

1 **Mediterranean winter rainfall in phase with African monsoon during past 1.36 million**  
2 **years**

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68 Precipitation is a key factor for socioeconomic development in densely populated and summer  
69 dry regions such as the Mediterranean realm. Seasonal and regional changes are critical, but  
70 difficult to project accurately. While current climate model simulations indicate a progressive  
71 summer drying over the next century, precipitation changes during winter months are less  
72 well constrained<sup>1</sup>. Only a few continental proxy records capable of capturing hydroclimate  
73 change cover multiple Northern Hemisphere summer insolation maxima<sup>2,3</sup> with different  
74 underlying orbital geometries, necessary to validate climate model data on Quaternary time  
75 scales. Here we use a 1.36 million year proxy time series from Lake Ohrid, coupled to a long  
76 transient climate model hind cast, to show that high winter precipitation anomalies occur  
77 during phases with strong seasonal contrast in insolation and high African summer monsoon  
78 activity. While this is counter-intuitive at first sight, our data suggest that increased sea-  
79 surface temperatures amplify local cyclogenesis while also refuelling North Atlantic low  
80 pressure systems entering the Mediterranean during phases characterized by low continental  
81 ice volume and high atmospheric CO<sub>2</sub> concentrations. Comparison with modern reanalysis  
82 data shows that current drivers of rainfall amount in the Mediterranean share some similarities  
83 to those driving the reconstructed precipitation increases. Our extended record covers multiple  
84 insolation maxima and therefore is an important benchmark for testing climate-model  
85 performance.

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88 Mediterranean climates are characterized by strong seasonal contrasts between dry and warm  
89 summers, and wet and mild winters. The amount and temporal extent of precipitation during  
90 the winter half-year (October through March) determines the prevailing type of vegetation  
91 and water availability for agrarian land-use in the Mediterranean borderlands. In recent  
92 decades, reduction of winter precipitation has become a regular phenomenon in this region,

93 with anthropogenic greenhouse gas (GHG) and aerosol forcing identified as potential  
94 contributors<sup>4</sup>. Current climate model simulations, using the Representative Concentration  
95 Pathway (RCP) 4.5 and 8.5 scenarios, predict a progressive summer drying over the next  
96 century<sup>1</sup>. Precipitation changes during the Northern Hemisphere (NH) winter months are less  
97 well constrained, with different simulation runs showing trends both towards wetter and drier  
98 conditions. The uncertainty in winter precipitation projections limits the extent to which  
99 current modelling approaches are useful for decision makers<sup>5,6</sup>.

100 Long-term, empirical baseline data are helpful to constrain uncertainties in climate  
101 modelling proxy records. Proxy records and modelling experiments suggest that enhanced  
102 precipitation in the Mediterranean region is in phase with the northward shift of the  
103 intertropical convergence zone (ITCZ) and increase in African monsoon strength during  
104 precession minima causing Northern Hemisphere summer insolation (NHSI) maxima and  
105 winter insolation (NHWI) minima<sup>2,7,8,9</sup>. However, most continental records that are capable of  
106 capturing hydroclimate change do not cover multiple NHSI maxima with different underlying  
107 orbital geometries. In fact, the majority of records are limited to the Holocene<sup>10,11</sup>, yet the  
108 Early Holocene NHSI maximum was relatively weak compared to most other Quaternary  
109 interglacials, due to lower eccentricity. Terrestrial proxy time series covering multiple NHSI  
110 maxima from the Mediterranean region are scarce<sup>2,3</sup>. Sediment records from the  
111 Mediterranean Sea provide continuity throughout the Plio-Pleistocene and capture cessations  
112 of deep-water ventilation associated with the formation of prominent, organic-rich sapropel  
113 layers<sup>12,13</sup>. While multiple factors contribute to sapropel formation, increased freshwater  
114 input, particularly from the African continent during NHSI-forced monsoon maxima, is  
115 considered the most important<sup>14,15</sup>. Hence, the Mediterranean sapropel record is thought to be  
116 an excellent indicator of the relative timing of increased African monsoon strength rather than  
117 a direct indicator of precipitation in, and runoff from, the entirety of the Mediterranean realm.  
118 Reconstructed precipitation increases in the northern Mediterranean borderlands during

119 sapropel formation have been interpreted to be a product both of intensified summer and  
120 winter precipitation<sup>15,16</sup>. Modelling experiments explain increased winter precipitation by  
121 stronger wintertime storm tracks<sup>2</sup> or air-sea temperature difference, and locally induced  
122 convective precipitation that dominate freshwater budget changes on obliquity time scales<sup>17</sup>.  
123 Alternatively, conceptual models based on proxy time series have suggested increases in the  
124 frequency and intensity of low-pressure systems evolving in the Mediterranean region, mostly  
125 during fall and early winter<sup>7,8,16</sup>. Hence, a well-dated proxy record covering multiple glacial-  
126 interglacial cycles and being sensitive to changes in Mediterranean hydroclimate is key to  
127 addressing long-standing questions regarding the underlying mechanisms, timing, and  
128 amplitude of precipitation variability under different climate boundary conditions (GHG  
129 concentration, orbital geometries, continental ice sheet volume and extent).

130         Here, we assess precipitation variability in a continuous, independently dated 1.36  
131 Myr sedimentary record from Lake Ohrid (Fig. 1, Extended Data Fig. 1). Climate variations at  
132 this site represent broader climate variability across the northern Mediterranean borderlands<sup>18</sup>.  
133 We compare our sedimentary proxy time series with transient climate simulation data and  
134 prominent monsoon records, to provide a mechanistic understanding of precipitation  
135 variability and seasonality, as well as phase relationships to orbital forcing.

136         Lake Ohrid is of tectonic origin and 293 m deep. The lake is hydrologically open and  
137 primarily fed by an extensive karst aquifer system, which supplies ions (mainly Ca<sup>2+</sup> and  
138 HCO<sub>3</sub><sup>-</sup>) to the lake and filters particulate matter<sup>19</sup>. Scientific drilling in 2013 resulted in a 584-  
139 m-long composite sediment succession from the lake centre, comprised of fine-grained hemi-  
140 pelagic muds in the upper 447 m<sup>18,20</sup>. Sedimentation is thought to have been uninterrupted,  
141 with no evidence of unconformities or erosion surfaces. Independent age control from 16  
142 interspersed tephra layers in combination with magnetostratigraphy (Fig. 1, Extended Data  
143 Fig. 2, Extended Data Table 1, Extended Data Table 2) provides a robust chronological

144 framework. This framework allows us to match changes in orbital parameters with our proxy  
145 data to refine the age-depth relationships. The data demonstrate that the Lake Ohrid record  
146 spans the last 1.36 Myr (Fig. 1).

147 Indicators for detrital input (quartz, potassium), catchment vegetation (arboreal pollen  
148 excluding pine (AP-P), deciduous oaks), and hydrological variability (total inorganic carbon  
149 (TIC), Ca/K,  $\delta^{18}\text{O}_{\text{calcite}}$ ,  $\delta^{13}\text{C}_{\text{calcite}}$ ) show clear orbital-scale cyclicity, also characterized by a  
150 precessional (~21 ka) component (Fig. 2; Extended Data Figs 3, 4, and 5). During periods of  
151 global ice volume minima and NHSI maxima, we observe prominent peaks in the  
152 hydrological and vegetation proxy data (Fig. 2). We interpret these peaks in TIC (mainly from  
153 endogenic calcite) and Ca/K (a proxy for the concentration of calcite) to result from enhanced  
154 activity of, and ion supply from, the karst aquifers combined with higher aquatic productivity  
155 due to warmer conditions<sup>19</sup>. Pollen show a simultaneous increase in vegetation cover,  
156 particularly deciduous oaks, during early phases of interglacials. Deciduous oaks benefit from  
157 a limited length of the summer dry season<sup>21</sup>. Lower  $\delta^{13}\text{C}_{\text{calcite}}$  values during these periods  
158 suggest greater soil development, while lower  $\delta^{18}\text{O}_{\text{calcite}}$  (Extended Data Fig. 3) indicate more  
159 positive precipitation/evaporation (P/E) balance<sup>18</sup>. Thus, aquatic and terrestrial datasets  
160 suggest higher temperatures along with maxima in annual precipitation amount and potential  
161 shorter summer aridity during interglacials (Extended Data Fig. 4).

