING. WE ADJUSTED IT

10 P8, 17 and following. Describe the ‘end of MIS 6’ within chapter 4.1

YES, HERE IS JUST USED AS A COMPARISON

P9, 8 -16. This section should be mentioned in the chapter ‘Materials & methods’.

15

WE DON’T AGREE: THIS SECTION TRIES TO EXPLAIN THE DIFFERENCES IN THE RESULTS, DUE TO THE DIFFERENT METHODS; SO IT’S BETTER TO KEEP IT IN THE DISCUSSION PART.

20 P9, 19-20. To be consistent with the text, could you add the discussed pioneer shrubs (e.g. Juniperus) to the selected pollen diagram (Figure 2).

OK

25 P9, 28 and following. For the better understanding and demonstration, it would be very helpful to show the comparison of your Eemian climate reconstructions with those from the JO2004 record. Please insert the JO2004 climate reconstruction, for example, in Figure 4.

30 THE CLIMATE RECONSTRUCTION BASED ON THE JO2004 RECORD DONE WITH A MULTI-METHOD APPROACH (PEYRON ET AL., PERS. COMM.) IS NOT YET PUBLISHED; SO IT’S NOT POSSIBLE TO INCLUDE IT FOR COMPARISON IN FIG .4.

P10, 12. The phrase ‘. . .export of terrestrial organic matter. . .’ sounds a bit odd. Please rephrase.

OK

35

P10, 18 and 19. Delete ‘. . .inferred from pollen.’ due to the repetition from the previous sentence. At this point, it is obvious that TANN and PANN were calculated from pollen.

OK

5

P10, 18-29. There seem to be some logical steps missing. I cannot work out how lake level changes can be visible in the pollen record. I also cannot see a decline in terrestrial vegetation at the end of MIS 6 - in fact, quite the opposite. It shows a continuous increase in mesophilous and coniferous trees! In addition, I assume that significant lake level changes should be reflected in the TIC /TOC values, but again I cannot see any changes in these proxies at the DEEP site. Furthermore, the ‘clearly seen’  
10 change in the pollen record of Co2012 is not presented in this manuscript! These subjects should be explained more clearly in the text.

THE REFEREE IS RIGHT, LAKE LEVEL CHANGES ARE NOT VISIBLE IN THE POLLEN RECORD! WE USED OTHER EVIDENCES FROM PUBLISHED ARTICLES: “THE DISTINCT HIGH-AMPLITUDE FLUCTUATIONS  
15 INFERRED FROM POLLEN DURING THE FINAL PART OF MIS 6, COULD AT LEAST PARTLY BE DUE TO LAKE LEVEL CHANGES AS THE WATER TABLE DURING THIS PERIOD WAS GENER- ALLY ON THE RISE (LINDHORST ET AL., 2010, HOLTVOETH ET AL., 2017; WAG- NER ET AL., 2017)”. THIS IS IN VERY GOOD AGREEMENT WITH “A CONTINUOUS INCREASE IN MESOPHILOUS AND CONIFEROUS TREES” AS EVIDENCED BY REFEREE 2. ANYWAY, IT APPEARS THAT WE HAVE NOT BEEN CLEAR ENOUGH, WE WILL  
20 TRY TO BE MORE EFFECTIVE.

P10, 31-34. In my opinion, a difference of 500 years is NOT a discrepancy. The authors should soften the language.

WE THOUGHT THAT USING “SLIGHT” COULD HAVE BEEN ENOUGH, AND IT IS NOT FOR REFEREE 2. . . BUT  
25 REFEREE 1 SAYS IS NOT THAT SLIGHT. . . SO THE OPPOSITE “THIS SLIGHT DISCREPANCY” (NAMELY 500 YEARS) “IS PROBABLY DUE TO DIFFERENCES IN THE CHRONOLOGY ESTABLISHED FOR THE TWO CORES”. WE WILL EMPHASIZE THAT THE TWO CHRONOLOGIES HAVE BEEN ASSESSED INDEPENDENTLY.

