Rapid Late Pleistocene climate change reconstructed from a lacustrine ostracod record in central Italy (Lake Trasimeno, Umbria)

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This study presents, for the first time, a detailed quantitative reconstruction of winter (January) and summer (July) palaeotemperatures from the Late Pleistocene to Holocene transition in central Italy based on ostracod assemblages in an 8.59 m long sediment core retrieved in Lake Trasimeno. Of 19 ostracod species recovered, 13 were calibrated according to their living temperature ranges, enabling us to reconstruct mean January and July temperature ranges using the Mutual Ostracod Temperature Range (MOTR) method. The occurrences of *Cytheromorpha fuscata* and *Limnocythere suessenbornensis* from 44 000 to 25 500 cal. a BP showed mean January temperatures at least 7 °C colder and mean July temperature at least 1 °C cooler in some intervals compared to present day temperatures. Comparison of the MOTR-derived January minima curve with a Greenland oxygen isotope record (NGRIP) shows a remarkable correlation of warmer Greenland Interstadial and the colder Greenland Stadial events with clear peaks and troughs in the MOTR signal. These correlations were tested successfully by tuning the MOTR curve to the NGRIP record, resulting in an improved age-depth model combining radiocarbon ages with MOTR tie-points. The results demonstrate that a record of rapid climate change in the North Atlantic region is archived in lacustrine ostracod assemblages in central Italy.

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In the light of rapid climate warming at the present day, it has become increasingly important to delineate the impact of the North Hemispheric (NH) forcing on the climate of the Mediterranean Region. Because of its semi-enclosed nature, this area is particularly sensitive to climate change. It is thus fundamental to better assess and quantify the rates and scales of the rapid climate variability induced by NH forcing.

Because of their often excellent preservation in sediments, abundance and sensitivity to environmental changes, non-marine ostracods have long been considered an invaluable proxy to assess Quaternary climate changes (Horne *et al*. 2012). Analyses of their relationship to several climatically influenced variables, such as salinity, temperature, water depth and solute chemistry, enable the reconstruction of climate-driven variations in the hydrochemistry and hydrology of waterbodies (e.g. Smith *et al*. 2003; Horne *et al*. 2012; Viehberg & Mesquita-Joanes 2012; Marchegiano *et al*. 2018, 2019). Many studies have relied on qualitative palaeoenvironmental interpretations, although the ability to carry out quantitative reconstructions has increased, for example with the development of several transfer functions for non-marine ostracods (e.g. Frenzel *et al*. 2010; Marco-Barba 2010; Pint *et al*. 2012; Viehberg & Mesquita-Joanes 2012).

The Mutual Climate Range (MCR) method for reconstructing Quaternary palaeoclimate was established by Atkinson *et al*. (1986, 1987) using Coleoptera, since when the approach has been developed for different groups such as mammals (Lyons 2003; Lopez-Garcia & Cuenca-Bescos 2010), amphibians and squamate reptiles (e.g. Blain *et al*. 2009, 2010), terrestrial molluscs (Moine *et al*. 2002), herpetofauna (Sinka 1993; Holmes *et al*. 2010), plant macrofossils (Sinka & Atkinson 1999), pollen (Pross *et al*. 2000; Pross & Klotz 2002) and ostracods (Horne 2007). The principle of the MCR approach is to determine the climatic range (usually in terms of mean monthly temperatures for winter and summer) within which a fossil assemblage of organisms could have co-existed when they were alive. It is assumed that climatic factors such as mean monthly air temperature have a significant influence on the geographical distribution of species. The calibration of species is achieved by comparing their geographic distribution with a climate dataset, so as to determine their distribution in "climate space". An advantage of the MCR method is that it does not consider the abundance of species but only their presence, so it can be used even in samples that yield only low numbers of specimens.

Palaeoenvironmental reconstructions based on the 8.59 m long Co1320 sediment core, covering the last *c.* 47000 cal. years from Lake Trasimeno have recently been the aim of multidisciplinary investigations by Marchegiano *et al*. (2018, 2019). The marine isotope stages (MIS) 3 and 2 have been subject to rapid, abrupt and significant, climate variations, characterized by relatively warm and humid (interstadials) and cold and dry (stadial) periods. This high-frequency climate variability has been indicated by several different proxies (e.g. ice core stable isotope, speleothems and pollen records) and recognized worldwide (Voelker 2002; Abrantes *et al*. 2012).

Using ostracod assemblages as the main proxy, Marchegiano *et al*. (2018, 2019) detected important changes in the Lake Trasimeno hydrology, pointing out the alternation of humid periods associated with high lake levels and dry periods with shallower/temporary waterbody conditions. In particular, higher lake levels prevailed from *c.* 44 000 to 35 700 cal. a BP and from *c.* 10 000 to 9 200 cal. a BP, while shallow/ephemeral lacustrine conditions existed from 35 700 to 10 000 cal. a BP.

The aim of the current study was to obtain a quantitative reconstruction of the effects that the North Atlantic climate changes had on central Italy, by comparing our

mutual ostracod temperature range (MOTR) results from Lake Trasimeno with the Greenland ice-core record (NGRIP δ^{18}O, North Greenland Ice Project; Rasmussen *et al*. 2014). In order to achieve a more precise correlation an improvement of our age-depth model was necessary. To this purpose, we tested the possible correlations by tuning our record to the NGRIP record, combining radiometric dating with assumed synchronicity of features of both records.

Study area and methods

Study area
Lake Trasimeno (latitude 43°09'N; longitude 12°06'E, province of Perugia, Umbria) is the largest lacustrine system of central Italy with a surface of c.128 km^2 (Fig. 1). The area is today characterized by a Mediterranean climate, with the maximum rainfall in autumn and a minimum in summer, and with coldest temperatures in January (mean 5 °C) and warmest in July (mean 22 °C).