162 To provide a better understanding of the observed precipitation variability from the  
163 Lake Ohrid record in a regional context, we analysed climate data time series derived from a  
164 transient 784 kyr simulation using the earth system model LOVECLIM<sup>22,23</sup> (Extended Data  
165 Fig. 6) as well as NOAA reanalysis precipitation data of the Lake Ohrid region for the time  
166 period 1979–2017. Temperature time series of the 5°x5° Lake Ohrid grid cell simulated by  
167 the LOVECLIM earth system model closely resemble records of first-order global ice volume  
168 (Extended Data Fig. 3), such as the LR04 benthic oxygen isotope stack<sup>24</sup> ( $r=-0.8737$  or

169  $r^2=0.76$  based on 1000-year averages of both data sets). The close match to changes in the  
170 amount of detrital siliciclastics and tree pollen (AP-P) confirms the sensitivity of the Lake  
171 Ohrid record to global-scale climate fluctuations (Fig. 2; Extended Data Figs 3 and 4). The  
172 highest amplitudes in precipitation time series occur during phases of reduced ice volume,  
173 with prominent peaks during NHSI maxima. The significant positive relationship between  
174 simulated precipitation and our precipitation proxy time series ( $r^2=0.38$ ) and the persistence of  
175 the relationship with the orbital parameters (Extended Data Fig. 4) suggest that the local  
176 response recorded at Lake Ohrid also captures changes in regional hydroclimate back to 1.36  
177 Ma (Fig. 2).

178         Seen both in paleo records and in climate model simulations, the intensification of NH  
179 monsoon systems during precession minima and NHSI maxima is a prominent example of  
180 orbitally-forced changes in precipitation variability<sup>14,15,25</sup>. Iconic records of monsoon strength,  
181 such as the Chinese speleothem<sup>26</sup>, eastern Mediterranean sapropel<sup>12,13,26</sup> and planktonic  
182 foraminifera oxygen isotope records<sup>14,15,27</sup>, show a positive phase relationship with Lake  
183 Ohrid hydrological proxy time series (Fig. 2). Strengthening of NH monsoons results from a  
184 northward displacement of atmospheric circulation systems, including the position of the  
185 Hadley cells and the ITCZ during NH summer. The shift of the Hadley cell amplifies  
186 subsidence over, and persistence of, high-pressure systems in the Mediterranean region,  
187 leading to warmer and drier summers<sup>17</sup>, and higher sea-surface temperatures (SST)<sup>16,28</sup>.  
188 Reduced NHWI has highest impact on tropical and subtropical latitudes<sup>2</sup> and leads to low  
189 latitude cooling and a southward shift of the ITCZ and the NH Hadley and Ferrel cells.  
190 Furthermore, this cooling results in a reduced meridional temperature gradient leading to a  
191 weakening of the westerlies based on the thermal wind relationship. The observed  
192 relationship between the Lake Ohrid precipitation record (Fig. 2, Extended Data Figs 3 and 4)  
193 and the monsoon archives suggests increased precipitation during the winter half-year for this  
194 region when NHWI is low.

195           The Lake Ohrid record, in combination with the transient simulation time series and  
196 the NOAA reanalysis data, may provide fundamental insights into the mechanisms invoked  
197 by orbital forcing on Mediterranean precipitation. The monthly NOAA reanalysis data of the  
198 last 39 years show high precipitation anomalies (defined as above two standard deviations) to  
199 occur between the months of September and December (Extended Data Fig. 7a,b). The  
200 atmospheric pattern associated with these precipitation events exhibits a trough in the Gulf of  
201 Genoa region (Extended Data Fig. 7c), pointing to either increased cyclogenesis over or  
202 advection of North Atlantic low pressure into the western Mediterranean region.

203           The annual cycle of simulated Lake Ohrid precipitation in LOVECLIM is in good  
204 agreement with the reanalysis data; the model, however, underestimates the annual mean  
205 precipitation (Extended Data Fig. 8b). Maxima in our simulated precipitation time series  
206 (defined as above two standard deviations) indicate a positive anomaly from September to  
207 November (SON) in agreement with the reanalysis data (Fig. 3, Extended Data Fig. 8b).  
208 Despite important differences in the geographical expansion of geopotential height anomalies,  
209 both the NOAA and LOVECLIM data show pronounced troughs in the central Mediterranean  
210 area and an increase of rainfall during winter half-year in our focus region (Fig. 3). Our  
211 observations support previous modelling experiments suggesting that weakened atmospheric  
212 stratification and reduced hemispheric temperature contrasts<sup>2</sup>, in combination with an  
213 increased contrast between warm SST and lower continental air temperatures<sup>17</sup>, fuel  
214 precipitation increase in the Mediterranean. Such a preconditioning is particularly pronounced  
215 at the beginning of the fall, when the stronger thermal inertia of the sea relative to the land  
216 promotes local cyclogenesis<sup>17,29</sup>. Local cyclogenesis in combination with the southward shift  
217 in the NH atmospheric circulation cells during the winter half-year, which also favours a more  
218 southerly trajectory for storm tracks across the North Atlantic and into the Mediterranean<sup>2</sup>,  
219 lead to increased winter rainfall in the Mediterranean mid-latitudes.



220 Owing to the significant positive correlation between the simulation and our proxy  
221 time series (Extended Data Fig. 4), in terms of timing and amplitude, we infer that this  
222 mechanism primarily controlled precipitation at Lake Ohrid for the last 1.36 Myr. Indeed,  
223 similar to the NH summer monsoon records, we observe a strong influence of NHSI and a  
224 reduced winter temperature contrast in the NH throughout the entirety of our multiproxy time  
225 series, suggesting persistence of the mechanism during different climate boundary conditions.  
226 The positive phase relationship between the Lake Ohrid precipitation proxy time series and  
227 sapropel records (Fig. 2) indicates a strong coherence of African summer monsoon strength  
228 and widespread Mediterranean winter half-year precipitation. Some peaks in our precipitation  
229 proxy time series, which are not represented by sapropel layers (Fig. 2), may indicate lower  
230 monsoon strength and reduced runoff from the African continent or that the general setting  
231 required for sapropel deposition and preservation was not established in the Mediterranean  
232 Sea during these periods<sup>15</sup>. During colder and drier glacial periods<sup>3</sup> with increased global ice  
233 volume, lower atmospheric CO<sub>2</sub> concentrations, and stronger mid-latitude westerlies,  
234 insolation forcing on precipitation appears suppressed in our record. This is in agreement with  
235 the sensitivity simulations conducted to disentangle the individual effects of orbital forcing,  
236 NH ice sheets, and CO<sub>2</sub> on Lake Ohrid precipitation (Extended Data Fig. 6).