P10, 39-41. Please avoid the use of so many ‘and’ in this sentence. Please rephrase.

30

OK

P10, 42 and following. There is something odd about the line of reasoning here. It is not clear to me what do the authors mean with ‘from 120 ka and culminating at 119.4 ka’? In Fig. 4, I cannot identify a ‘culmination’ in the TIC decrease during this  
35 interval. At the DEEP site, the TIC and TOC values already continuously decrease after ca. 126 ka! In addition, how can a

progressive drying (P11, 3) take place when precipitation increases at the same time (P11, 1)? By the way, I cannot see an increase in precipitation after 120 ka! Please clarify.

OK, WE CLARIFIED THIS PART IN THE TEXT

5

Chapter 5.3. It would be nice to see a direct comparison of climate parameters between Lake Ohrid, LGdM, Ioannina, and the records in France (e.g., in Figure 5). Unfortunately, the southern European records are only summarized in Figure 6. I think it would be helpful for your argumentation. Be careful with simplification of complex interactions! When I am looking at the comparison between LO, Northern Europe, and Southern Europe (Figure 6), I can recognize several different responses to global climate changes in all records. In my opinion, the authors should make it unequivocally clear the transitional position from Mediterranean climate influenced climate to more temperate northern European climate conditions with, e.g., a distinct temperature decrease after 125 ka, which is not that pronounced at LO (more comparable to the southern European records).

WE AGREE WITH YOU. THE IOANNINA AND MONTICCHIO CLIMATE RECONSTRUCTIONS HAVE BEEN DONE BY BREWER ET AL. (2008); FOR IOANNINA NO SINGLE CURVE FOR CLIMATE RECONSTRUCTION IS AVAILABLE, THE CLIMATE RECONSTRUCTIONS HAVE BEEN USED TO BE INCLUDED AS SUMMARY CURVE FOR SOUTHERN EUROPEAN SITES. MOREOVER, WE CANNOT USE THEM FOR COMPARISON IN THE FIGURE 5 BECAUSE THIS STUDY ONLY FOCUSES ON THE EEMIAN PART. THEREFORE, WE HAVE USED THESE SITES IN THE FIGURE 6 (EEMIAN PART) FOR COMPARISON WITH OHRID (SOUTH EUROPE CLIMATE CURVE IS BASED ON IOANNINA, MONTICCHIO AND 2 MARINES CORES); SO, YES WE HAVE USED IOANNINA AND MONTICCHIO CLIMATE RECONSTRUCTIONS TO COMPARE OUR DATA WITH THE MORE GENERAL SOUTH EUROPEAN CURVES (FIG 6).

P11, 26. The period from 135-105 ka comprises the late MIS 6 to MIS 5c, as you already mentioned it in the next sentence!

25

YES, THE REFEREE IS RIGHT. WE USED IN FACT THE VERB “INCLUDES”, MEANING THAT IS NOT ONLY THE WHOLE EEMIAN: “THE PERIOD 135-105 KA, WHICH INCLUDES THE WHOLE EEMIAN”

P11, 29. In the direct comparison between LO and Grande Pile & Bouchet, there are opposite trends in the anomalies at the end of MIS 6. Between ca. 140-133 ka: high anomalies at LO, low at GP; between ca. 133-128 ka: low anomalies at LO, high at GP. Please clarify.

OK, DUE TO THE PROBLEMS ALREADY LISTED IN HAVING PRESENT-DAY ANALOGUES FOR AMARANTHACEAE STEPPE, IT’S NOT APPROPRIATE TO GO IN THESE DETAILS

35

P12, 11. Delete the repetition of 'Fig.5'.

OK

- 5 P12, 18. As I already wrote above, add the 'other pollen records from Lake Ohrid' to the figures. It would be helpful for the following of your argumentation.