The origin and evolution of Lake Trasimeno are related to and driven by the Northern Apennines extensional tectonics since the Early Pliocene (Gasperini *et al*. 2010). The lake is very shallow (6 m maximum depth) and has a uniform bathymetry (Ludovisi *et al*. 2005). Because of its endorheic nature, the hydrological system strictly depends on climatic variations, which are mainly governed by the precipitation/evaporation ratio (Dragoni *et al*. 2012). Above all, the lake level and salinity variations seem to be driven primarily by temporal change in climate (Gambini 1995; Burzigotti *et al*. 2003; Dragoni *et al*. 2012; Marchegiano *et al*. 2018, 2019). Those changes also affect the organisms living in the lake, which react with physiological adaptations and/or in a change of the species assemblages (Elia *et al*. 2010; Marchegiano *et al*. 2018, 2019). Lake Trasimeno is considered a mesotrophic to eutrophic lake. Its present total dissolved salinity (TDS) ranges from 0.7 to 0.9 g L $^{-1}$ and pH values range from 6.9 to 8.7 (Marchegiano *et al*. 2017). The water has been classified as chloride, sulphate-calcium and magnesium-rich (Marchegiano *et al*. 2017). Being a polymictic lake, waters are completely mixed throughout the year producing a homogenization of all the physical and chemical parameters (no stratification). However, seasonal changes in precipitation/evaporation ratio cause variations of their values during the year.

Micropalaeontological sample preparation
The 8.59 m long sediment core, stored at the University of Cologne (Germany), was subsampled for micropaleontological analyses at 2 cm intervals (428 in total). After a 1 h treatment with 5% H_2O_2, aimed to remove the organic matter, samples were sieved with 125 µm-sieve mesh using deionized water and oven-dried at 40 °C. In each sample, ~300 ostracods valves (juvenile and adults) were picked and identified under a miscroscope. In the very few samples in which fewer than 300 valves were present, we picked all the shells. Microslides containing the ostracod assemblages are stored at the Department of Earth Sciences of the University of Geneva (Switzerland).

Mutual Ostracod Temperature Range method
In order to investigate the relationship between temperature and hydrological regime at regional scale, we herein apply the mutual ostracod temperature range (MOTR) method, an MCR method for non-marine ostracods (Horne 2007; Fig. 1). This is a non-analogue method that utilizes all the calibrated species present in an ostracod assemblage, not just those that occur together at the present day (Horne 2007).

Examples of the application of the MOTR method to palaeoclimatic reconstruction can be found in Horne (2007), Holmes *et al*. (2010), Horne *et al*. (2012), Anadón *et al*. (2012), Bridgland *et al*. (2013), Whittaker *et al*. (2013), Bellucci *et al*. (2014), Langford *et al*. (2014a, b, 2017), Pint *et al*. (2015), Cosentino *et al*. (2017) and Benvenuti *et al*. (2017).

The MOTR method (Horne 2007) uses temperature ranges of species that have been calibrated by mapping their distributions with DIVA-GIS software (version 7.5) and comparing them with the WorldClim database (version 1.3) (Hijmans *et al*. 2001). The ostracod distributions have been taken primarily from the Non-marine Ostracod Distribution in Europe (NODE) database integrated with records from other datasets, e.g. for North America (Horne *et al*. 2012). The reconstruction of the past mean January and July air temperature ranges for specific ostracod assemblages is made following the MCR principle: the overlap of the calibrated temperature ranges (Table 1) of each species present in a given assemblage yields the mutual temperature range for that interval. Fig. 2 shows an example of the application of the method using the assemblage from sample 374 of the Trasimeno sediment core.

The temperature ranges were calculated for all the samples from 7.4 to 3.1 m depth in the Co1320 Trasimeno core to obtain the palaeotemperature variations during the deposition of the whole sediment succession. The MOTR method could not be applied from 8.6 to 7.5, from 7.2 to 7.0 m and for the upper 3.1 m because of the absence of ostracods and/or calibrated species.

Of the 19 species identified by Marchegiano *et al*. (2018), 13 could be used to determine mutual mean January and July air temperature ranges (Table 1). Eleven of those used the calibrations of Horne *et al*. (2012), while two species required new calibrations. For *Eucypris mareotica* a new calibration was based on a distributional dataset (53 records) compiled from available literature, including living records from Algeria and Spain in the west to Mongolia and western China in the east. In the case of the extinct fossil species *Limnocythere suessenbornensis* calibration of a living North American species was used. *Limnocythere suessenbornensis* was recorded by Marchegiano *et al*. (2018, 2019) as *L. blankenbergensis*, a small limnocytherid species known in Europe in the Lateglacial–Early Holocene deposits of Germany (Diebel 1968; Günther 1987; Griffiths 1995; Pint *et al*. 2012). Both species were first described by Diebel (1968). Subsequently, Preece *et al*. (2007) suggested that they represent adults (*L. suessenbornensis*) and juveniles (*L. blankenbergensis*) of the same species; this taxonomic opinion was accepted by Whittaker & Horne (2009). Following examination of their respective type specimens at the Museum für Naturkunde, Berlin, by David J. Horne in 2019, we consider them as synonymous. *Limnocythere suessenbornensis* was recorded (as *L. blankenbergensis*) for the first time in Italy in the Co1320 Trasimeno core during the cool and cold periods corresponding to the MIS 3 interstadials and MIS 2 (Marchegiano *et al*. 2018), but it has never been found living in Europe. As calibration of the temperature range of an extinct species is not possible and as shell size and morphology of *L. suessenbornensis* are very similar to *Limnocythere friabilis* Benson & MacDonald 1963, which is common living today in the Great Lakes region of North America (Smith & Horne 2016), specimens of this species in the Delorme Collection (Canadian Museum of Nature, Gatineau) were examined by David J. Horne in 2016. It is reasonable to consider *L. friabilis* as the same morphospecies and the closest living relative of *L. suessenbornensis,* and, thus, to apply temperature range calibrations for *L. friabilis* (based on living North American records) to *L.*

suessenbornensis. A definitive resolution of this taxonomic issue is beyond the scope of this paper.

The distribution of *Cyprideis torosa* is not sufficiently represented in NODE to allow calibration. As a matter of fact, this species, widespread in brackish waters, was recorded for the first time in fresh waters in the living fauna of Lake Trasimeno (Marchegiano *et al.* 2017). Taxa not identified to species level (*Amnicythere* sp, and *Ilyocypris* sp.) or for which no calibrations are yet available (*Trajancypris serrata, Potamocypris paludum* and *Herpetocypris helenae*) were also excluded (see Table 1 for full taxonomic names of all ostracod species mentioned in the text).