237 Precessional forcing on insolation is not only the key driver of the NH monsoons, it  
238 also exerts a strong control on precipitation variability in the Mediterranean mid-latitudes  
239 during the Quaternary. Lake Ohrid sediment cores record highly resolved and chronologically  
240 well-constrained information on precipitation maxima during phases of lower  
241 intrahemispheric temperature contrast and peak SST's over the last 1.36 Myr. The apparent  
242 equivalence of the past regional key drivers of precipitation extremes to those produced by  
243 continued anthropogenic increase of atmospheric GHG concentrations may help to reduce  
244 simulation uncertainties and makes these results also relevant to predictions for the future  
245 evolution of Mediterranean climate.

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247 **References:**

- 248 1. IPCC, 2013: Annex I: Atlas of Global and Regional Climate Projections [van  
249 Oldenborgh, G. J., M. Collins, J. Arblaster, J. H. Christensen, J. Marotzke, S. B. Power,  
250 M. Rummukainen and T. Zhou (eds.)]. In: Climate Change 2013: The Physical Science  
251 Basis. Contribution of Working Group I to the Fifth Assessment Report of the  
252 Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M.  
253 Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)].  
254 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA  
255 (2013).
- 256 2. Kutzbach, J. E., Chen, G., Cheng, H., Edwards, R. & Liu, Z. Potential role of winter  
257 rainfall in explaining increased moisture in the Mediterranean and Middle East during  
258 periods of maximum orbitally-forced insolation seasonality. *Clim. Dyn.* **42**, 1079–1095  
259 (2014). doi:10.1007/s00382-013-1692-1
- 260 3. Tzedakis, P. C., Hooghiemstra, H. & Pälike H. The last 1.35 million years at Tenaghi  
261 Philippon, revised chronostratigraphy and long-term vegetation trends. *Quat. Sci. Rev.*  
262 **25**, 3416–3430 (2006). doi:10.1016/j.quascirev.2006.09.002
- 263 4. Hoerling, M. et al. On the increased frequency of Mediterranean drought. *J. Climate* **25**,  
264 2146–2161 (2012). doi:10.1175/JCLI-D-11-00296.1
- 265 5. Weisheimer, A. & Palmer, T. N. On the reliability of seasonal climate forecasts. *J. Royal*  
266 *Soc., Interface* **11**, 20131162 (2014). doi.org/10.1098/rsif.2013.1162
- 267 6. Totz, S., Tziperman, E., Coumou, D., Pfeiffer, K. & Cohen, J. Winter Precipitation  
268 Forecast in the European and Mediterranean Regions Using Cluster Analysis. *Geophys.*  
269 *Res. Lett.* **44**, 12,418–12,426 (2017). doi.org/10.1002/2017GL075674

- 270 7. Milner, A. M. et al. Enhanced seasonality of precipitation in the Mediterranean during the  
271 early part of the Last Interglacial. *Geology* **40**, 919–922 (2012). doi:10.1130/G33204.1
- 272 8. Toucanne, S. et al. Tracking rainfall in the northern Mediterranean borderlands during  
273 sapropel deposition. *Quat. Sci. Rev.* **129**, 178–195 (2015).  
274 doi:10.1016/j.quascirev.2015.10.016
- 275 9. Stockhecke, M. et al. Millennial to orbital-scale variations of drought intensity in the  
276 Eastern Mediterranean. *Quat. Sci. Rev.* **133**, 77–95 (2016). doi: 10.1016/  
277 j.quascirev.2015.12.016
- 278 10. Roberts, N. et al. Stable isotope records of Late Quaternary climate and hydrology from  
279 Mediterranean lakes: the ISOMED synthesis. *Quat. Sci. Rev.* **27**, 2426–2441 (2008).  
280 doi:10.1016/j.quascirev.2008.09.005
- 281 11. Magny, M. et al. North–south palaeohydrological contrasts in the central Mediterranean  
282 during the Holocene: tentative synthesis and working hypotheses. *Clim. Past* **9**,  
283 2043–2071 (2013). doi:10.5194/cp-9-2043-2013
- 284 12. Emeis K.-C., Camerlenghi A., McKenzie J. A., Rio D. & Sprovieri R., The occurrence  
285 and significance of Pleistocene and Upper Pliocene sapropels in the Tyrrhenian Sea. *Mar.*  
286 *Geol.* **100**, 155–182 (1991). doi:10.1016/0025-3227(91)90231-R
- 287 13. Kroon, D. al. Oxygen isotope and sapropel stratigraphy in the Eastern Mediterranean  
288 during the last 3.2 million years, in *Proceedings of the Ocean Drilling Program.*  
289 *Scientific results*, A. H. F. Robertson, K.-C. Emeis, C. Richter, A. Camerlenghi. Eds.  
290 (College Station, Texas, 1998), vol. 160, pp 181–190 (1998).
- 291 14. Rossignol-Strick, M. Mediterranean Quaternary sapropels, an immediate response of the  
292 African monsoon to variation of insolation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*  
293 **49**, 237–263 (1985). doi:10.1016/0031-0182(85)90056-2

- 294 15. Rohling, E. J., Marino, G. & Grant, K. M. Mediterranean climate and oceanography, and  
295 the periodic development of anoxic events (sapropels). *Earth Sci. Rev.* **143**, 62–97  
296 (2015). doi:10.1016/j.earscirev.2015.01.008
- 297 16. Tzedakis, P. C. Seven ambiguities in the Mediterranean palaeoenvironmental narrative.  
298 *Quat. Sci. Rev.* **26**, 2042–2066 (2007). doi:10.1016/j.quascirev.2007.03.014
- 299 17. Bosmans, J. H. C. et al. Precession and obliquity forcing of the freshwater budget over  
300 the Mediterranean. *Quat. Sci. Rev.*, **123**, 16–30 (2015).  
301 doi:10.1016/j.quascirev.2015.06.008
- 302 18. Wagner, B. et al. The environmental and evolutionary history of Lake Ohrid  
303 (FYROM/Albania): Interim results from the SCOPSCO deep drilling project.  
304 *Biogeosciences* **14**, 2033–2054 (2017). doi:10.5194/bg-14-2033-2017
- 305 19. Vogel, H., Wagner, B., Zanchetta, G., Sulpizio, R. & Rosén, P. A paleoclimate record  
306 with tephrochronological age control for the last glacial-interglacial cycle from Lake  
307 Ohrid, Albania and Macedonia. *J. Paleolimnol.* **44**, 295–310 (2010).  
308 doi:10.1007/s10933-009-9404-x
- 309 20. Francke, A. et al. Sedimentological processes and environmental variability at Lake  
310 Ohrid (Macedonia, Albania) between 637 ka and the present. *Biogeosciences* **13**,  
311 1179–1196 (2016). doi:10.5194/bg-13-1179-2016
- 312 21. Forner, A. et al. Extreme droughts affecting Mediterranean tree species' growth and  
313 water-use efficiency: the importance of timing. *Tree Physiol.* **38**, 1127–1137 (2018).  
314 doi:10.1093/treephys/tpy022
- 315 22. Friedrich, T., Timmermann, A., Tigchelaar, M., Timm, O. E. & Ganopolski, A. Nonlinear  
316 climate sensitivity and its implications for future greenhouse warming. *Sci. Adv.* **2** (2016),  
317 p. e1501923. doi:10.1126/sciadv.1501923

