

Frequency and dynamics of millennial-scale variability during Marine Isotope Stage 19: Insights from the Sulmona Basin (central Italy)

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2	Frequency and dynamics of millennial-scale variability during Marine Isotope Stage 19: Insights
3	from the Sulmona Basin (central Italy)
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16	

17 Abstract

Among past interglacial periods, Marine Isotope Stage (MIS) 19 is particularly interesting because its orbital geometry is very similar to that of the present interglacial. Here we present a high-resolution (subcentennial) multiproxy record covering the ca. 790-770 ka interval, i.e. the interglacial MIS 19c and the ensuing glacial inception of MIS 19b, from a lacustrine sediment sequence retrieved from the Sulmona Basin (central Italy). The record has an independent chronology based on radiometric dating of six volcanic ash layers, and the resulting age model has a mean associated uncertainty of ± 2.6 kyr. Variations in sediment geochemistry and mineralogy are interpreted in terms of past hydrological and

temperature changes. Several millennial and sub-millennial events of reduced precipitation are well 25 expressed. Comparisons with continental and marine records from the mid-latitude and sub-polar North 26 Atlantic suggest a broad spatial expression for the observed events. Events occurring within the 27 interglacial are not clearly associated with changes in marine proxies in the Iberian Margin, although 28 similarities with the record from the sub-polar North Atlantic can be recognized and tentatively linked to 29 changes in local hydrography having a downstream effect amplified by changes in atmospheric 30 circulation. During the glacial inception, however, changes in the Sulmona record are coherent with 31 32 changes in North Atlantic records, with drier events likely associated with meltwater-induced intervals 33 of AMOC weakening. An event at ca. 785.6 ka may also reflect oceanic changes caused by freshwater discharges from residual ice-sheets and an outburst flood, similar to the 8.2 ka event in the Holocene. 34

Keywords: Stable isotope geochemistry, interglacial variability, central Italy, lacustrine succession, MIS
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37 **1. Introduction**

The recovery of high-resolution records of climate variability from oceans, ice-sheets and continental 38 archives has profoundly modified our perspective on global climate change by revealing the pervasive 39 existence of very rapid and high-amplitude climate changes in the past (e.g. Gottschalk et al., 2015). 40 41 Although such abrupt climatic changes can be triggered by different forcing, it is conceivable that human activity has likely increased their probability (Alley et al., 2003). Thus, the recognition of short-term (i.e. 42 multi-decadal to sub-millennial), global-scale, climate variability during previous interglacial periods is 43 of fundamental importance to provide the context of natural variability in which human-induced changes 44 operate (Tzedakis et al., 2009). 45

Among older interglacial periods, Marine Isotope Stage (MIS) 19c has received particular attention due
to its orbital geometry, which was very similar to that of the present interglacial (i.e., low eccentricity

and weak precession, and similar phasing between precession and obliquity: Berger and Loutre, 1991; 48 Pol et al., 2010; Tzedakis, 2010; Tzedakis et al., 2012). Modelling studies have highlighted that this 49 period is the best analogue for the Holocene when annual and seasonal temperatures are taken into 50 account, although it appears less similar when the summer-half yearly insolation is considered (Yin and 51 Berger 2010, 2012). Because MIS 19c occurred before the Mid-Brunhes Event (~450 ka) - i.e. before 52 the culmination of a series of changes of the global climate system resulting in the establishment of longer 53 and deeper glacial-interglacial cycles (e.g. Head et al., 2008) - it was also characterized by slightly lower 54 55 global temperatures and atmospheric CO₂ concentrations with respect to the preindustrial Holocene, and 56 possibly by higher residual global ice-volume (Bintanja et al. 2005; Bintanja and van de Wal 2008; Lüthi et al., 2008; Lisiecki and Raymo, 2005; Elderfield et al., 2012). Millennial- to centennial-scale climate 57 oscillations during MIS 19, and particularly within substage MIS 19c, have been previously reported 58 from both marine and continental archives (Sánchez-Goñi et al., 2016; Maegakiuchi et al., 2017; Oliveira 59 et al., 2018; Kleiven et al., 2011; Maiorano et al., 2016; Marino et al., 2015; Ferretti et al., 2015; Nomade 60 et al., 2019). The findings of a ~5-kyr periodicity, i.e., similar to the fourth harmonic of precession, in 61 both the coupled marine-pollen record from the southern Iberian margin (site U1385, Sánchez-Goñi et 62 al., 2016) and in the planktonic and benthic δ^{18} O record from low to mid-latitude North Atlantic and 63 Mediterranean records (Ferretti et al., 2015; Weirauch et al., 2008; Nomade et al., 2019) led to the 64 suggestion that variations in the tropical seasonal insolation cycle, driven by precession and its 65 66 harmonics, caused periodic oscillations in the latitudinal thermal gradient. These oscillations were considered capable of altering both sea-surface conditions and westerly wind trajectories, modifying the 67 68 northward transport of heat and water vapour (Sánchez-Goñi et al., 2016). Further north, however, the record of outflow speed from the Nordic Sea and the isotopic composition of surface and bottom waters 69 70 from site ODP-983 (Fig. 1, Kleiven et al., 2003, 2011), located near the eastern source of North Atlantic Deep Water (NADW), shows a series of millennial-scale episodes of reduced ventilation of intermediate 71

waters and reduction in deep convection strength during the whole MIS 19 period. These oscillations 72 have been related to changes in local convection and to reduced NADW formation, leading to intervals 73 of weakened Atlantic Meridional Overturning Circulation (AMOC) (Kleiven et al., 2011). As AMOC 74 disruptions affect also Mediterranean climate, causing decreases in temperature and precipitation (e.g. 75 Columbu et al., 2017; Drysdale et al., 2007; Fletcher et al., 2013; Margari et al., 2009; Regattieri et al., 76 2015, 2016, 2018; Tzedakis et al., 2018), the ODP-983 record points to high-latitude forcing of the 77 observed variability. These contrasting findings thus leave open questions about oceanic and atmospheric 78 79 mechanisms operating at sub-millennial scales during MIS 19 and, particularly, in its interglacial portion, 80 and it is not clear if and how these processes can be linked to boundary conditions. Part of this uncertainty is also due to the lack of robust and independent chronologies, an issue which until now has clearly 81 hampered our capability to asses the timing, rate, propagation and duration of changes. 82

Here we present a multiproxy biogeochemical record (high resolution stable oxygen and carbon isotope 83 on lacustrine calcite, low-resolution elemental and mineralogical composition on the bulk sediment, 84 85 biogenic silica content) from a stratigraphic interval containing the MIS 19c, which is part of the lacustrine succession hosted in the Sulmona Basin (central Italy, Fig. 1). Sediment proxies from Sulmona 86 Basin record local environmental conditions, which can be linked to North Atlantic climate variability 87 (Giaccio et al., 2015; Regattieri et al., 2015, 2016, 2017). An important feature of the Sulmona succession 88 is the presence of numerous volcanic ash (tephra) layers interbedded within the lacustrine sediment (e.g. 89 Giaccio et al., 2012, 2009). ⁴⁰Ar/³⁹Ar dating performed directly on those tephra layers provides robust 90 91 and independent chronological constraints for the observed variability. Giaccio et al. (2015) presented the entire MIS 20 to MIS 17 interval from Sulmona, providing a relatively low-resolution stable isotope 92 record for the 820-720 ka period and with a particular focus on the length of the MIS 19c interglacial. 93 Here, this interglacial is investigated at higher resolution (sub-centennial) using a multi-proxy approach, 94

95 and the record is anchored to an improved chronology. We explore the environmental expression, the 96 pacing and the periodicities of the centennial- to millennial-scale variability revealed by the Sulmona 97 record. We then compare this to marine records from the mid- and high-latitudes of the North Atlantic, 98 to unravel the potential forcing and the mechanisms for short-term instability within MIS 19c at the extra-99 regional scale.