Chronology

The published chronology of core Co1320 shows that the sedimentary record covers the last 47000 cal. years (Fig. 3; Marchegiano *et al.* 2018). Preliminary inspection of the MOTR results based on this chronology showed that major peaks and troughs of the January temperature reconstruction can be matched with key peaks and troughs of the NGRIP $\delta^{18}O$ record (Fig. 4). The July minima show a very similar pattern but with lower amplitude difference between peaks and troughs. It seems reasonable to assume that some minor shifting, between NGRIP and MOTR curves, could be explained by variations in the sediment accumulation rate in Lake Trasimeno throughout the interval we are studying. The radiocarbon-based age-depth model (Fig. 3; see Marchegiano *et al.* 2018 for more details) shows a low sedimentation rate between 10 000 and 30 000 cal. a. BP and a higher rate between 30 000 and 50 000 cal. a BP (Fig. 5), but it lacks adequate chronological resolution for precise correlations with the high-resolution NGRIP record. We therefore tested the apparent correlations by tuning the MOTR January minima record to the NGRIP $\delta^{18}O$ record, considering such an approach to be justified by the prior recognition of Greenland ice-core rapid climate change features in the Lake Monticchio record (Allen *et al.* 1999), which satisfies Blaauw's (2012: p. 46) criterion that "Any tuning should be limited to within regions that have independently been shown to pertain to the same climate regime." The two-stage test was designed to determine (i) whether the obvious peaks and troughs in our signal could be matched with the NGRIP signal with minimal adjustments and without omissions, and (ii) whether the resulting tuned signal could be used to produce a new age-depth model (combing radiometric and relative tuning-based dating points) for the Lake Trasimeno core with plausible changes in sediment accumulation rates (Blaauw 2012; Fig. 5). To establish a consistent and reproducible methodology we set three rules for the tuning: (i) positions of selected tie points (peaks or troughs) could be adjusted along the depth/age axis to align with peaks or troughs (as appropriate) on the NGRIP signal; (ii) to maintain the integrity of the MOTR signal no adjustment was allowed along the temperature axis; and (iii) any tie-points falling within the ± ranges of radiocarbon ages were restricted to adjustment only within those ranges. A new age-depth model was produced, utilising tuned MOTR tie-points and radiocarbon ages (Figs 4, 5).

The application of a 5-point simple running mean is a method widely used with time-series data method to smooth short-term fluctuations and emphasize long-term trends. Our data set includes inter-sample variability due to different numbers of specimens being counted in different samples and/or vertical sample intervals that encompass different time intervals. In the former case the results of MOTR method may be influenced because in some samples the specimen count was not high enough to detect a rare but significant species. In the latter case, the variability is typically undetectable; in continuous sampling, a standard interval of (e.g.) 2 cm may represent

different time intervals in each sample due to variations in sedimentation rate on a finer scale than the age-depth model can resolve. The application of a 5-point simple running mean to our MOTR signal can result in artifacts such as peaks appearing in the smoothed signal where there were troughs in the data (and vice versa). Smoothing a signal may result in "sucking in" or "smearing" of proxy events due to chronological uncertainties (Blaauw 2012), which we consider in our palaeoclimate reconstruction below. For the NGRIP ice-core oxygen isotope signal, with which we compare our MOTR signal, a 20-year average trade-off between the smoothing of noise and the retention of good resolution is considered to be optimal (Rasmussen *et al.* 2014).

Results

Calibrated temperature ranges of ostracod species
Among all the species recovered in core Co1320, those with the narrowest calibrated temperature ranges are *L. suessenbornensis* (equivalent to *L. friabilis)*, *Cytheromorpha fuscata*, *Candona angulata* and *C. neglecta* (Table 1). However, it should be noted that even taxa with broad ranges can play a significant role in determining the mutual temperature range of an assemblage, if the palaeotemperature is in the vicinity of one end or the other of the species' calibrated range.

Limnocythere friabilis is a freshwater, interstitial species living in North America, common in littoral zones of lakes including the Great Lakes (Smith & Horne 2016). Using records from the Delorme Ostracode Autecological Database (curated by the Canadian Museum of Nature) we have determined the temperature range of living *L. friabilis* (January –15 to –3 ºC, July +16 to +23 ºC) and applied it to *L. suessenbornensis* in our MOTR analyses.

Cytheromorpha fuscata has not been found living in present-day Italy, but has been recorded alive in permanent lentic and lotic brackish to freshwater environments in Finland, Poland, Germany and Britain (Sywula 1966, 1971; Hagerman 1967; Usskilat 1975; Savolainen & Valtonen 1983; Olenska & Sywula 1988) as well as in Canada (Neale & Delorme 1985). Horne *et al*. (2012) define its temperature range as January –27 to +4 °C and July +10 to +21.

Candona angulata lives today in Lake Trasimeno (Marchegiano *et al.* 2017) and its temperature range is January –5 to +7 °C and July +16 to +25 °C (Horne *et al.* 2012).

Candona neglecta is part of the Italian living fauna (Pieri *et al.* 2009) but has not been found living in Lake Trasimeno (Marchegiano *et al.* 2017). It has a wider temperature range than the previously mentioned species: January –10 to +13 °C and July +7 to +27 °C (Horne *et al.* 2012).

Sarscypridopsis aculeata, *Heterocypris salina*, *Limnocythere inopinata* and *Eucypris mareotica* have wide temperature ranges (Table 1). In the Lake Trasimeno palaeoenvironmental reconstruction (Marchegiano *et al.* 2018), these four species were interpreted as indicators of mainly temporary/ephemeral lacustrine conditions, as suggested by their capacity to survive dry intervals in a torpid stage and/or as resting eggs. Moreover the first two of these four species are typically found in brackish environments (Margalef 1956; De Deckker 1981; Mezquita *et al.* 1999) and the others are tolerant of brackish water. *Limnocythere inopinata* can tolerate seasonal desiccation and a wide range of salinities; it is found associated with high alkaline water depleted in Ca^+ (Keatings *et al.* 2010). *E. mareotica* is able to inhabit both fresh and highly saline waters up to 110 per mil (Löffler 1990; Aladin *et al.* 2008).