- 318 23. Timmermann, A. & Friedrich, T. Late Pleistocene climate drivers of early human  
319 migration. *Nature* **538**, 92–95 (2016). doi:10.1038/nature19365
- 320 24. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed  
321 benthic  $\delta^{18}\text{O}$  records. *Paleoceanography* **20**, PA1003 (2005).  
322 doi:10.1029/2004PA001071
- 323 25. Cheng, H. et al. The Asian monsoon over the past 640,000 years and ice age  
324 terminations. *Nature* **534**, 640–646 (2016). doi:10.1038/nature18591
- 325 26. Konijnendijk, T. Y. M., Ziegler, M. & Lourens, L. J. Chronological constraints on  
326 Pleistocene sapropel depositions from high-resolution geochemical records of ODP Sites  
327 967 and 968. *Newslett. Stratigr.* **47**, 263–282 (2014). doi:10.1127/0078-0421/2014/0047
- 328 27. Colleoni, F., Masina, S., Negri, A. & Marzocchi, A. Plio–Pleistocene high–low latitude  
329 climate interplay: a Mediterranean point of view. *Earth Planet. Sci. Lett.* **319–320**, 35–44  
330 (2012). doi:10.1016/j.epsl.2011.12.020
- 331 28. Martrat, B., Jimenez-Amat, P., Zahn, R. & Grimalt J. O., Similarities and dissimilarities  
332 between the last two deglaciations and interglaciations in the North Atlantic region. *Quat.*  
333 *Sci. Rev.* **99**, 122–134 (2014). doi:10.1016/j.quascirev.2014.06.016
- 334 29. Trigo, R. M., Osborne, T. J. & Corte-Real, J. M. The North Atlantic Oscillation influence  
335 on Europe: climate impacts and associated physical mechanisms. *Clim. Res.* **20**, 9–17  
336 (2002). doi:10.3354/cr020009
- 337 30. Laskar, J. et al. A long-term numerical solution for the insolation quantities of the earth.  
338 *Astron. Astrophys.* **428**, 261–285 (2004). doi:10.1051/0004-6361:20041335  
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378

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384 at <https://climatedata.ibs.re.kr/grav/data/loveclim-784k>.

385

386 **Figure legends:**

387 **Fig. 1. Chronology and location of the Lake Ohrid DEEP site record.** (a) The age model  
388 is based on tephrostratigraphic correlation of 16 tephra layers to their radiometrically dated  
389 proximal deposits (red, first-order tie points) (b) tuning of total organic carbon (TOC) minima  
390 in the DEEP site record vs. inflection points in insolation and winter season length (blue,

391 second-order tie points), and cross evaluation of two paleomagnetic age reversals (a; dashed  
392 lines). The age model was calculated following the methodological approach for the upper  
393 247 meters composite depth (mcd) of the record<sup>20</sup> (see Methods). For the ages and errors of  
394 the tephra layers, see Extended Data Table 1. The tuning points (green) include an error of  
395  $\pm 2,000$  years. (c) The insert shows the location of Lake Ohrid and the approximate position of  
396 the intertropical convergence zone (ITCZ) in summer and winter.

397 **Fig. 2. Lake Ohrid precipitation indicators and global monsoon records for the last 1.4**  
398 **million years. (a)** Eastern Mediterranean (EM) Sapropel ages (green = sapropel, red = red  
399 interval/oxidized sapropel, violet = ghost sapropel)<sup>12,13,27</sup>; **(b)** Chinese Speleostack  $\delta^{18}\text{O}$ <sup>26</sup> in  
400 ‰ relative to VPDB; **(c)** Medstack  $\delta^{18}\text{O}$  planktonic<sup>28</sup> in ‰ relative to VPDB; SST=sea-  
401 surface temperature, SSS=sea-surface salinity; **(d)** Lake Ohrid  $\delta^{13}\text{C}$  endogenic calcite in ‰  
402 relative to VPDB; **(e)** Lake Ohrid deciduous oaks pollen percentage; **(f)** Lake Ohrid total  
403 inorganic carbon (TIC) concentrations; **(g)** Northern Hemisphere winter insolation difference  
404 between the tropic of cancer and the arctic circle<sup>30</sup>; **(h)** annual mean precipitation amount for  
405 the Lake Ohrid grid cell from the LOVECLIM simulation; **(i)** Lake Ohrid arboreal pollen  
406 excluding *Pinus* pollen (AP-P) percentages. Tenaghi Philippon arboreal pollen (AP)  
407 percentages<sup>3</sup> **(k)** and LR04 benthic  $\delta^{18}\text{O}$  stack<sup>25</sup> in ‰ relative to VPDB with odd numbers for  
408 interglacials **(l)** are shown for comparison. Red and white diamonds indicate the position of  
409 radiometrically dated tephra layers, blue and white diamonds the position of reversals of  
410 Earth's magnetic field in the Lake Ohrid sediment record.

411 **Fig. 3. Simulated Lake Ohrid precipitation and atmospheric anomaly pattern associated**  
412 **with precipitation maxima. (a)** Simulated precipitation ( $\text{cm yr}^{-1}$ ) for the Lake Ohrid grid  
413 cell. Data based on 1,000-year averages. Dashed line indicates two standard deviations above  
414 the mean. Red shading highlights precipitation values exceeding two standard deviations. See  
415 Methods for details on the model simulations. **(b)** Composite anomalies of September-



416 November (SON), 800 hPa geopotential height (m, shading) and wind ( $\text{m s}^{-1}$ , vectors)

417 associated with precipitation maxima shown in (a).

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423 **Methods:**

424 **Lake and lake hydrology**

425 Lake Ohrid (41°02'N, 20°43'E, 693 m a.s.l.; Fig. 1c) is located in the sub-Mediterranean  
426 climate zone with average monthly air temperature ranging from +26°C during summer to -  
427 1°C during winter. Precipitation in the Lake Ohrid watershed increases from 698 to 1,194 mm  
428 yr<sup>-1</sup> with increasing altitude and occurs primarily during winter months<sup>31</sup>. The lake is ~30 km  
429 long, ~15 km wide, and has a maximum water depth of 293 m (Extended Data Fig. 1).  
430 Sublacustrine karst springs (55%), direct precipitation, and river inflow (45%) constitute the  
431 water input. Due to an oligotrophic state, bottom waters remain partly oxygenated for several  
432 years, although the lake is oligomictic and a complete overturn occurs only every few years at  
433 present<sup>32</sup>.

434

435 **Sediment cores**

436 Sediment cores from the Lake Ohrid DEEP site were recovered in spring 2013, using the  
437 Deep Lake Drilling System (DLDS) of Drilling, Observation and Sampling of the Earth's  
438 Continental Crust (DOSECC) and within the framework of the multinational and  
439 interdisciplinary Scientific Collaboration on Past Speciation Conditions in Lake Ohrid  
440 (SCOPSCO) project that was co-sponsored by the International Continental Scientific Drilling  
441 Program (ICDP). The composite sediment record is based on 6 parallel boreholes that reached  
442 a terminal depth of 568 m<sup>33</sup>. Sediment recovery from 0 to 456.1 m composite depth (mcd) is  
443 99.8%. Small gaps occur between 204.719 and 204.804 mcd (8.5 cm) and between 447.89  
444 and 448.19 mcd (30 cm)<sup>33</sup>. Mass movement deposits (<3 cm) occur between 117 and 107  
445 mcd, and between 55 and 50 mcd. Subsampling in the upper 447.12 mcd excluded mass  
446 movement and tephra deposits.

447

448 **Scanning-X-ray fluorescence (XRF) analysis**

449 Scanning-XRF analysis was performed at the University of Cologne, Germany, on split core  
450 surfaces at 2.5 mm increments and 10 s dwell time using an ITRAX XRF core scanner (Cox  
451 Analytics) equipped with an energy dispersive silicon drift detector and a Cr-tube set to 30  
452 kV/30 mA. Raw data were processed and element-specific photon energy peaks were  
453 integrated in Q-spec (Cox Analytics).