100

101 **2.** Site setting and stratigraphy

The Sulmona Basin (Fig. 1) is a block-faulted intermountain depression located in the central Apennine 102 Ridge (central Italy). The basin experienced discontinuous lacustrine sediment accumulation during the 103 Quaternary (Cavinato and Miccadei, 2000; Giaccio et al., 2012, 2013). Its location and the geological, 104 stratigraphic and chronological framework were described in detail in previous studies (Giaccio et al., 105 2009, 2012, 2013; Regattieri et al. 2015, 2016, 2017; Zanchetta et al., 2017). Briefly, the Sulmona 106 sedimentary succession is divided into three main unconformity-bounded lithostratigraphic units (SUL6, 107 SUL5 and SUL4-3), composed of alluvial, fluvial and lacustrine sediments. These units were 108 chronologically constrained by magnetostratigraphy and tephrochronology (Giaccio et al., 2012, 2013, 109 2015; Sagnotti et al., 2014, 2016). This study focuses on the outcropping 35-43 m depth interval of the 110 SUL6 lacustrine unit (Fig. 1). The SUL6 unit spans the period between MIS 20 and MIS 16 (820-650 111 ka) and encompasses the Matuyama-Brunhes geomagnetic reversal (Sagnotti et al., 2014; Mark et al., 112 113 2017). The SUL6 succession has been described by Giaccio et al. (2009), with important chronological 114 amendments in Giaccio et al. (2013). Sediments are composed of light-coloured lacustrine calcareous marls (Freytet and Verrecchia, 2002), with up to 90% wt CaCO3 and abundant diatom remains (SOM-115 Fig. S1). The carbonate fraction is almost entirely made up of euhedral to sub-euhedral calcite crystals 116 of ~3–5 µm (SOM-Fig. S1), typical of biologically-mediated inorganic carbonate precipitation from Ca²⁺ 117

and HCO₃⁻ ions dissolved in surface water. Hereafter we refer to it as endogenic calcite (e.g. Jones and Bowser, 1978). The contribution of clastic carbonates from the catchment is negligible and thus has no effect on the stable isotope (δ^{18} O and δ^{13} C) composition of calcite (Regattieri et al., 2016, 2017). Several tephra layers occur within the SUL6 unit (Fig. 1) and form the basis of its chronology.

122 The topographic surface of the Sulmona basin is located between 340 and 400 m a.s.l., but its hydrology is dominated by a network of karst springs fed by recharge occurring in the surrounding mountain areas 123 (up to 2500 m a.s.l.) (Barbieri et al., 2005; Desiderio et al., 2005a, 2005b; Falcone et al., 2008). Spring 124 waters are characterized by a pH close to 7.5, an electrical conductivity of $<500 \mu$ S and a high discharge 125 (e.g. average 7 m³ s⁻¹ for the main spring, Capo Pescara), especially during snow melt in spring (Barbieri 126 et al., 2005) and likely accounted for most of the paleolake recharge (Regattieri et al., 2015, 2016, 2017). 127 128 Owing to the intense neotectonic activity, which has reshaped the local hydrography, the hydrological regime of Sulmona paleolake cannot be defined. However, based on the modern hydrography and 129 hydrogeochemistry of the basin, as well as the observation that sediments are almost entirely composed 130 of massive beds of endogenic calcite containing abundant and well-preserved diatom remains, it can be 131 argued that it was a freshwater and hydrologically open basin. The stable isotope composition of the 132 endogenic calcite is also consistent with this interpretation (Regattieri et al., 2015, 2016, 2017). 133

134 Local precipitation averages ~700 mm/yr but increases up to 1200 mm/yr at high altitude. Rainfall is unevenly distributed, showing maxima during autumn and winter, and minima during the summer 135 season. Winter precipitation is mostly related to north-westerly circulation. Cyclones originate over the 136 North Atlantic and take a mid-latitude storm track, following a prevailing NW-SE direction (Reale and 137 Lionello, 2013). Secondary cyclones, often associated with the passage of major cyclones north of the 138 Mediterranean, form within the basin and especially in the Gulf of Genoa, the most important 139 Mediterranean cyclogenetic centre (Lionello et al., 2006). The amount of winter precipitation reaching 140 the Mediterranean is influenced by several large-scale atmospheric patterns, which induce changes in 141

storm-track activity. In particular, at multiannual and decadal scales, the amount of winter precipitation 142 is inversely correlated with the North Atlantic Oscillation (NAO) index (e.g. Lopez-Moreno et al., 2011; 143 Ulbrich et al., 2012; Cullen et al., 2002), because during negative NAO phases westerly storm tracks are 144 shifted southward and allow a greater penetration of storms into the basin, and because negative NAO 145 phases enhance Mediterranean cyclogenesis (Ulbrich et al., 2012). Summer droughts are due to the 146 expansion of the Azores high (Xoplaki et al., 2003; Ulbrich et al., 2012 and references therein). Summer 147 precipitation is scarce and mostly related to local heat lows, which owe their genesis to thermal heating 148 149 overland, and to evaporation and convection influenced by the surrounding mountain topography.

150 **3. Methods**

151 *3.1. Sampling and stable isotope analyses*

The studied interval comprises three distinct outcropping and partially overlapping sections that are 152 lithostratigraphically correlated through clearly distinguishable tephra horizons (Fig. 1). The composite 153 section is eight metres thick and was sampled for stable isotope analyses at 2.5 cm vertical resolution, 154 155 for a total of ~320 samples. Sample preparation followed the procedure described in Regattieri et al. (2015). Stable isotope analyses were performed at the Stable Isotope Laboratory of the Institute of 156 Geosciences and Earth Resources of the Italian National Research Council (IGG-CNR, Pisa, Italy) with 157 a Gas Bench II (Thermo Scientific) coupled to a Delta XP IRMS (Finnigan), following the method 158 presented in Regattieri et al. (2016). Sample results are reported on the VPDB scale and calibrated against 159 the international standards NBS-18 and NBS-19. Analytical uncertainties were 0.17‰ and 0.15‰ for 160 δ^{18} O and δ^{13} C respectively (2 σ). 161

162 *3.2. Elemental, mineralogical and biogenic silica analyses*

163 X-ray fluorescence spectrometry (XRF) and X-ray powder diffraction (XRPD) analyses were performed 164 on untreated leftover powders of the stable isotope analyses at the Earth Sciences Department of the University of Pisa (Italy). Elemental analyses were conducted with a NITON XL3t GOLDD + hand-held
XRF unit (HHXRF, see Gemelli et al., 2015 for performance), following the analytical procedure for
sediment samples described in Regattieri et al. (2016).