MOTR application

The MOTR method reconstructs ranges, represented by maximum and minimum values, of mean January and mean July air temperature. The actual temperatures may be anywhere between the maxima and minima of the reconstructed ranges. However, it is not possible to attribute greater probability to, e.g., the mean value of the two extremes. The MOTR-based temperature reconstruction from core Co1320 is shown in Fig. 6. The minima curve of the MOTR reconstructed ranges for January and July corresponds well with each other (despite their amplitudes being quite different) in terms of "colder" and "warmer" intervals, as do the maxima curves for January and July. While it is impossible to determine precisely the actual temperatures within the reconstructed ranges, some constraints may at least be discussed. For example the curve for January maxima can be taken to represent a coldness threshold (i.e. it was at least as cold as this) to compare with present-day mean January air temperature. This shows that some periods, particularly in the lower half of the core (44,000 to 25,500 cal. a BP), show mean temperatures at least a few degrees colder than today. These periods are mainly determined by the occurrence of *C. fuscata* and *L. suessenbornensis*, which were particularly significant in determining colder winter and summers, with mean January temperature at least 7 °C colder and mean July temperature at least 1 °C cooler. However, the July and January maxima curves often show higher-than-present-day temperatures, particularly during the MIS 2, and this is unlikely. We consider that during cold climate stages in southern Europe it is the minima (representing the northern limits of species' ranges), rather than the maxima (representing southern limits of ranges), that will reflect the actual palaeotemperatures most closely, because the species were living close to their northern distributional limits.

Supported by our radiocarbon-based chronology the tuned MOTR January minima record allows the identification of Greenland stadials and interstadials 1–11 as well as the Younger Dryas stadial in the Lake Trasimeno record (Fig. 4). Comparison between the tuned and untuned MOTR curves suggests lower lake sediment accumulation rates between 27 000 and 15 000 cal. a BP, consistent with the radiocarbon age-depth model. The new, higher-resolution age-depth model (Fig. 5) shows relatively minor deviations from the model based solely on radiocarbon ages and no changes in sediment accumulation rate are evident. The highest accumulation rate is seen between *c.* 7.5 and 6.6 m depth (Fig. 5), where a distinctive sand unit (*c.* 7.0 – 6.8 m) has excluded from the profile prior to age-depth modelling in Marchegiano *et al.* (2018). This unit was deposited during an interval of fluctuating lake levels (Marchegiano *et al.* 2018) and presumably represents relatively rapid deposition. The tuned signal supports the correlations suggested by Marchegiano *et al.* (2018: fig. 12) although application of our improved age-depth model may result in minor adjustments.

Discussion

The analysed core encompasses an interval (*c.* 47 000–9000 cal. a BP) spanning a long mild period (MIS 3), a cold and dry phase (MIS 2) and the Holocene transition (Termination 1). The MIS 3 and MIS 2 intervals are known to be characterized by high-frequency climate variations consisting of cycles of warmer (interstadial) and colder (stadial) periods (Abrantes *et al.* 2012). These climate changes have been previously identified in the Lake Trasimeno sediment record (Marchegiano *et al.* 2018). This study showed that the Lake Trasimeno ostracod faunas responded to and

recorded climatic variations with important qualitative changes in their assemblages. In detail, three main associations were recognized: i) *Cyprideis torosa* association indicating a permanent lake with high lake levels and low salinity conditions; ii) *Sarscypridopsis aculeata* association linked to very shallow/temporary waterbody conditions, and iii) *Sarscypridopsis aculeata – Eucypris mareotica* association indicating temporary waterbodies affected by high salinity. Variations in TDS are likely due to changes in precipitation/evaporation ratio, as suggested by previous studies (Ludovisi & Gaino 2010). A change in solute composition is unlikely as Lake Trasimeno has very few tributaries and the groundwater contributes only *c.* 2.5% to the total water input (Arpa Umbria 2005).

In Fig. 6 the MOTR-derived curves are compared to the ostracod assemblages recognized by Marchegiano *et al.* (2018) throughout the core. The tight correlation between the MOTR-derived curve and the reconstructed lake level variations at Lake Trasimeno can be explained by the regional connection between the moisture and the temperature regimes, in which humid conditions correspond to warmer periods and dry intervals to colder ones. This study thus confirms what was previously indicated by several palynological studies (summarized in Fletcher *et al.* 2010) that in central Italy the interstadials are characterized by humid conditions, whereas dry ones prevailed during stadials.

The MOTR method could not be applied to the interval from *c.* 47 000-44 000 cal. a BP because of the absence of ostracods and of calibrated species. From *c.* 47 000 to *c.* 45 400 cal. a BP the absence of ostracods is probably due to a very low carbonate concentration in the lake water that prevents the ostracods from secreting their calcium carbonate shell (Marchegiano *et al.* 2018). The humid conditions recorded for this interval, with the consequent increased precipitation, resulted in more diluted lake water (Marchegiano *et al.* 2018). From *c.* 45 400 to *c.* 44 000 to cal. a BP the ostracod assemblage is monospecific, with the only occurrence of *C. torosa* a species, as already explained, that has been not calibrated yet.

From *c.* 44 000-25 500 cal. a BP (Fig. 6) the Lake Trasimeno ostracod record indicates high lake level conditions. During this period, *C. fuscata* and *L. suessenbornensis/friabilis*, the coldest species, both of which are thought to require permanent waters (Curry & Baker 2000), are significant components of the ostracod assemblages. In contrast, the period *c.* 25 500-9000 cal. a BP (Fig. 6) is characterized by prolonged dry conditions that caused a strong reduction of the lake waterbody to possible temporary pools (Marchegiano *et al.* 2018). In this interval, the persistence of *S. aculeata* (a species tolerant of brackish water and with desiccation-resistant eggs, adapted to life in ephemeral waterbodies) is significant, while *C. fuscata* is completely absent and *L. suessenbornensis* occurs only sporadically. It is noteworthy that despite their absence, the MOTR-derived curves continue to record a strong relationship between local and NGRIP temperatures variations (Fig. 4). This demonstrates that all the ostracod species present in an interval, contribute to the MOTR result and not only those ones tolerating a narrow range of temperatures.