454

#### 455 **Elemental analysis**

456 Elemental analysis was performed on 16-cm-spaced samples (2794 samples, ~480 yr)  
457 following freeze-drying and homogenization at the University of Cologne. For total carbon  
458 (TC) and total inorganic carbon (TIC) measurements, an aliquot of 40 mg of the homogenized  
459 sample material was dispersed in 10 ml deionized water. TC was determined at combustion of  
460 900°C and TIC was measured after treatment with 40% H<sub>3</sub>PO<sub>4</sub> at 160°C using a DIMATOC  
461 100 and a DIMATOC 200 (DIMATEC Corp., Germany). The total organic carbon (TOC)  
462 content was calculated as the difference between TC and TIC.

463

#### 464 **Fourier Transform Infrared Spectroscopy (FTIRS)**

465 Relative concentration changes for quartz were assessed using FTIRS, on samples spaced at  
466 32 cm (1462 samples, ~1,000 yr). Measurements were performed using a Bruker Vertex 70  
467 equipped with a LN<sub>2</sub>-cooled MCT (mercury-cadmium-telluride) detector, a KBr beam splitter,  
468 and a HTS-XT accessory unit (multisampler) in an air-conditioned laboratory at the  
469 University of Bern, Switzerland. For this purpose, 11 mg of each sample and 500 mg of oven-  
470 dried spectroscopic grade KBr (Uvasol®, Merck Corp.) were homogenized and scanned 64  
471 times at a resolution of 4 cm<sup>-1</sup> (reciprocal centimetres) for the wavenumber range from 3,750  
472 to 520 cm<sup>-1</sup> in diffuse reflectance mode. Data processing encompassed a linear baseline  
473 correction to remove baseline shifts and tilts by setting two points of the recorded spectrum to  
474 zero (3,750 and 2,210–2,200 cm<sup>-1</sup>). Peak areas diagnostic for symmetric stretching of SiO<sub>4</sub> in

475 quartz (778 and 798  $\text{cm}^{-1}$ ), and representative for relative abundance<sup>34,35</sup> were integrated  
476 using the OPUS (Bruker Corp.) software package.

477

#### 478 **Palynology processing and analysis**

479 Pollen analysis was carried out on sediment samples spaced at 64 cm (697 samples, ~2000 yr)  
480 following processing, identification, and counting approaches as described in<sup>36</sup>. Dry sediment  
481 (1.0–1.5 g) samples were treated with cold HCl (37% vol), cold HF (40% vol), and hot NaOH  
482 (10% vol) to dissolve carbonates, silicates, and humic acids, respectively. Glycerin-mounted  
483 residues were analysed by transmitted light microscopy to a mean of ~533 (incl. *Pinus*) and  
484 ~250 (excl. *Pinus*) grains/sample. Relative abundances are based on the total terrestrial pollen  
485 sum excl. *Pinus* due to overrepresentation and potential long-distance transport of this  
486 taxon<sup>36</sup>. Deciduous oak abundances represent the combined percentages of *Quercus robur* and  
487 *Q. cerris* types<sup>37</sup>, which is commonly used as an indicator for mid-elevation, relatively humid  
488 forest across the Mediterranean<sup>38,39,40,41</sup>.

489

#### 490 **Isotope analysis**

491 Oxygen and carbon isotopes were analysed on bulk carbonate (calcite)<sup>42</sup> in samples spaced at  
492 16 cm through zones of higher TIC (>0.5%), comprising a total of 1309 sediment samples.  
493 The samples were immersed in 5% NaClO solution for 24 h to gently disaggregate the  
494 sediment and oxidize reactive organic material. Potential biogenic carbonate was removed by  
495 sieving and the <64  $\mu\text{m}$  fraction washed with deionized water, dried at 40°C, and then ground  
496 to a fine powder in an agate mortar.  $\text{CO}_2$  was evolved from 10 mg  $\text{CaCO}_3$  powders by  
497 reaction with anhydrous  $\text{H}_3\text{PO}_4$  overnight inside a vacuum at a constant temperature of 25°C.  
498 The liberated  $\text{CO}_2$  was cryogenically purified under vacuum and collected for analysis on a  
499 VG Optima dual inlet mass spectrometer. Oxygen and carbon isotope values are reported in  
500 standard delta notation ( $\delta^{18}\text{O}_{\text{calcite}}$  and  $\delta^{13}\text{C}_{\text{calcite}}$ , respectively) in per mille (‰) calculated to

501 the Vienna Pee Dee Belemnite (VPDB) scale using a within-run laboratory standard (MCS)  
502 calibrated against international NBS standards. Analytical reproducibility for the within-run  
503 standard was  $<0.1\%$  ( $\pm 1\sigma$ ) for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ .

504

#### 505 **Magnetostratigraphic analyses**

506 Remanent magnetization in its natural state (NRM) and after step-wise alternating field  
507 demagnetization (10 steps up to 100 mT) was measured on ~900 discrete cube ( $6.3\text{ cm}^3$ )  
508 samples with an average 48-cm-spacing at the Paleomagnetic Laboratory at the  
509 GeoForschungsZentrum, Potsdam, Germany, using a 2G Enterprises cryogenic  
510 magnetometer. Paleomagnetic directions (declination and inclination) were calculated using  
511 principle component analysis (PCA) after removal of low-coercivity magnetic overprints.  
512 After identification of geomagnetic polarity transitions, ~500 additional samples were taken at  
513 2 to 3-cm-spacing across these transitions for high-resolution analysis at the Istituto Nazionale  
514 di Geofisica e Vulcanologia, Rome, Italy, using the same analytical set up and routine as in  
515 Potsdam. As glacial intervals of the core contain diagenetically formed greigite, which  
516 overprints the primary paleomagnetic signal<sup>43</sup>, paleomagnetic transitions are faithfully  
517 preserved only in interglacial intervals, at the base of the Jaramillo sub-Chron (373.8 mcd)  
518 and at the Matuyama/Brunhes (M/B) boundary (287.6 mcd).

519

#### 520 **Tephrostratigraphic analysis**

521 Eleven tephra and three cryptotephra layers have successfully been identified in the upper 247  
522 mcd of the record<sup>44,45,46</sup>. Two additional tephra layers from the lower ( $>247$  mcd) part of the  
523 DEEP site record are introduced here. The tephrostratigraphic correlation of these tephras is  
524 based on geochemical fingerprinting of single glass shards using Wavelength Dispersive  
525 Electron Microprobe Analysis (WDS-EPMA) as described in <sup>44</sup>.

526  $^{40}\text{Ar}/^{39}\text{Ar}$  dating was performed at the LSCE facility (CEA, UVSQ and University  
527 Paris-Saclay). V5 tephra (=OH-DP-2669 layer) was collected in Montalbano-Jonico  
528 (Southern Italy, N40°17'32.8''; E16°33'27.4''). Twenty pristine sanidine crystals, of the  
529 fraction 0.6-1.0 mm, were extracted from V5 and irradiated for 2 h in the Cd-lined, in-core  
530 CLICIT facility of the Oregon State University TRIGA reactor (Irradiation CO 001).  
531 Subsequently, 14 crystals were individually loaded in a copper sample holder and put into a  
532 double vacuum Cleartran window. Each crystal was individually fused using a Synrad CO<sub>2</sub>  
533 laser at 10-15% of nominal power (~50 W). The extracted gas was purified for 10 min by two  
534 hot GP 110 and two GP 10 getters (ZrAl). Ar isotopes ( $^{36}\text{Ar}$ ,  $^{37}\text{Ar}$ ,  $^{38}\text{Ar}$ ,  $^{39}\text{Ar}$  and  $^{40}\text{Ar}$ ) were  
535 analysed by mass spectrometry using a VG5400 equipped with an electron multiplier Balzers  
536 217 SEV SEN coupled to an ion counter. Neutron fluence J for each sample is calculated  
537 using co-irradiated Alder Creek Sanidine (ACs-2) standard with an age of 1.1891Ma<sup>47</sup> and  
538 the total decay constant of<sup>48</sup>. J-values computed from standard grains is  $0.00053220 \pm$   
539  $0.00000160$ . Mass discrimination was estimated by analysis of air pipette throughout the  
540 analytical period, and was relative to a  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of 298.56<sup>49</sup>.