Mineralogical composition was investigated on 36 unevenly spaced samples through XRPD analyses with a Bruker D2 Phaser diffractometer equipped with a Lynxeye fast detector. Phase identification was obtained with the Bruker Diffrac-Suite EVA and Topas-Academic software (Coelho, 2018). A semiquantitative estimation of mineral abundances (quartz/calcite ratio, qz/ct hereafter), was calculated with the abovementioned software as the ratio between spectral peak areas of quartz and calcite.

Biogenic silica (bSi) concentrations were measured on the same samples analysed with XRF, using Fourier transform infrared spectroscopy (FTIRS) at the Institute of Geological Sciences, University of Bern, Switzerland. Analyses were performed using the method described in Vogel et al. (2008) and adopting the sample preparation protocol of Vogel et al. (2016). Calibration, accuracy and precision are detailed in Meyer-Jacob et al. (2014).

178 *3.3. Ar/Ar dating and age modelling*

The Bayesian age model (Fig. 2) is based on 40 Ar/ 39 Ar dating of six tephra layers (Fig. 1 and Table 1). 179 Four of these tephra layers occur within the interval analysed in this study (35-43 m depth, Fig. 1), while 180 181 the remaining two occur in close proximity (at 46.14 m and 29.70 m) and were employed to better constrain the age-modelling procedure. For five of the six tephra, ages are from Giaccio et al. (2015), 182 here recalculated using the new Optimisation Model age for the ACs monitor standard (1.891 Ma; 183 Niespolo et al., 2017). A new ⁴⁰Ar/³⁹Ar dating for the SUL2-19 tephra, obtained at the CNRS-LSCE 184 (Centre National de la Recherche Scientifique, Laboratoire des Sciences du Climat et de 185 l'Environnement, Gif Sur Yvette, France), is presented here (Fig. 2). Analytical procedures are as 186 described in Giaccio et al. (2015). Details concerning the analytical procedure and the full dataset are 187 both given in supplementary material (SOM text 1 and SOM Table 1). This new age is calibrated against 188

the ACs-2 age of 1.1891 (i.e. FCs at 28.294 Ma; Niespolo et al., 2017) and calculated using the total K decay constant of Renne et al. (2010). The Bayesian age model (Fig. 2) was constructed using the Bacon software (Blaauw et al., 2011). "*A priori*" settings were chosen to accommodate the actual mean sedimentation rate (28.7 yr/cm), and to allow for larger variations around the mean value. Successive calculations with different settings held statistically indistinguishable age-depth relationships, although the current model minimizes the difference between radiometric and modelled tephra ages (Table 1).

195 *3.4. Wavelet analyses*

Continuous wavelet analyses (CWT) was performed on δ^{18} O data series for the whole interval between 196 800 ka and 750 ka, including lower resolution data from Giaccio et al. (2015) for the periods not covered 197 by the new record, employing a self-implemented Matlab code described in Tognarelli et al. (2018) and 198 in Tognarelli (2018). No filtering was performed before the wavelet analysis in order to preserve the 199 original frequency content of the input data. Only a linear interpolation is applied to the data to produce 200 a regular sampling over time, and a Δt of 1 yr is used as sample rate. 95% significance levels in the 201 wavelet power spectrum were computed by means of a chi-square test with two degrees of freedom, 202 203 where the null hypothesis assumes the that the local wavelet power spectrum corresponds to the rednoise spectrum with a lag-1 coefficient of 0.73. Power bands for the most intense periodicities were 204 205 extracted from the spectra through the inverse continuous wavelet transform.

206 4. Results and discussion

207 *4.1. Chronology*

Full analytical details for the 35 individual sanidine crystals of the SUL2-19 tephra are given in Table S1. Among the 35 analysed, 29 yielded ages overlapping within uncertainty, allowing the calculation of a weighted mean age of 784.7 ± 2.4 ka (2σ including J uncertainty) (Fig. 2 and Table 1). According to the age model presented in Fig. 2, the new high-resolution δ^{18} O record presented in this study spans the 769.8 ± 2.2 ka to 789.9 ± 2.1 ka period. The mean associated uncertainty of the record is 2.6 kyr, ranging from 2.1 to 2.8 kyr (Fig. 2). The resulting average temporal resolution of the stable isotope series is 60 years, while the temporal resolution of XRF and bSi analyses is 230 years. XRD samples are not evenly spaced, but on average their resolution is ~ 600 years. The sedimentation rate is on average 0.45 mm/yr, ranging from 0.18 mm/yr to 0.73 mm/yr.

217 4.2. Proxy interpretation

Different sediment properties presented in this work (δ^{13} C, δ^{18} O, Ca content, biogenic silica content mineralogical composition, Fig. 3) have been measured and discussed previously for other lacustrine intervals in Sulmona (Giaccio et al., 2015; Regattieri et al., 2015, 2016, 2017), so their paleoclimatic interpretation is only briefly outlined here and the reader is referred to previous works for more detailed explanation.

223 <u>4.2.1 Oxygen and carbon stable isotopes</u>

The oxygen stable isotope composition (δ^{18} O) of lacustrine, biologically-induced, endogenic calcite 224 depends on temperature and oxygen isotopic composition of the lake surface water (e.g. Leng and 225 Marshall, 2004). In the Mediterranean region, the temperature effect during carbonate precipitation (ca. 226 -0.24‰/°C; Kim and O'Neil, 2007) is negligible, because it is counterbalanced by a gradient of ca. 227 +0.3‰/°C observed between mean annual δ^{18} O of meteoric precipitation and temperature (Bard et al., 228 2002). The δ^{18} O of lake water depends on the δ^{18} O of precipitation and on the precipitation/evaporation 229 (P/E) ratio (e.g. Leng and Marshall, 2004). The δ^{18} O of Mediterranean precipitation has a strong 230 empirical relationship with the amount of rainfall (ca. -2%/100 mm), with lower values related to 231 increased precipitation and higher values related to reduced precipitation (Bard et al., 2002). Previous 232

studies on lacustrine carbonates from the Sulmona Basin have shown that the influence of lake water 233 evaporation for the final calcite δ^{18} O is negligible, likely due to the large and sustained karstic recharge, 234 to presumable hydrologically open conditions and relatively short water residence times within the lake. 235 Therefore, the δ^{18} O composition of endogenic calcite at Sulmona can be used as a first-order proxy for 236 precipitation amount in the high-altitude catchment of the karst recharge system (Giaccio et al., 2015; 237 Regattieri et al., 2015, 2016, 2017). Changes in isotopic composition driven by changes in the source 238 area of moisture always contribute to changes in the δ^{18} O of precipitation, and thus of precipitated 239 240 carbonates. However, these variations have proven to be significant especially during glacial/interglacial 241 transitions (e.g. Marino et al., 2015), but can be considered negligible during interglacial periods such as the period discussed here (Tzedakis et al., 2018). 242