Comparison with other records

The millennial-scale climatic changes that characterized the North Atlantic during the last glaciation were firstly recognized in the ice-core record from Greenland (Johnsen *et al.* 1992; Grootes & Stuiver 1997) and found thereafter in climatic records all over the world (Voelker 2002). The synchronous responses to these events in Mediterranean area were detected in several lacustrine and marine records using a wide range of proxies (e.g. Cacho *et al.* 1999; Drysdale *et al.* 2007; Wagner *et al.*

2010; Regattieri *et al.* 2014, 2017). A prompt response was found in the vegetation records analysed, among the most recent, at Lake Ohrid (Macedonia; Sinopoli *et al.* 2018), Lake Prespa (Greece; Panagiotopoulos 2014) Tenaghi Philippon (Greece; Milner *et al.* 2016) and Abric Romaní (northeast Iberia; Biltekin *et al.* 2019). However, none of these studies showed a continuous and/or direct reconstruction of temperatures. To our knowledge, the only pollen-derived mean January air temperature reconstruction comes from Lago Grande di Monticchio (Allen *et al.* 1999), which is located approximately 375 km southeast of Lake Trasimeno. In the record from Lago Grande di Monticchio, stadial and interstadial events derived from the January mean temperature curve (Allen *et al.* 1999) are less pronounced than in Lake Trasimeno. However, the Monticchio January mean T curve, ranging from –15 to 0 °C, would fit within the January MOTR minima and maxima, consistent with the interpretation that the actual temperatures lay somewhere between the extremes of the MOTR ranges.

Although the MOTR method has frequently been applied to infer past climatic conditions, this is the first time it has been used successfully to produce continuous palaeotemperatures data over a long time interval. Anadon *et al.* (2012) used the MOTR method to reconstruct mean values curves for discrete, discontinuous, mid-Pleistocene to Holocene core intervals from Valle di Castiglione near Rome, Italy, rather than maxima and minima as used in our study. The MOTR method is capable of reconstructing only ranges within which the real temperature existed, and considering mean values of the maxima and minima to be more likely to represent the actual temperatures is regarded as unjustified and inadvisable (Horne & Mezquita 2008; Horne *et al.* 2012).

Conclusions

The application of the MOTR method to the Lake Trasimeno ostracod record between 44 000 and 9000 cal. a BP demonstrates for the first time the ability of the method to provide a continuous record of rapid climate change. Comparison between MOTR-derived curves and the ostracod record (Marchegiano *et al.* 2018) proves the presence of relatively rapid variability between warm and humid and cold and dry periods in central Italy during the MIS 3 and MIS 2. The correlation of the tuned MOTR reconstruction with the Younger Dryas and Greenland stadial (GS) and interstadials (GI) 1–11 confirms a southern European (Mediterranean) record of rapid environmental change during this interval, previously recognized using pollen-based methods elsewhere in Italy.

Author contributions. - MM developed the general idea and conducted the research. DJH developed the idea on how to improve the age model. MM and DJH carried out the interpretation of the data. AF and BW provided the core material. EG, AF, BW

and DA sustained the interpretation of the data. M.M wrote the text with the contribution from all authors.

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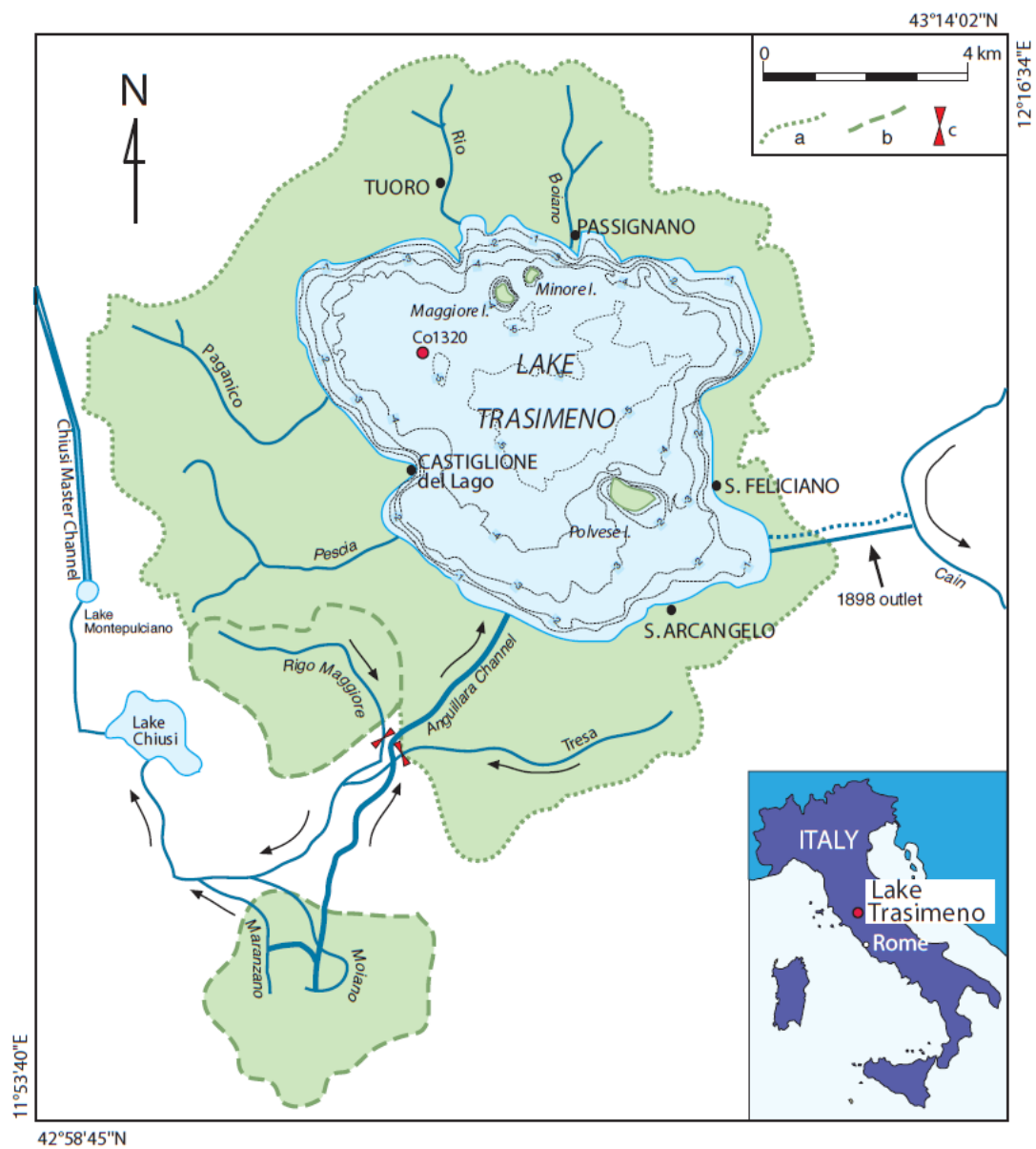
FIGURES