541 Tephra OH-DP-2669 is a 2.5 cm thick, yellowish layer with sharp upper and lower  
542 boundaries comprising up to 500  $\mu\text{m}$  large platy glass shards and minor elongated  
543 micropumices. Its distinct trachytic composition (Extended Data Fig. 2) and the stratigraphic  
544 position between the M/B boundary (287.6 mcd) and OH-DP-2060 (Tufo di Bagni Albula,  
545 524.84 ka<sup>44</sup>; Extended Data Table1) narrow potential tephrostratigraphic equivalents. Tephra  
546 layer SC1-35.30/SUL2-1 from the Sulmona basin in the Italian Apennines is the only tephra  
547 with a similar trachytic composition<sup>50,51</sup> for this interval (Extended Data Fig. 2, Extended  
548 Data Table 2). SC1-35.30/SUL2-1 was correlated with tephra V5 from the MJS<sup>52,53</sup>. The  
549 majority of the SC1-35.30/SUL2-1 and OH-DP-2669 analyses correlate well with the more  
550 evolved group of V5 (V5b: SiO<sub>2</sub> >63% wt.; CaO <1.5% wt.). Only few analyses plot in the  
551 field of the less evolved group V5a (Extended Data Fig. 2, Extended Data Table 2). Tephra

552 layer SUL2-1 and V5 were  $^{40}\text{Ar}/^{39}\text{Ar}$  dated at  $722.8\pm 2.4$  ka<sup>50</sup> and  $719.5\pm 12.6$  ka<sup>53</sup>,  
553 respectively.  
554 The previous proposed correlation of SUL2-1/V5 with the Parmenide ash found in the  
555 Crotone basin<sup>50,52</sup> is not considered here due to a slightly younger  $^{40}\text{Ar}/^{39}\text{Ar}$  age of the  
556 Parmenide ash ( $710\pm 5$  ka)<sup>54,55,56</sup> and the differences in the geochemical data to OH-DP-2669  
557 (Extended Data Fig. 2, Extended Data Table 2).

558 Tephra OH-DP-2898 is a ~0.8 cm thick, whitish-yellowish band of lenses comprising  
559 fine-grained glass shards with a high degree of vesicularity and a phonolitic composition  
560 (Extended Data Fig. 2). It is located ~2 m below the M/B boundary, in calcareous sediments  
561 indicative for interglacial conditions<sup>20</sup>. The comparison of OH-DP-2898 glass composition  
562 with those of Sulmona tephra SUL2-19, -20, -25, -29 and -31 in a similar  
563 magnetostratigraphic position exclude a correlation (Extended Data Fig. 2). Other Sulmona  
564 tephra close to the M7B transition, SUL2-22, -23, and -27, have a composition similar to OH-  
565 DP-2898, but SUL2-23 has slightly lower alkali and higher CaO, FeO, TiO<sub>2</sub> concentrations  
566 (Extended Data Fig. 2, Extended Data Table 2). SUL2-27 is geochemically indistinguishable  
567 from OH-DP-2898, but deposited in glacial sediments of the MIS 20<sup>57</sup>. SUL2-22 is also  
568 geochemically indistinguishable from OH-DP-2898 and shares a similar stratigraphic position  
569 below the M/B boundary<sup>58,59</sup> and at the transition from MIS 20 to MIS 19<sup>57</sup>. A correlation of  
570 OH-DP-2898 with tephra V4 from the MJS is not possible due to differences in the  
571 compositional range (Extended Data Fig. 2, Extended Data Table 2) and a younger  $^{40}\text{Ar}/^{39}\text{Ar}$   
572 age of  $773.9\pm 1.3$  ka of V4<sup>52</sup>, quasi-synchronous position during the <sup>10</sup>Be peak or M/B  
573 transition<sup>60</sup>. Also a correlation of OH-DP-2898/SUL2-22 with tephra V3 of the MJS  
574 ( $801.2\pm 19.5$  ka) is excluded due to differences in the geochemical composition (Extended  
575 Data Fig. 2, Extended Data Table 2) and deposition of V3 during glacial conditions of MIS 20  
576 <sup>60</sup>. The Pitagora ash from the Crotone basin is found in a similar magneto- and  
577 climatostratigraphic position<sup>55,61,62</sup>, but differs geochemically from OH-DP-2898/SUL2-22.

578 Therefore, we regard a correlation of OH-DP-2898 with SUL2-22 as most robustly and use its  
579  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $791.9 \pm 1.9$  ka<sup>58</sup> for our chronology.

580 In addition to the new tephra correlations, we updated ages for the upper tephra layers  
581 (Extended Data Table 1). This update includes the Campanian Ignimbrite (Y-5/OH-DP-  
582 0169)<sup>63</sup> and tephra layers OH-DP-0404/POP2 and OH-DP-0435/X-6, based on new results  
583 from the Sulmona section<sup>64</sup>. The tephrostratigraphy of the Fucino record<sup>65</sup> improved and  
584 reassessed the correlations established for OH-DP-0617 and OH-DP-0624<sup>44</sup>.  $^{40}\text{Ar}/^{39}\text{Ar}$  dating  
585 of TF-17, correlated to OH-DP-0624, yielded a much more precise age of  $158.8 \pm 3.0$  ka,  
586 which replaced the age of Vico B/OH-DP-0617 ( $162 \pm 6$  ka)<sup>66</sup>.

587 Furthermore, the correlation of cryptotephra OH-DP-1700.6 with the Vico  $\beta$  eruption<sup>45</sup>  
588 provided a new chronological tie-point at  $410 \pm 2$  ka<sup>67</sup>. The previously established correlation  
589 of tephra layer OH-DP-1955 with tephra layer SC-5 from the Mercure basin<sup>44</sup> was rejected in  
590 the light of its large uncertainty ( $\pm 10.9$  ka) and the new tephrostratigraphic data.

591 Reassessment of the raw Ar-isotope data of SC1-35.30/SUL2-1, the equivalent to OH-  
592 DP-2669, by updating the value of the atmospheric Ar-composition ( $^{40}\text{Ar}/^{36}\text{Ar}$ : 298.5 instead  
593 of 295.5 originally) and removing xenocrysts<sup>58</sup> yielded a new age of  $715.02 \pm 5.4$  ka (Extended  
594 Data Table 1) using the decay constant of<sup>48</sup> and an age of 1.1891 Ma for the ACs-2 flux  
595 standard<sup>47</sup>. Our new  $^{40}\text{Ar}/^{39}\text{Ar}$  age of V5 ( $716.2 \pm 5.4$  ka; MSWD = 0.8, P = 0.7) is  
596 undistinguishable within uncertainty and thus used for our chronology. All other  $^{40}\text{Ar}/^{39}\text{Ar}$   
597 used were recalculated using the software ArAR<sup>68</sup> with a given decay constant and age for  
598 ACs-2 (1.1891 Ma) and Fish Canyon sanidines (FCs) ages of 28.294 Ma.