The stable carbon isotope composition of lacustrine endogenic calcite derives from that of the dissolved 243 inorganic carbon (DIC) of the lake water (Whittington et al., 2015; Zanchetta et al., 2012, 2018;). The 244 DIC of the Sulmona paleolake was likely significantly influenced by the input of the large karst springs 245 recharging the basin, which today show higher $\delta^{13}C_{DIC}$ ($\delta^{13}C_{DIC(karst)}$) compared to smaller and more 246 surficial springs, due to the longer rock-water interaction times (Falcone et al., 2008). Variations in 247 δ^{13} C_{DIC(karst)} are related to rainfall and temperature fluctuations, with dry/cool periods characterized by 248 reduced soil OM stocks and longer water residence times, leading to higher $\delta^{13}C_{DIC(karst)}$. Conversely, 249 250 warmer and wetter conditions promote soil and vegetation development and a faster water flow, leading to more negative $\delta^{13}C_{DIC(karst)}$, as commonly inferred from speleothem studies (e.g. Genty et al., 2002; 251 Regattieri et al., 2014). Within the lake, the $\delta^{13}C_{DIC(karst)}$ signal is mediated by additional processes, which 252 involve equilibration with atmospheric CO₂, photosynthetic ¹²C uptake, and consumption and recycling 253 of organic matter in the water column as well as in the sediment. These processes largely depend on the 254 lake hydrological budget and settings (e.g. Leng and Marshall, 2004). In our record, a generally weak 255 covariance between δ^{13} C and δ^{18} O is observed, especially for the decreasing trend at the beginning of the 256 11

record and for a similar interval of enriched values at ca. 772 ka (Fig. 3). On the whole, δ^{13} C and δ^{18} O 257 also show a weak though significant statistical correlation (r=0.37, Fig. 4), though is visually clear that 258 their relationship change during different intervals. A positive covariation of the two isotopes is usually 259 observed in hydrologically closed lakes (e.g. Talbot and Kelts, 1990). In hydrologically open lakes, 260 where calcite precipitation is mediated by primary productivity, an inverse relationship between δ^{13} C and 261 δ^{18} O is instead expected (e.g. Talbot and Kelts, 1990). The current hydrology of the Sulmona Basin and 262 the negligible effects of evaporation on the δ^{18} O signal strongly suggest hydrologically open conditions 263 264 for the Sulmona Lake, and relatively short water residence times within the lake. Thus, the weak covariance between δ^{13} C and δ^{18} O, rather than an indication of hydrological closure, likely indicates that 265 the δ^{13} CDIC(karst) signal is dominant on the final δ^{13} C of calcite, and that the evolution of the δ^{13} CDIC(karst) 266 is modulated by climate conditions, mostly via the regulation of soil CO₂ leached to the lake (Zanchetta 267 et al., 2018). However, a divergence is apparent in the long-term trends of the two isotope time series, 268 with progressively more negative δ^{13} C values corresponding to increasing δ^{18} O (Fig. 3). This decoupling 269 could be related to the increasing influence of in-lake processes compared to that of karst recharge, which 270 may possibly decrease. Alternatively, the trend towards more negative δ^{13} C values can be explained by 271 the slow post-glacial development of soils in the catchment, supplying more ¹³C depleted CO₂, following 272 the progression of the interglacial, as already observed for speleothem records from high-altitude 273 recharge areas (Drysdale et al., 2005, Regattieri et al., 2014, Zanchetta et al., 2007). 274

275 <u>4.2.2 Productivity and detrital proxies</u>

In the Sulmona lacustrine sediment, Ca occurs mostly as endogenic calcite, as demonstrated by previous studies and by SEM microphotographs of the sediment (SOM, Fig. S1). Endogenic calcite precipitates through algal fixation of CO₂, thus in this context Ca content is an indirect proxy for lake primary productivity. Biogenic silica (bSi) in the sediment primarily derives from diatom frustules and thus also

provides information on primary productivity (Vogel et al., 2010). Rising spring and summer 280 temperatures and nutrient availability promote primary productivity. Calcite precipitation rate depends 281 also on HCO₃⁻ and Ca²⁺ concentrations in the lake water, with enhanced ion supply through soil/epikarst 282 dissolution processes and high soil CO₂ production and leaching, both leading to higher dissolved ion 283 content, during wetter and warmer periods (e.g. Francke et al., 2016). General agreement is observed 284 between Ca and bSi content, but some differences are apparent (Fig. 3). At Sulmona, volcanic material 285 from tephra deposition in the lake and mobilization of volcanoclastic deposits in the catchment was likely 286 287 an important source for the Si and Fe needed for diatom growth. The single sample with high bSi content 288 at ca. 789 ka occurs in close proximity (i.e. within 5 cm) of tephra T22. Tephra deposition following large eruptions can trigger short-term diatom blooms, which are not necessarily climate-related 289 (Cvetkoska et al., 2015; D'Addabbo et al., 2015). It is also interesting that the main rise in bSi seems to 290 lag the increase in Ca (Fig. 3). This difference could be potentially related to post-depositional dissolution 291 of calcite. However, the sediment lithology does not show any evidence of anoxic, low pH conditions in 292 the respective horizons (i.e. no laminations are present and the sediments are always massive, indicating 293 294 continuing bioturbation and thus oxygenated conditions at the lake bottom), which would support such dissolution. Another possibility could be that hydrological variations controlling the supply of HCO3⁻ 295 and Ca²⁺ ions were less important for Fe and Si concentrations in water. This would imply a stronger 296 dependence from rainfall fluctuations for the Ca content, whereas diatom growth (i.e. bSi content) would 297 298 respond mostly to temperature variations, with superimposed fluctuations influenced by occasional Fe and Si inputs. 299

XRPD analyses of the bulk sediment reveal the predominant presence of calcite, accompanied only by a
small amount of quartz. Quartz is typically present in small quantities in limestone. When carbonate rock
dissolves, quartz remains in the soil together with other silicate minerals and Fe oxides and hydroxides.
These can be transported to the lake by runoff, which is enhanced when the vegetation cover is reduced.

Part of the quartz can also be linked to erosion and transport processes from silicate rocks in the lake 304 catchment, but these rocks are virtually absent in the Sulmona Basin, thus their contribution is likely to 305 be insignificant. Quartz can also have an aeolian origin, as suggested for quartz-rich loess deposits along 306 307 the Apennines (Giraudi et al., 2013) and for quartz grains in central Italy maar lake sediments (Narcisi, 2000). Sourcing and transport of aeolian particles is also enhanced when the vegetation is less developed 308 (Boretto et al., 2017). Thus, at Sulmona the quartz/calcite ratio (Fig. 3) can be considered a simple, semi-309 quantitative way to express variations in soil erosion in the catchment and/or in aeolian input to the lake, 310 311 with higher ratios indicating decreased erosion and/or reduced aeolian transport, likely both arising from 312 vegetation development under wetter and warmer conditions.