THE REFEREE IS RIGHT, BUT A COMPARISON OF THE DIFFERENT POLLEN RECORDS (NOT ALL AVAILABLE TO US) FROM LAKE OHRID IS NOT THE TOPIC OF THIS PAPER AND JUSTIFY A SEPARATE PUBLICATION

10

P12, 24-35. What is the 'striking feature' of these interstadials, just the occurrence? Add some more explanations. I think these two short-term interstadial can be correlated with the Dansgaard-Oeschger events DO 19 and 20, which are also visible in the eastern Mediterranean records, such as Thenaghi Philippon (Müller et al., 2011) and Lake Van (Pickarski et al., 2015), even though the climate was significantly more continental during this time.

15

YES, THEY CAN BE PROBABLY CORRELATED WITH THE DANSGAARD- OESCHGER EVENTS DO 19 AND 20.

P13, 17 & 23. The ODP-976 record is not presented in the manuscript!

- 20 YES, THE REFEREE IS RIGHT, IT'S A MISTAKE, WE CORRECTED IT

P13, 16-24. There are some important differences visible between LO and other records (e.g., at ODP-977, Villars cave) especially at the early Eemian, which are not discussed in the text. Be careful with generalization! Please add more details and discussed that differences a bit more.

25

YES, THERE ARE DIFFERENCES, WE ARE AWARE OF, DIFFICULT TO EXPLAIN. IT ANYWAY GOES BEYOND THE SCOPE OF THIS PAPER TO EXPLAIN ALL DIFFERENCES WITH OTHER RECORDS IN DETAIL.

- 30 P13, 25 -34. There are some logical steps missing. Which event centered at ca. 115? Melisey I? C25? I am a bit lost in this section! In addition, C25 event is not visible in the SST record! Please clarify!

OK, WE WILL CLARIFY THIS PART.

P14, 5. A period is missing at the end of the sentence.

35

OK, WE CLARIFIED THIS PART.

P14, 8. Insert ‘...Last Interglacial Complex (LIC, 128 to 70 ka),...’ due to the used abbreviation in the next sentence.

5 OK. JUST IN CASE SOME READERS ARE JUST READING THE CONCLUSIONS.

P14, 12. ‘. . .occurring during the late MIS 6, MIS 5 and the early MIS 4.’ A Table 1 Please use a uniform nomenclature. It would be nice if you could mark the different MIS 5 stages (MIS 5e to a) in the ‘Marine Stratigraphy’ column.

10 WE DID IT

Figures Figure 1 Where is the ‘Struga meteorological station’ located? Can you mark it on the map? Please pay more attention to the consistence of facts between the text and the figures. For example, you mentioned in P4, 7 that Lake Ohrid is located at 693 m asl. In your figure 1, it is written 694 m asl. The same discrepancy is evident in the mean annual temperature at Lake

15 Ohrid (P4, line 15).

OK, THANK YOU

Figure 2 Perhaps it is better to use the terms ‘Mesophilous taxa/biome’ and ‘Mediterranean taxa/biome’ instead of ‘trees’, because Hedera is not a tree, it is a liane, and Cistus (depending on the species) grows also as shrub. The figure caption is a bit confusing. If you are showing, e.g., only Poaceae within the group of grasslands than delete the additional information that grasslands consist of Poaceae and Cyperaceae. The same goes for ‘Steppe’. Please, show in the first column (left) the MIS 6 to 4 and in the second column the nomenclature of the northern and central Europe. That goes also for the other figures.

25 WE USED THE SAME CATEGORIES AND NAMES USED IN SINOPOLI ET AL. 2018 AND SADORI ET AL. 2016 FOR UNIFORMITY.

Figure 3 MAT method is shown in a blue line, not in black! Regarding GDD5: The legend of the figure is not clear to me. Are these 1000-3000 years over 5âU°eÇ per year/season/? Are these 1000-3000âU°eÇ. Please, clarify! Delete the repetition of

30

### REPLY TO REFEREE 3

After a debate among authors, we decide to reply more in detail to the referees clarifying how we intend to improve the manuscript. We would ask the editor and the referees to consider this version.