599

## 600 **Chronology**

601 Following the methodological approach for the upper 247 mcd of the record<sup>20</sup>, the chronology  
602 of the DEEP site sediment succession down to 447.12 mcd uses tephrochronological data<sup>44,45</sup>,  
603 <sup>46</sup> as 1<sup>st</sup>-order tie points and tuning of climate-sensitive proxy data (TOC; ~480 yr resolution)



604 against orbital parameters as 2<sup>nd</sup>-order tie points considering that maxima in TIC represent  
605 interglacial periods<sup>19,20</sup>. Some chronologically well-constrained tephra layers deposited at the  
606 DEEP site since the penultimate glacial period (Y-5, X-6, P-11, and A11/12) occur at depths  
607 where TOC shows minima at times of the perihelion passage in March<sup>20</sup>. These perihelion  
608 passages in March correspond to the inflection points of increasing local summer insolation  
609 (21<sup>st</sup> June) and winter-season length (number of days between the September and March  
610 equinoxes) at the latitude of Lake Ohrid (41°N; Fig. 1). Increasing summer insolation  
611 promotes high summer temperatures, primary productivity in the water column and increases  
612 organic matter (OM) supply to the sediments. An extended winter season improves lake-water  
613 mixing which enhances oxidation of OM in the water column and the surface sediments<sup>20</sup>.  
614 Thus, minima in TOC result from moderate OM supply to the sediments and improved  
615 oxidation of OM at the sediment surface and are due to their available high temporal  
616 resolution in the DEEP site record used for tuning purposes.

617 The independent chronological information obtained from the 16 tephra and  
618 cryptotephra layers and 66 2<sup>nd</sup>-order tie points obtained from orbital tuning were cross  
619 evaluated by the two paleomagnetic age constraints (base of the Jaramillo sub-Chron and  
620 Matuyama/Brunhes M/B; Fig. 1). The age model was calculated using Bacon 2.2<sup>69</sup>,  
621 considering overall uniform (mem.strength=60, mem.mean=0.9, thick=80 cm) sedimentation  
622 rates (acc.shape=1.5, acc. mean=20) at the DEEP site<sup>33</sup>. An error of ±2,000 years was applied  
623 to the 2<sup>nd</sup>-order tie points to account for tuning inaccuracy. The 95% confidence intervals of  
624 ages for specific depths produced by the Bacon Bayesian age modelling average at ±5,500  
625 years with a maximum of ±10,680 years. The resulting chronology implies that the upper  
626 447.12 m of the DEEP site record covers the last 1.364 Myr, continuously.

627 We<sup>20</sup> evaluated the DEEP site's chronology against the 0-160 ka U/Th dated Soreq  
628 Cave speleothem record<sup>70</sup> and found agreement within errors of the chronologies. Arboreal

629 pollen (AP) percentages in the DEEP site record are also in agreement with those from the  
630 orbitally-tuned Tenaghi Philippon record<sup>3</sup> back to 1.364 Ma (Fig. 2).

631

### 632 **Model simulations and forcing**

633 Transient simulations with the Earth system model LOVECLIM were conducted to study the  
634 impacts of orbital forcing, Northern Hemisphere (NH) ice sheets, and variations in  
635 atmospheric greenhouse gases (GHGs) on glacial-interglacial climate change.

636 LOVECLIM is a coupled ocean-atmosphere-sea ice-vegetation model<sup>71</sup>. The  
637 atmospheric component of LOVECLIM is the spectral T21, three-level model ECBilt<sup>72</sup> based  
638 on quasi-geostrophic equations extended by estimates of ageostrophic terms. The ocean-sea  
639 ice component of LOVECLIM consists of a free-surface Ocean General Circulation Model  
640 with a 3°x3° horizontal resolution coupled to a dynamic-thermodynamic sea-ice model<sup>73</sup>.

641 Atmosphere and ocean components are coupled through the exchange of freshwater and heat  
642 fluxes. The vegetation model VECODE<sup>74</sup> computes the evolution of terrestrial vegetation  
643 cover based on annual mean surface temperature and precipitation.

644 The transient simulations of the last 784,000 years were forced by time-dependent  
645 boundary conditions for orbital parameters, atmospheric GHG concentrations, NH ice sheet  
646 orography, and albedo following the methodology described in<sup>75</sup>. The orbital forcing was  
647 calculated according to<sup>76</sup>. Atmospheric GHG concentrations were prescribed according to  
648 reconstructions from EPICA Dome C for CO<sub>2</sub><sup>77</sup> as well as CH<sub>4</sub> and N<sub>2</sub>O<sup>78</sup>. Orbital forcing and  
649 atmospheric GHG concentrations were updated every model year. The effects of NH ice  
650 sheets on albedo and land topography were prescribed according to<sup>79</sup>. The forcing was applied  
651 with an acceleration factor of 5, which compresses 784,000 forcing years into 156,000 model  
652 years. This acceleration factor is appropriate for quickly equilibrating surface variables. The  
653 model simulation is an updated version of the one presented in<sup>75</sup> and uses a higher climate

654 sensitivity resulting in a better representation of the glacial-interglacial surface temperature  
655 amplitude<sup>23</sup>.

656 Four sensitivity simulations were conducted in addition to the full-forcing simulation  
657 described above (Extended Data Fig. 6). The sensitivity simulations cover the last four glacial  
658 cycles (408,000 years) and aim at exploring the individual effects of atmospheric GHGs, NH  
659 ice sheets and orbital parameters to glacial-interglacial climate change. The first sensitivity  
660 simulation uses transient forcing as described above but constant preindustrial (PI)  
661 atmospheric GHG concentrations. The “GHG effect” can then be calculated as the difference  
662 between the simulation using the full forcing and this simulation. The second sensitivity  
663 simulation uses transient forcing as described above but constant PI NH ice sheets (extent and  
664 albedo). The “NH ice sheet effect” is calculated as the difference between the full-forcing  
665 simulation and this simulation. Two simulations were designed to study the role of orbital  
666 forcing under warm and cold climate. For both simulations, transient orbital parameters are  
667 used. However, one simulation was run under constant PI atmospheric CO<sub>2</sub> concentration of  
668 280 ppm, whereas the second simulation uses a constant atmospheric CO<sub>2</sub> concentration of  
669 200 ppm resulting in a colder background climate.

670

## 671 **Data analysis**

672 To assess the temporal evolution of dominant periodicities in the DEEP site TIC and  
673 deciduous oak pollen percentage data, a wavelet power spectrum was computed for the  
674 respective time series. The time series were resampled at regular intervals (linear  
675 interpolation) at 0.3 kyr (TIC) and 1.0 kyr (pollen), and subsequently submitted to continuous  
676 wavelet transform (CWT, Morlet window) using PAST v.3.21 software<sup>80</sup> following the  
677 approach by <sup>81</sup>. Results of the CWT show persistent presence of 100 kyr and ~21 kyr orbital  
678 frequencies, and a clear presence of 41 kyr in the early half of the pollen record. Relative to

679 the pollen, the CWT results of the TIC show a more pronounced 100 kyr cyclicity over the  
680 entire record, and less pronounced 21 kyr signals.

681 To quantitatively test the observed correlation between deciduous oak and TIC  
682 maxima against precession forcing, the bandpass-filtered 18–25 kyr component of the proxy  
683 data was regressed against precession based on the La2004 orbital solution<sup>30</sup>.

684 Partial least squares regression (PLSR) was used to test the correlation of TIC and  
685 deciduous oaks as predictive variables with LOVECLIM temperature and precipitation output  
686 data. PLSR was performed using SIMCA 14 (Sartorius Stedim Biotech). All datasets were  
687 filtered using a frequency centred at 0.05 and a bandwidth of 0.02 prior to multivariate  
688 statistical analysis to accommodate for slight age offsets between proxy and simulation data.