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4.3. Paleoenvironmental and paleohydrological evolution during MIS 19 in the Sulmona Basin.

Based on the interpretations introduced above, the new high-resolution δ^{18} O record for MIS 19c shows 315 rapidly increasing precipitation after 788 ka (Fig. 3). This trend follows that observed in the low-316 resolution δ^{18} O time-series by Giaccio et al. (2015; Fig. 3) and represents the latest part of the 317 deglaciation occurring between MIS 20 and MIS 19. The deglaciation is accompanied by rising lake 318 primary productivity (increasing Ca and bSi) and by enhanced supply of soil CO₂ (lower δ^{13} C), both 319 320 indicating warmer temperature, and by a strong decrease in the clastic/aeolian input to the lake 321 (decreasing qz/ct), likely arising from the increasing vegetation cover (Fig. 3). Peak precipitation was reached at ca.786.0 ka, but was rapidly interrupted by a prominent, ~0.8 kyr long, drier period starting at 322 785.6 ka (Fig. 3, Table 2). This event, denoted by the Roman number I in Figure 3 and in Table 2, is 323 clearly expressed in all the other proxies. Precipitation increased again at 784.3 ka and remained 324 relatively high until ca. 779.0 ka. Within this period, however, two events of reduced precipitation are 325 apparent (II and III; Table 2, Fig. 3). Between 779 ka and 777 ka, precipitation and primary productivity 326 327 decrease and conditions remain consistently drier and colder compared to the previous interval. Three

further events of increasing dryness and reduced productivity occur between 779 ka and 775 ka (IV, V, 328 VI; Table 2, Fig. 3). Aside from event I, changes of δ^{18} O values during event II to VI are of low 329 magnitude (0.2-0.4‰). However, all of them are coherently expressed by several data points (Fig. 3), 330 suggesting that they represent a real short-term, low-amplitude hydrological variability. These events (II 331 to VI) are not clearly expressed by the other proxies, likely due to their lower temporal resolution and to 332 a more subdued response of these properties during period of overall wet conditions. From 773.0 ka, 333 there is a large and abrupt decrease in precipitation, immediately followed by increased clastic input and 334 335 reduced primary productivity lasting until 771.2 ka (event VII in Fig. 3, Table 2). This period is followed 336 by an increase in precipitation and productivity (Fig. 3), although erosion rates in the catchment remain quite high until the end of the high-resolution section at 769.8 ka. 337

338 4.4. Regional significance of the Sulmona record and potential links with North Atlantic variability

Few paleoclimatic records spanning MIS 19c with a temporal resolution comparable to our record exist 339 from the Mediterranean and the North Atlantic regions (Nomade et al., 2019, Ferretti et al., 2015; 340 341 Sánchez-Goñi et al., 2016), and none possesses an independent radiometric chronology. The coupled marine-pollen record from marine core U1385 on the southern Iberian Margin (Hodell et al., 2015; 342 Sánchez-Goñi et al., 2016, Figs. 5 and 6) provides a relatively high-resolution, multi-proxy bio-343 geochemical record for the MIS 19 (resolution of ~300 yr for pollen and alkenones and of ~160-200 yr 344 for planktonic and benthic stable isotope composition), capable of capturing both orbital and millennial-345 scale climatic change (Sánchez-Goñi et al., 2016). The U1385 chronology relies on the 346 climatostratigraphic tuning to the global benthic stack LR04, and has a mean absolute uncertainty of ~ 5 347 ka (Lisieki and Raymo, 2005). The benthic δ^{18} O from U1385 shows that MIS 19 ranges from 791 ka to 348 758 ka, and that MIS 19c ends at ca. 775 ka. The pollen record from the same core shows that the onset 349 of the terrestrial interglacial (Tajo interglacial) occurs at ca. 787 ka, slightly after the onset of MIS 19c, 350

whereas its end is almost coincident with that of the benthic substage (Sánchez-Goñi et al., 2016). Seven 351 events of forest contraction have been identified within MIS 19 (Sánchez-Goñi et al., 2016, Fig. 5). Of 352 these, only those occurring after ca. 770 ka, i.e. well after the interglacial, appeared to be coupled with 353 changes in oceanic conditions. For the other events, a warm sea/cold-dry land decoupling was observed 354 and proposed to represent an increased latitudinal thermal contrast causing a northward shift in westerly 355 wind trajectories. By analogy with the present positive mode of the NAO, this would have caused reduced 356 precipitation over southern Iberia (Sánchez-Goñi et al., 2016), and by extension in the central and eastern 357 358 Mediterranean region (e.g. Regattieri et al., 2019; Smith et al., 2016). Frequency analysis of the whole 359 U1385 record shows evidence for a strong ~5-kyr periodicity (Sánchez-Goñi et al., 2016). This led to the conclusion that the variability observed in the pollen record can be attributed to precession harmonics-360 related changes in yearly solar radiation in the tropics, relaxing or amplifying the thermal latitudinal 361 contrast and affecting mostly the strength of low-latitude low-pressure systems and thus atmospheric 362 circulation (Sánchez-Goñi et al., 2016). 363

The comparison between the Sulmona and the U1385 records reveals a striking similarity between the 364 lacustrine δ^{18} O and Mediterranean forest pollen percentage (Fig. 5). The intervals of forest reduction in 365 the pollen record correspond to dry periods in the Sulmona record, where the higher resolution allows a 366 better exploration of their internal structure and the identification of additional events (Fig. 5). Rainfall 367 amount exerts a dominant control on the composition of southern European vegetation (e.g. Quezel et 368 369 al., 2002; Gouveia et al., 2008) and the oxygen isotope composition of Mediterranean continental carbonates (lacustrine sediment and speleothem; e.g. Bard et al., 2002; Roberts et al., 2008), with forest 370 371 expansion and ¹⁸O-depleted precipitation associated with higher rainfall amount. This provides a basis for creating a common time scale between the Sulmona δ^{18} O and the Iberian margin pollen records, an 372 approach already employed to transfer the radiometric chronology of a central Italy δ^{18} O speleothem 373 record to a marine pollen record covering the Last Interglacial (Tzedakis et al., 2018). Thus, we aligned 374