- 5 The quantitative palaeoclimate reconstructions during the Quaternary is an important to understand the climate changes and its potential forcing mechanisms, thus can helpful for predicting climate changes in future global warming. In this study, a quantitative reconstruction of climate parameters was provided based on the pollen data from the Lake Ohrid in southern Europe, using two complementary approaches including
- 10 ‘Modern Analogues Technique’ and ‘Weighted Averaging Partial Least-Squares Regressio’ during the period from 160 to 70 ka. It is useful for better understanding climatic changes during the key periods of MIS 6 and MIS 5 in the South Europe. In current version I would suggest a minor revision before accepting it for publication. Here are a few basic comments that could guide the authors to submit a more detailed manuscript. 1.For the reconstruction, Pinus has been excluded in this study due to its overwhelming presence in the DEEP would potentially masks climatically controlled environmental signals from other
- 15 taxa. Because this change should effect on the quantitative reconstruction, so a more detail comparison on reconstruction of climate parameters between Pinus including and its excluding is best presented in the supplementary information.

OF COURSE, OUR FIRST TEST WAS WITH PINUS. AS SUGGESTED BY THE REVIEWER, WE ADDED, IN THE SUPPLEMENTARY INFORMATION, A FIGURE (FUIGURE A) ON THE CLIMATE RECONSTRUCTION WITH

20 PINUS INCLUDED. WE DON’T DISCUSS IT BECAUSE THE RESULTS ARE CLEARLY LESS GOOD THAN THE FINAL RESULTS OBTAINED EXCLUDING PINUS.

2.In Figure A2, the most values of Squared-chord distance between the first and the last analogue for a chosen climate parameter (TANN) calculated by MAT method are more than 0.3. The values may be larger than the no-analog/analog thresh-

25 old that could accurate and precise palaeoclimate reconstruction. Therefore, a systematically analysis between the Squared-chord distance and precision of palaeoclimate reconstruction need to employ.

WE ARE NOT SURE TO UNDERSTAND WHAT THE REVIEWER MEANS: THE DIFFERENCE BETWEEN THE FIRST AND THE LAST ANALOGUE IS CLOSE TO 0.1, NOT TO 0.3. THE THRESHOLD FOR THE ANALOGUES

30 SELECTION IS DE- FINED BY THE METHOD (SEE GUIOT ET AL. FOR DETAILS), AND HERE NO NO-ANALOGUE SITUATION HAS BEEN DETECTED.

3. Results suggest that the Lake Ohrid palaeoclimate reconstruction shows greater similarity with climate patterns inferred from northern European pollen records than with southern European records in figure 6. Because the Lake Ohrid locates in the southern European, thus a more detail explanation and possible mechanism should be mentioned.

5 WE DID IT, PLEASE LOOK MORE IN DEPTH THE DISCUSSION. FOR EXAMPLE: “THIS SIMILARITY IS PROBABLY DUE TO ITS HIGH ELEVATION, CAUSING ENHANCED PRECIPITATION IN RELATIVE TO THE REST OF SOUTHERN EUROPE AND MAKING IT SIMILAR TO REGIONS DIRECTLY SUBJECTED TO THE NORTH-ATLANTIC CIRCULATION” AND ”THE CONNECTION BETWEEN LAKE OHRID AND THE NORTH ATLANTIC (FIG. 7), IS ALSO HIGHLIGHTED BY THE EVIDENCE OF THE MELISEY I STADIAL, WHICH CORRESPONDS TO  
10 NORTH ATLANTIC EVENT C24 (AND TO GS25), THE MONTAIGU EVENT, CORRESPONDING TO C23 (AND GS24), AND THE MELISEY II STADIAL, WHICH CORRESPONDS TO C21 (AND GS22)”.

4. Please check all the language in the text, and correct it to the English, e.g. page 5 lines 1-3, and page 6 lines 35-36.

15 SURE, THANK YOU

#### **INTERACTIVE COMMENT OF ATTILA DEMÉNY**

WE THANK ATTILA DEMÉNY FOR HIS COMMENT. WE INCLUDE THE SUGGESTED PROXY IN THE  
20 DISCUSSION SECTION.