FIG. 1: Map of Lake Trasimeno showing the location of core Co1320. Legend: a = natural catchment area; b = artificially-joined basins; c = sluice gates of the artificially-joined channels (modified from Marchegiano *et al*. 2017).
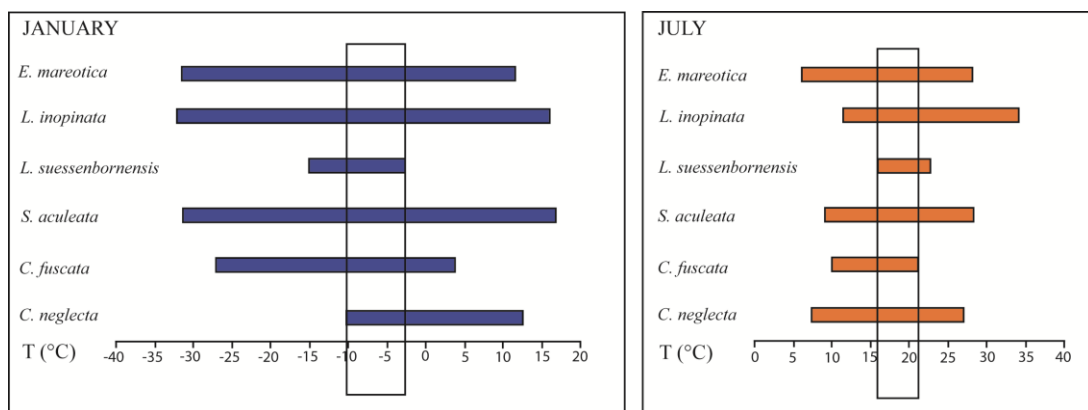
FIG. 2: Example of the application of the MOTR method on sample 374 of core Co1320. The results are: mean January air temperature range -10 to -3 °C, mean July air temperature range +16 to +21 °C.
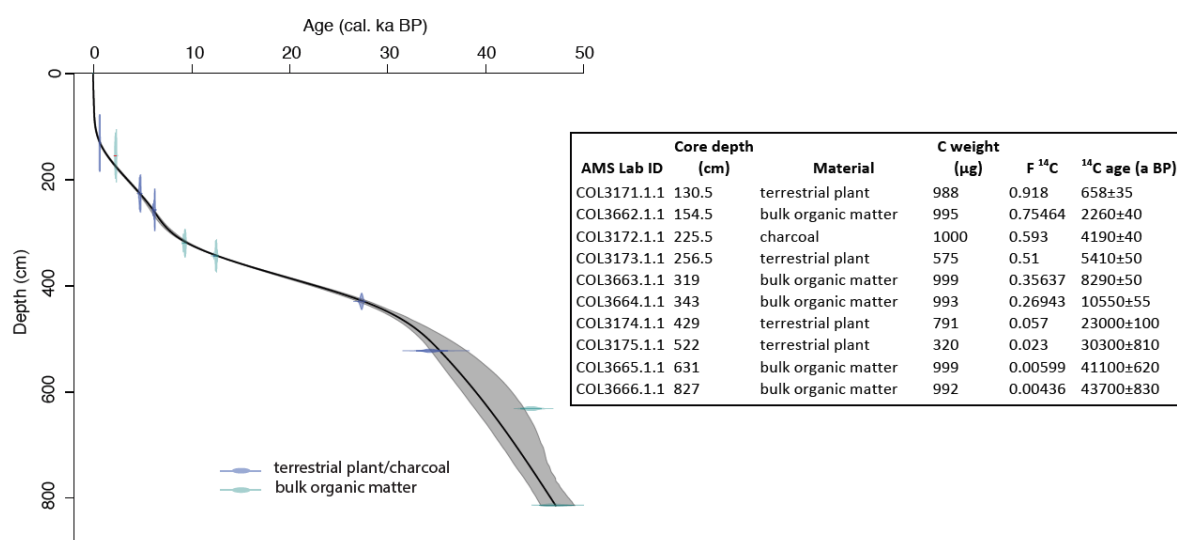