(sensu Govin et al., 2015 and Zanchetta et al., 2016) the peaks in Mediterranean pollen taxa 375 corresponding to the Tajo interglacial and to the two subsequent forest expansions from U1385 to their 376 analogous wet interstadials from the Sulmona δ^{18} O record (Fig. 5 and SOM-Table 2). This adjustment 377 produces minor shifts (average ~1.7 kyr) in the U1385 chronology, fully within the absolute 378 chronological uncertainty, but it allows us to better constrain the age of Marine sub-Stage MIS 19c 379 (starting at 791 ka) and that of the terrestrial interglacial as defined by Sánchez-Goñi et al. (2016) in 380 southern Iberia (787.6 - 776.9 ka). According to the Sulmona chronology, the Tajo interglacial in U1385 381 382 lasts 10.7 ± 2.8 ka, which is close to a half a precession cycle. A similar duration (i.e. 11.5 ± 3.4 kyr 383 long) for the MIS19c interglacial was recently proposed by Nomade et al. (2019) based on the marine section of Montalbano-Jonico (Southern Italy). The alignment between the U1385 pollen record and the 384 Sulmona isotope record allows us to explore whether the dry events from Sulmona can be associated with 385 changes in marine proxies (Fig. 6). It is worth noting that the resolution of stable-isotope analyses from 386 both archives is higher than that of the pollen and SST records, permitting a more detailed sea-land 387 comparison once a common time scale is defined. For the major events occurring at ca. 772 ka, 765 ka 388 and 760 ka based on the Sulmona chronology (VII, IIX and IX in Fig. 6), rainfall reductions are in phase 389 with prominent changes in oceanic conditions, i.e. decreasing benthic δ^{13} C and sea surface temperature 390 (SST), increasing planktonic δ^{18} O and C_{37:4} -based freshwater index, Fig. 6). These events have been 391 correlated to intervals of sub-polar Ice Rafted Debris (IRD) deposition (Sánchez-Goñi et al., 2016). The 392 393 freshwater flux associated with IRD deposition is known to induce intervals of AMOC slow-down or interruption (e.g. McManus et al., 1999). The resulting decrease in SST at the mid-latitudes reduced 394 395 evaporation and advection of air masses rich in moisture towards the Mediterranean region, leading to basin-wide colder and drier intervals during glacial and transitional periods (i.e., glacial/interglacial 396 397 transition and glacial inception), (e.g. Drysdale et al., 2007; Fletcher et al 2013; Margari et al., 2009; Regattieri et al., 2015, 2016; Sinopoli et al., 2018; Tzedakis et al., 2004). Together with reduced 398

399 precipitation, for the event at ca. 772 ka the other proxies from Sulmona also show marked decreasing 400 primary productivity in the lake and in the surroundings soils, coherently indicating decreasing 401 temperatures (Fig. 3).

For events not associated with iceberg discharges in the North Atlantic (I to VI in Fig. 6), marine proxies 402 do not show major oscillations, but rather a low-amplitude variability (Fig. 6). The event I at ca. 786 ka 403 appears to correspond to a decrease in planktonic δ^{18} O comprising several data points, followed by a 404 similar increase (Fig. 6). Further, the benthic δ^{13} C and the SST records show coincident slightly 405 406 decreasing values (Fig. 6), suggesting that this event may be connected to a slight weakening of AMOC 407 activity. To some extent, a similar configuration is apparent also for the event at ca. 782 ka (Fig. 6), although it is not expressed by the benthic δ^{13} C record. For the other events, the relatively low resolution 408 and the low intensity variability hampers the possibility of a detailed correlation, though slightly 409 increased planktonic δ^{18} O values seem to correspond to event VI (Fig. 6). 410

To better define the relationship between Mediterranean hydrology and ocean conditions during the 411 interglacial, we compare our δ^{18} O record to the high-resolution (average 250 years) multiproxy record 412 from ODP-983 from the Gardar Drift, south of Iceland (Figs. 1 and 8, Kleiven et al., 2011). The Gardar 413 Drift is a key location to assess changes in NADW formation and related perturbations of AMOC 414 circulation (Kleiven et al., 2003, 2011). There, changes in deep hydrography are highlighted by decreases 415 in outflow speed and intensity from the Nordic Sea, recorded by changes in sediment grain size and 416 sorting (Kleiven et al., 2011; McCave and Hall, 2006) and by fluctuations in the benthic δ^{13} C record 417 (Oppo and Lehman, 1993). During warm periods, the site is bathed at depth by the vigorous outflow of 418 419 the Iceland-Scotland Overflow Water (ISOW), an essential component of the AMOC circulation that modulates European climate (Bianchi and McCave, 2000). Warm salty surface waters are advected 420 421 northward, where the site of deep convection and NADW formation is located (Knorr and Lohmann, 2007; Schmidt et al., 2004). At site 983 interglacial circulation appears substantially more stable 422

423 compared to glacial periods, when the centre of NADW formation shifted from the present Nordic Seas 424 position to the subpolar North Atlantic (Oppo and Lehman, 1993). However, all the warm stages of the 425 Middle Pleistocene show the occurrence of rapid shifts in the style or intensity of deep-water convection, 426 implying internal mechanisms that may generate AMOC instabilities also during periods of low ice-427 volume (Kleiven et al., 2003).

We first exported our independent chronology to the marine record. As discussed, events of IRD 428 deposition in the North Atlantic impact AMOC circulation and, as a consequence, the Mediterranean 429 430 hydrological cycle. Thus, we align the end of the IRD peaks occurring during the glacial inception to the 431 corresponding onset of wet interstadials in our record (Fig. 7 and SOM-Table 2), and the end of the last IRD peak occurring during the glacial termination with the onset of the terrestrial interglacial (Fig. 8 and 432 SOM-Table 2). As an independent test for alignment, we consider the correlations between U1385 and 433 ODP-983, both reported on the Sulmona chronology (Fig. 7). The onset and demise of the major intervals 434 of IRD deposition in the subpolar region show good chronological agreement with intervals of increased 435 C_{37:4} based fresh-water index (Fig. 7), despite the low resolution of the latter curve. Also, the stadial-436 interstadial pattern of the two planktonic δ^{18} O time-series is consistent. Decreasing/increasing δ^{18} O 437 planktonic values can be linked to increasing/decreasing temperature or to decreased/increased salinity. 438 In the ODP-983 record, IRD events are accompanied by decreasing planktonic δ^{18} O values (Fig. 7), likely 439 due to the influence of ¹⁸O-depleted meltwater releases, whereas on the Iberian margin the freshwater 440 flux is associated with decreasing SST and related increases of planktonic δ^{18} O values (Fig. 7). 441

Now that a common time scale is defined, we can check in detail if intra-interglacial continental events have a counterpart in the sub-polar record (Fig. 8). As with U1385, the ODP-983 record shows only a subdued variability during the interglacial. However, the event I at ca. 786 ka is marked by a significant reduction in deep-water ventilation (lower benthic δ^{13} C), and by a decrease in outflow strength (lower sortable silt percentage; Fig. 8), suggesting the occurrence of a short-term AMOC perturbation. It also

corresponds to a slight and steep decrease and a subsequent sudden increase in planktonic δ^{18} O (Fig. 8). 447 The other events recorded at Sulmona do not clearly correlate with variations in ODP-983 proxies due 448 to the subdued variability of the latter record. However, considering the combined age uncertainties, a 449 similar pattern between the deep outflow from the Nordic Sea (represented by the sortable silt percentage, 450 Fig. 8) and the Sulmona δ^{18} O record is apparent. Fluctuations in the sortable silt percentage are small, 451 but a similar variability observed during the Holocene in the record of nearby marine core NEAP-15K 452 (Bianchi and McCave, 2000) has been considered significant, and interpreted as reflecting subtle changes 453 454 in the ISOW strength.

455 4.5. Forcing and pacing for millennial- to-centennial-scale variability during the MIS 19

Our analyses point to different forcing for millennial and sub-millennial variability during MIS 19. After 456 the interglacial and following 772 ka, coherent changes in marine and continental proxies (Figs. 6 and 8) 457 indicate a rapid transfer of northern North Atlantic climate changes into the western Mediterranean 458 region. The North Atlantic record suggests that this variability arises from interactions between ice-sheet 459 460 dynamics (testified by the IRD-C_{37:4} events) and the AMOC. Within the interglacial, event I centred at ca. 786 ka also shows a coupling between continental and marine conditions (Figs. 6 and 8). This rainfall 461 reduction and forest contraction in southern Europe appears to be related to a temporary, low-intensity 462 AMOC disturbance. The marine records show lower benthic δ^{13} C at both sites, decreased SST on the 463 Iberian Margin, and reduced convection in the northern North Atlantic (Figs. 6 and 8). Concomitant 464 decreasing δ^{18} O planktonic values in the marine records can be related to increasing temperature, which 465 is in contrast with the SST record from the Iberian margin, or to decreased salinity, potentially related to 466 freshwater influx. This evidence suggests that this event could be an analogue to the Holocene 8.2 ka 467 event, i.e., the final outburst from the proglacial lake Agassiz (e.g. Alley et al., 1997; Alley and 468 Angustsdottir, 2005; Barber et al., 1999; Clarke et al., 2004). The related freshening of surface water 469

impacted convection in the Labrador Sea, where the western centre of NADW production is located, 470 producing a slowdown of the AMOC, and a consequent widespread climate anomaly. The occurrence of 471 similar events has been also postulated for interglacials other than Holocene, as for the Last Interglacial 472 (Nicholl et al., 2012; Galaasen et al., 2014), and the MIS 11 (Koutsodendris et al. 2012). Interestingly, 473 474 although the lower resolution and the chronological mismatching prevent a secure correlation, a shortlived period of climate perturbation is apparent within several MIS 19c records. Indeed, a cooling event 475 in the early part of the interglacial has been reported from the pollen record of the Montalbano Jonico 476 477 section (Southern Italy, Bertini et al., 2015; Marino et al., 2015), and from a marine core from the Osaka 478 Bay (Japan, Maegakiuchi et al., 2016). For the other intra-interglacial events, the coupling between 479 terrestrial and marine proxies, especially those from the Iberian Margin, is not as clear, perhaps pointing to a different forcing. Changes in north-westerly circulation and related moisture transport are likely 480 involved, but the ultimate causes for these atmospheric oscillations remain currently largely unexplained. 481 To explain changes in local convection observed at the ODP-983 site during interglacial intervals, it has 482 483 been proposed that enhanced sea-ice formation south of Iceland might have created an unstable density 484 stratification in the water column, causing a slow-down in the advection of southern warm waters, and an attendant cooling over the northern North Atlantic, with a downstream effect amplified by changes in 485 the atmospheric circulation (Kleiven et al., 2011). State-of-the-art coupled models also have shown the 486 occurrence of positive feedbacks between the atmosphere and the sea-ice, with stochastic atmospheric 487 488 changes inducing AMOC weakening and larger sea-ice cover, leading to cooling in the sub-polar and to strengthening of high-pressure system at the high latitudes (Drijfhout et al., 2013; Kleppin et al., 2015). 489 490 The similarity between the oxygen record from Sulmona and the record of deep-water ventilation and outflow speed from the Nordic Sea (Fig. 8) suggests that this cooling impacted atmospheric circulation 491 492 patterns also in the Mediterranean by altering the intensity and trajectories of westerly winds. In particular, it would have led to a northern shift of the westerlies, reducing their penetration, and thus the 493

amount of rainfall, within the Mediterranean Basin. This would have resembled an atmosphericconfiguration similar to the positive state of the NAO.

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497 Further insights on the ultimate forcing for the MIS 19 millennial and sub-millennial variability can be obtained from the dominant periodicities resulting from the Sulmona CWT analyses and by analysing 498 the timing and pacing of events. The real wavelet power spectrum for the oxygen time series, including 499 low-resolution data from Giaccio et al. (2015) for the younger (i.e. after 770 ka) and older portions (prior 500 501 to 790 ka) of the record, is shown in Fig. 9. Both the spectrum and the curves for the most energetic 502 periodicities (Fig. 9) show prominent changes throughout the investigated period and especially between the transitional periods (deglaciation and glacial inception) and the interglacial portion of the record. 503 Considering only those periodicities which i) are enclosed in the region of greater than 95% confidence, 504 ii) fall above the COI and iii) are longer than the uncertainty associated to the record (median 2.5 kyr), 505 two main wavelength bands can be recognized. Starting from the longest, a ~5.0-6.0 kyr cycle (Fig. 9) 506 can be observed throughout the investigated period. Periodicities of ca. 5-6 kyr, i.e. similar to the fourth 507 precession harmonic have been observed in several MIS 19 records (Sánchez-Goñi et al., 2016; Ferretti 508 et al., 2016; Weirauch et al., 2008; Nomade et al., 2019). However, in our record the intensity of this 509 periodicity almost vanishes in the middle portion of the interglacial, especially between ca. 784 and 778 510 ka (Fig. 9). Further, the pacing of both intra- and post-interglacial events is non-stationary, ranging from 511 512 ca. 4 to 2 kyr (Table 2). The non-stationarity is evident whatever approach is used to define the temporal relationships among different events, i.e. either when the onset, the mid-point and the end of events are 513 514 considered. The length of events is also rather variable (Table 2), with an average duration between 0.9 and 0.6 kyr within the interglacial and 2.3 kyr for the early glacial (Table 2). Although our observation 515 516 cannot rule out an initial forcing by precession harmonics, that can be modulated by sea-ice changes and may affect the timing of the millennial scale variability by producing non-stationary cycles throughout 517

the MIS 19 (Ferretti et al., QSR, 2015), the observation that intra-interglacial events occur too often to
be explained by a 5-6 kyr cyclicity, suggest that a precession forcing is likely not the cause of intrainterglacial events apparent in the Sulmona record.

Another significant periodicity of between ca. 4.2 and 3.5 kyr is also evident (Fig. 9), but its intensity is also reduced during the MIS 19c, again suggesting that forcing of millennial and sub-millennial scale variability changed between interglacial and transitional periods.