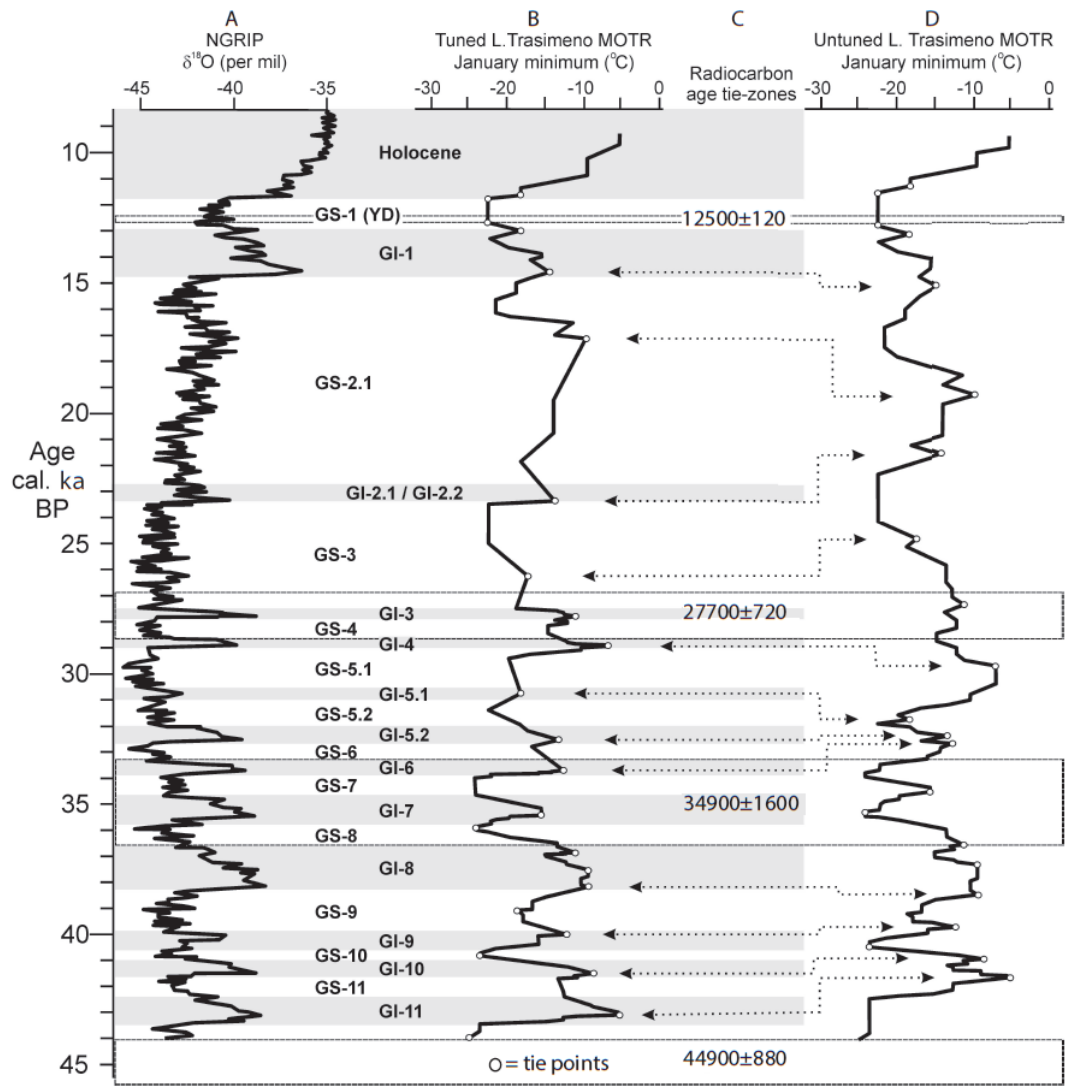FIG. 3: Age model of core Co1320 (from Marchegiano *et al.* 2018).