524

525 **6.** Conclusions

526 In this work, we have presented a multiproxy record (high resolution stable carbon and oxygen isotope, low resolution elemental and mineralogical composition, and biogenic silica content) obtained from 527 endogenic lacustrine sediments of the Sulmona Basin (central Italy). The record is anchored onto a fully 528 independent time-scale based on ⁴⁰Ar/³⁹Ar dating of six tephra layers interbedded in the lacustrine 529 sediment, and covers the ca. 790-770 ka period, thus encompassing the interglacial portion of Marine 530 Isotope Stage MIS 19, or MIS 19c (~788-777 ka). Hydrological and environmental proxies coherently 531 indicate that the post-interglacial period is marked by major changes in climatic and environmental 532 conditions. Within the MIS19c interglacial, a low-intensity, though significant, centennial- to millennial-533 scale hydrological and environmental variability is present and shows a non-stationary pacing. In 534 particular, a major event of rainfall reduction and environmental deterioration, ~ 1 kyr long, occurred at 535 ca. 786 ka according to our age model. Comparison of the Sulmona record with records from the Iberian 536 margin (Sánchez-Goñi et al., 2016) and from the sub-polar North Atlantic (Kleiven et al., 2011), both 537 reported on the radiometric Sulmona chronology through paleoclimatic alignment (sensu Govin et al., 538 2015) points to different mechanisms operating in different periods. Major dry events on land occurring 539

after the end of the interglacial are associated with AMOC disruptions and increased iceberg discharge 540 in the sub-polar north Atlantic. Within the interglacial (ca. 788-777 ka), the event at ca. 786 ka also 541 appears related to a lower intensity perturbation of the oceanic circulation. Other intra-interglacial events 542 are not so clearly associated with changes in marine proxies, though similarities with the sub-polar record 543 suggest a link between rainfall amount is southern Europe and deep hydrography in the northern North 544 Atlantic. We propose that changes in local convection, potentially related to feedbacks between 545 atmosphere and sea-ice, may have created unstable density stratification conditions, which may have 546 547 impacted the westerly circulation and the related moisture transport over the Mediterranean Basin. 548 Noteworthy, for MIS 19 as a whole, a higher global ice volume was proposed based on modelled global sea level (Bintanja et al. 2005; Bintanja and van de Wal 2008). Possibly, this configuration would have 549 caused a more pronounced "glacial" character for the MIS 19c interglacial, with larger global ice volume 550 influencing dynamics and intensity of deep convection in the eastern North Atlantic, with downstream 551 influences on rainfall variability over southern Europe. This suggests that also small changes in boundary 552 conditions (and particularly of ice-volume and temperature) can strongly influence the millennial-scale 553 554 climate variability during interglacial periods.

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874 Tables and Figure Captions

Table 1- Names, ages, uncertainties and depths of tephra layers used in the age-depth modelling procedure. Grey cells indicate tephra occurring within the interval discussed here. *Age from Giaccio et al. (2015); ** age from this study.

Table 2- - Age, length and pacing for events of reduced precipitation as from the Sulmona record. Roman
numbers are as in Figs. 3, 7 and 9; events reported in italics are from the low-resolution series from
Giaccio et al. (2015).

Figure 1- a) Location of the Sulmona Basin and of other sites mentioned in the text; b) Schematic
stratigraphy of the composite SUL6 lacustrine unit; c) Simplified morpho-stratigraphic scheme of the
Sulmona sedimentary succession.

Figure 2- Left panel: tephra position and labelling (see Table 1) and Bacon age model for the discussed interval. The red line represents the proposed age-depth relationship, light-green lines represent 95% confidence intervals. The interval highlighted in yellow represents the interval analyzed in the present work. Right panel: Age probability density spectrum for the SUL2-19 tephra. Blue and grey bars are the individual ages (2σ error) included and not included in the weighted mean age calculation, respectively. ACs value is from Niespolo et al., 2017.

Figure 3- Sulmona proxy time series presented in this work. A) and B) stable oxygen and carbon isotope composition of bulk lacustrine calcite (δ^{18} O and δ^{13} C composition), on A) the lower resolution δ^{18} O series from Giaccio et al. (2015) is shown as well (light blue line); C) Calcium content (XRF counting*sec); D) Biogenic silica content (% wt); E) Ratio of peak areas of quartz and calcite XRD
analyses. Grey shadings indicate events of reduced precipitation, roman numbers are as in Table 2.

Figure 4- Correlation plots of δ^{13} C and δ^{18} O composition

Figure 5- Tuning of the U1385 pollen record (with the published chronology by Sánchez-Goñi et al., 2016) on the Sulmona δ^{18} O time series (this study). Red circles indicate points used for alignment. Yellow shadings indicate the events of forest contraction identified by Sanchez-Goni et al., (2016) as well as the Tajo interglacial as apparent from the same record. Grey shadings are events of reduced precipitation as defined in Fig. 3 and Table 2. Dotted grey lines indicate proposed correlations between Sulmona and U1385 events.

Figure 6- Comparison between Sulmona δ^{18} O (a, light line is the lower resolution series from Giaccio et al. (2015) and the U1385 record (Sánchez-Goñi et al., 2016) on the Sulmona chronology; b) U1385 Mediterranean forest pollen percentage; c) U1385 planktonic δ^{18} O; d) U1385 benthic δ^{13} C; e) U1385 Alkenones Sea Surface Temperature; F) U1385 percentages of alkenone C_{37:4}. The top panel shows the U1385 benthic δ^{18} O record and MI stages and substages division. Roman numbers indicate the events of reduced precipitation from the Sulmona record (see Table 2). Grey rectangles are as from Table 2 and Fig. 3 and indicates events of reduced precipitation in the Sulmona basin.

Figure 7- Upper panel: tuning of the IRD record from core ODP-983 (Light-blue solid plot, on the original chronology by Kleiven et al., 2010) on Sulmona δ^{18} O time series (this study and Giaccio et al., 2015). Red circles indicate selected alignment points. Lower panel: comparison of U1385 (green, planktonic δ^{18} O‰ and C37:4 based freshwater index) and ODP-983 (blue, planktonic and IRD) records, both reported on the Sulmona chronology. Grey rectangles indicate the intervals of IRD deposition in the North Atlantic. Figure 8- Comparison between Sulmona δ^{18} O and the ODP-983 record (Kleiven et al., 2011) reported on the Sulmona chronology; b) ODP-938 Sortable silt percentage; c) ODP-983 planktonic δ^{18} O; d) ODP-917 983 benthic δ^{13} C; Roman numbers and grey rectangles indicate the events of reduced precipitation from the Sulmona record and are as shown in Table 2 and Figure 3.

Figure 9- Lower panel: Sulmona oxygen isotope real wavelet spectrum. The lower black line indicates the cone of influence. It delimits the spectrum in two regions, where the portion below the black line may be affected by edge effects and thus shows frequencies that are not significant considering the total length of the record (Tognarelli et al., 2018b). The contour delimited by the black line encloses the area with a confidence greater than 95%. Upper panel: the series reconstructed considering 5-6 and 4.2-4.5 kyr periodicities.

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926 Figure S1-FESEM images of Sulmona lacustrine sediment.







931 Figure 2









936 Figure 5



938 Figure 6





940 Figure 7









945 Figure 9