FIG. 4: Comparison between Lake Trasimeno tuned (B) and untuned (D) MOTR January minima (five-point moving averages) and the Greenland (NGRIP) oxygen stable isotope record (A). Radiocarbon age tie-zones are also indicated (C).
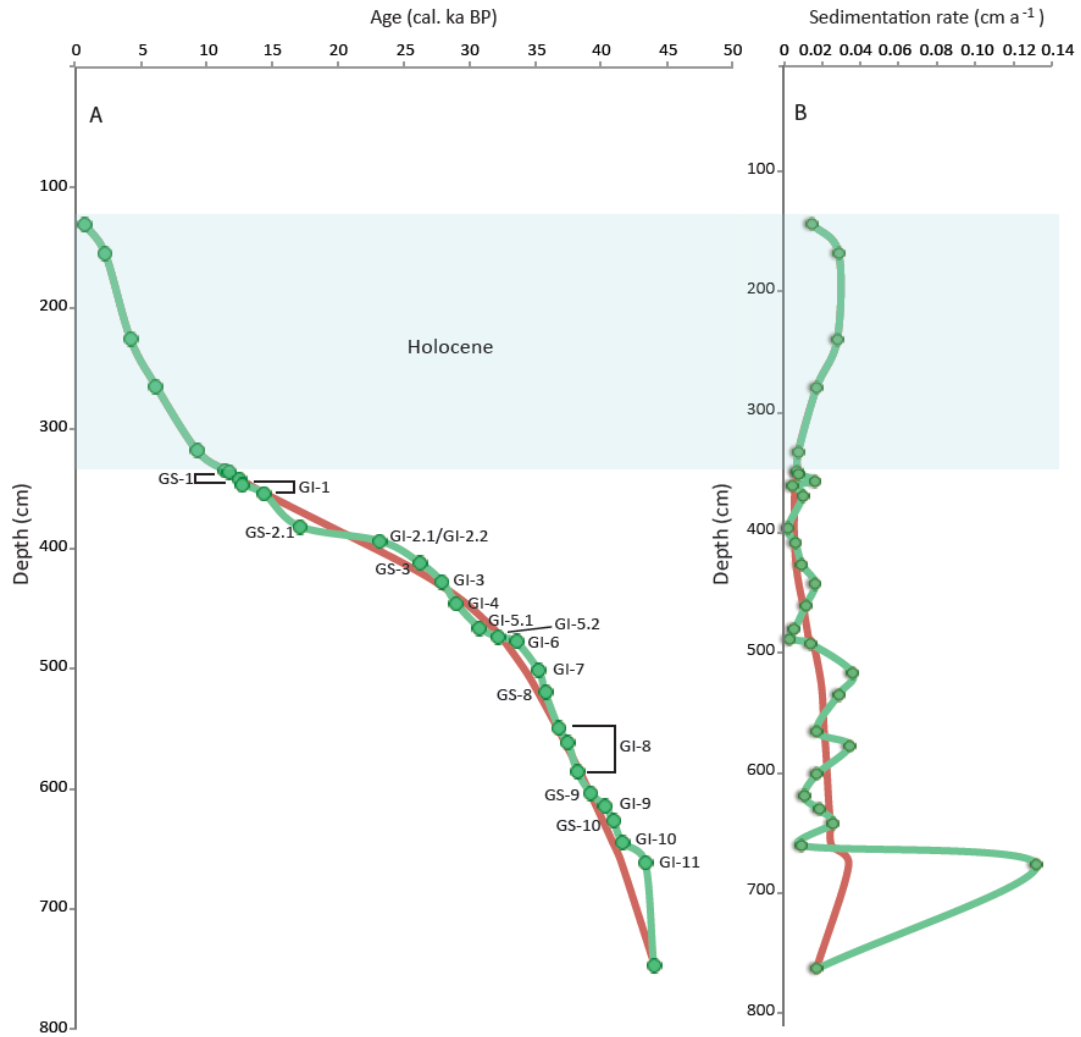
Fig. 5: A. New age-depth model produced (green curve), utilising tuned MOTR tie-points (showed in Fig. 4) and radiocarbon ages. The red curve indicates the previous age model reconstructed using only radiocarbon ages (Marchegiano *et al.* 2018). B. Calculated sedimentation rate for the tuned (green curve) and the un-tuned (red curve) age model.
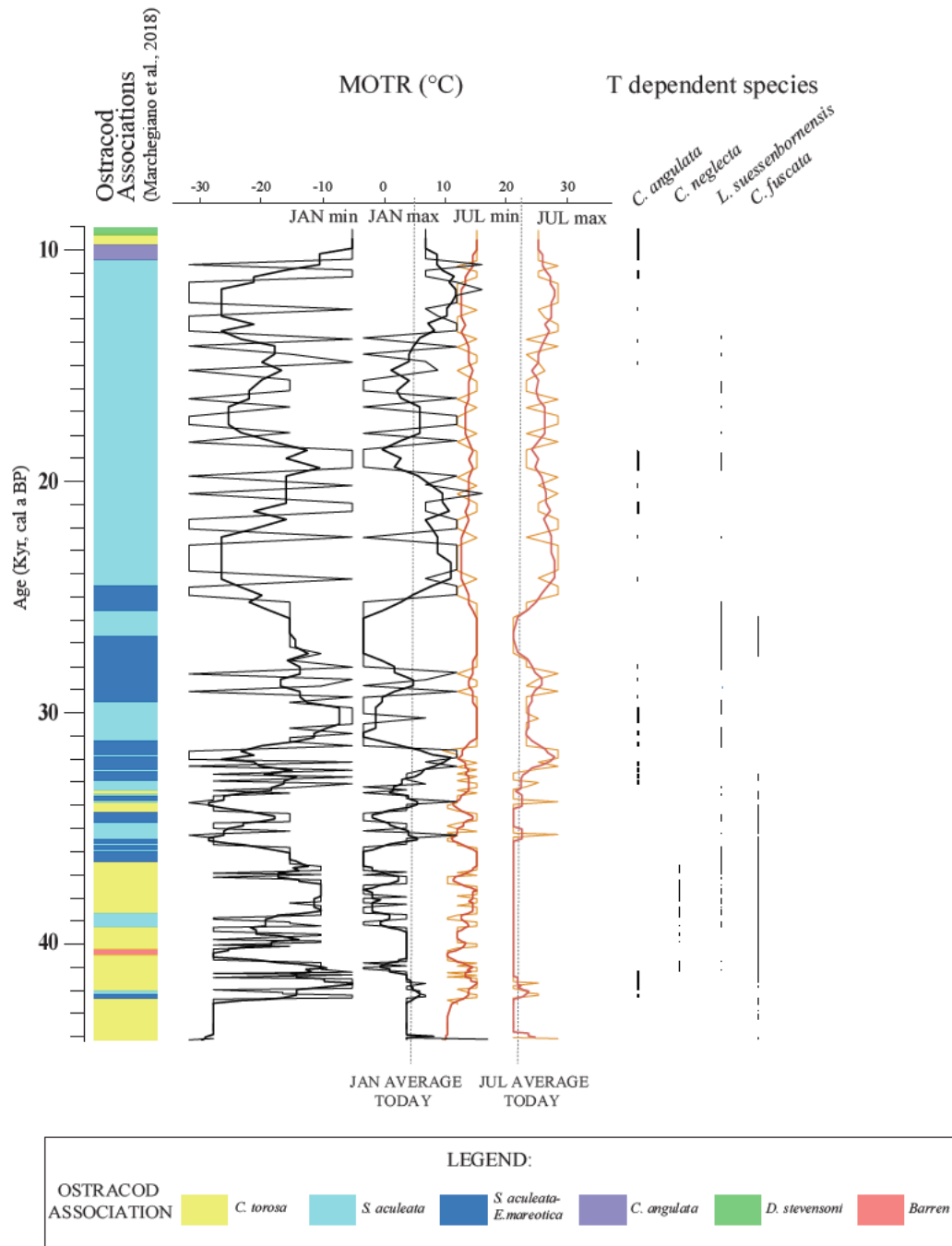
FIG. 6: MOTR application along the Co1320 sediment core. From the left, the ostracod associations identified by Marchegiano *et al.* (2018), the four MOTR-derived curves (thicker curves represent the five-point moving averages), the main temperature dependent species significant in determining the MOTR and the interval separation (refer to the main text).

TABLE 1. Ostracod species recovered in the Trasimeno sediment core and the calibrated mean January and July air temperature ranges for species used in the MOTR method application.

Species	July		Jan
	Min (°C)	Max (°C)	Min (°C)
Amnicythere sp	-	-	-
Candona (*Neglecandona*) *angulata* G.W. Müller	16	25	-5
Candona (*Candona*) *candida* O.F. Müller	6	26	-40
Candona (*Neglecandona*) *neglecta* Sars	7	27	-10
Cypridopsis vidua (O.F. Müller)	9	34	-32
Cytheromorpha fuscata (Brady)	10	21	-27
Cyprideis torosa (Jones)	-	-	-
Darwinula stevensoni (Brady & Robertson)	12	30	-31
Eucypris mareotica (Fischer)	6	28	-31
Herpetocypris helenae G.W.Müller	-	-	-
Heterocypris incongruens (Ramdohr)	5	28	-31
Heterocypris salina (Brady)	8	28	-31
Ilyocypris bradyi Sars	-	-	-
Limnocythere inopinata (Baird)	12	34	-32
Limnocythere suessenbornensis Diebel	16	23	-15
Plesiocypridopsis newtoni (Brady & Robertson)	12	27	-31
Potamocypris paludum Gauthier	-	-	-
Sarscypridopsis aculeata (Costa)	9	28	-31
Trajancypris serrata (G.W. Müller)	-	-	-