689

#### 690 **Methods and Extended Data files references:**

691 31. Popovska, C. & Bonacci, O. Basic data on the hydrology of Lakes Ohrid and Prespa.

692 *Hydrol. Process.* **21**, 658–664 (2007). doi:10.1002/hyp.6252

693 32. Matzinger, A., Spirkovski, Z., Patceva, S. & Wüest A. Sensitivity of ancient Lake Ohrid

694 to local anthropogenic impacts and global warming, *J. Great Lakes Res.* **32**, 158–179

695 (2006). doi:10.3394/0380-1330(2006)32[158:SOALOT]2.0.CO;2

696 33. Wagner, B. et al. The SCOPSCO drilling project recovers more than 1.2 million years of

697 history from Lake Ohrid. *Sci. Drill.* **17**, 19–29 (2014). doi:10.5194/sd-17-19-2014

698 34. Farmer, V. C. The infrared spectra of minerals, edited by: V. C. Farmer, Mineralogical

699 Society Monograph 4, 227 pp, Adlard & Son, Dorking, Surrey, (1974).

700 35. Chukanov, N. V. *Infrared Spectra of Mineral Species*. Springer, Dordrecht, Heidelberg,

701 New York, London (2014). doi:10.1007/978-94-007-7128-4

- 702 36. Sadori, L. et al. Pollen-based paleoenvironmental and paleoclimatic change at Lake Ohrid  
703 (south-eastern Europe) during the past 500 ka. *Biogeosciences* **13**, 1423–1437 (2016).  
704 doi:10.5194/bg-13-1423-2016
- 705 37. Beug, H.-J. *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*.  
706 Verlag Dr. Friedrich Pfeil, München, Germany (2004).
- 707 38. Cheddadi, R. et al. Imprints of glacial refugia in the modern genetic diversity of *Pinus*  
708 *sylvestris*. *Global Ecol. Biogeogr.* **15**, 271–282 (2006). doi:10.1111/j.1466-  
709 8238.2006.00226.x
- 710 39. Rossignol-Strick, M. The Holocene climatic optimum and pollen records of sapropel 1 in  
711 the Eastern Mediterranean, 9000–6000 BP. *Quat. Sci Rev.* **18**, 515–530 (1999).  
712 doi:10.1016/S0277-3791(98)00093-6
- 713 40. Langgut, D., Almogi-Labin, A., Bar-Matthews, M. & Weinstein-Evron, M. Vegetation  
714 and climate changes in the South Eastern Mediterranean during the Last Glacial–  
715 Interglacial cycle (86 ka): new marine pollen record. *Quat. Sci Rev.* **30**, 3960–3972  
716 (2011). doi:10.1016/j.quascirev.2011.10.016
- 717 41. Combourieu-Nebout, N. et al. Climate changes in the central Mediterranean and Italian  
718 vegetation dynamics since the Pliocene. *Rev. Palaeobot. Palynol.* **218**, 127–147 (2015).  
719 doi:10.1016/j.revpalbo.2015.03.001
- 720 42. Lacey, J. H. et al. Northern Mediterranean climate since the Middle Pleistocene: a 637 ka  
721 stable isotope record from Lake Ohrid (Albania/Macedonia). *Biogeosciences* **13**,  
722 1801–1820 (2016). doi:10.5194/bg-13-1801-2016
- 723 43. Just, J. et al. Environmental control on the occurrence of high-coercivity magnetic  
724 minerals and formation of iron sulfides in a 640 ka sediment sequence from Lake Ohrid  
725 (Balkans). *Biogeosciences* **13**, 2093–2109 (2016). doi:10.5194/bg-13-2093-2016

- 726 44. Leicher, N. et al. First tephrostratigraphic results of the DEEP site record from Lake  
727 Ohrid (Macedonia and Albania). *Biogeosciences* **13**, 2151–2178 (2016). doi:10.5194/bg-  
728 13-2151-2016
- 729 45. Kousis, I. et al. Centennial-scale vegetation dynamics and climate variability in SE  
730 Europe during Marine Isotope Stage 11 based on a pollen record from Lake Ohrid. *Quat.*  
731 *Sci. Rev.* **190**, 20–38 (2018). doi:10.1016/j.quascirev.2018.04.014
- 732 46. Francke, A. et al. Sediment residence time reveals Holocene shift from climatic to  
733 vegetation control on catchment erosion in the Balkans. *Global Planet. Change* **177**,  
734 186–200. 2019. doi:10.1016/j.gloplacha.2019.04.005
- 735 47. Niespolo, E. M., Rutte, D., Deino, A. L. & Renne, P. R. Intercalibration and age of the  
736 Alder Creek sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  standard. *Quat. Geochronol.* **39**, 205–213 (2017).  
737 doi:10.1016/j.quageo.2016.09.004
- 738 48. Renne, P. R., Balco, G., Ludwig, K. R., Mundil, R. & Min, K. Response to the comment  
739 by W. H. Schwarz et al. on “Joint determination of  $^{40}\text{K}$  decay constants and  $^{40}\text{Ar}^*/^{40}\text{K}$  for  
740 the Fish Canyon sanidine standard, and improved accuracy for  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology”  
741 by P. R. Renne et al. (2010). *Geochim. Cosmochim. Acta* **75**, 5097–5100 (2011).  
742 doi:10.1016/j.gca.2010.06.017
- 743 49. Lee, J. Y. et al. A redetermination of the isotopic abundances of atmospheric Ar.  
744 *Geochim. Cosmochim. Acta* **70**, 4507–4512 (2006). doi:10.1016/j.gca.2006.06.1563
- 745 50. Giaccio, B. et al. Revised Chronology of the Sulmona Lacustrine Succession, Central  
746 Italy. *J. Quat. Sci.* **28**, 545–551 (2013). doi:10.1002/jqs.2647
- 747 51. Giaccio, B. et al. Tephra layers from Holocene lake sediments of the Sulmona Basin,  
748 Central Italy: implications for volcanic activity in Peninsular Italy and tephrostratigraphy

- 749 in the Central Mediterranean area. *Quat. Sci. Rev.* **28**, 2710–2733 (2009).  
750 doi:10.1016/j.quascirev.2009.06.009
- 751 52. Petrosino, P. et al. The Montalbano Jonico marine succession: An archive for distal  
752 tephra layers at the Early–Middle Pleistocene boundary in southern Italy. *Quat. Internat.*  
753 **383**, 89–103 (2015). doi:10.1016/j.quaint.2014.10.049
- 754 53. Ciaranfi, N. et al. Integrated stratigraphy and astronomical tuning of Lower–Middle  
755 Pleistocene Montalbano Jonico section (Southern Italy). *Quat. Internat.* **219**, 109–120  
756 (2010). doi:10.1016/j.quaint.2009.10.027
- 757 54. Massari, F. et al. Interplay between tectonics and glacio-eustasy: Pleistocene succession  
758 of the Crotone basin, Calabria (southern Italy). *Geol. Soc. Am. Bull.* **114**, 1183–1209  
759 (2002). doi:10.1130/0016-7606(2002)114<1183:IBTAGE>2.0.CO;2
- 760 55. Capraro, L. et al. Climatic patterns revealed by pollen and oxygen isotope records across  
761 the Matuyama-Brunhes Boundary in the central Mediterranean (southern Italy). *Geol.*  
762 *Soc., London, Spec. Publ.* **247**, 159–182 (2005). doi:10.1144/GSL.SP.2005.247.01.09
- 763 56. Capraro, L. et al. Chronology of the Lower–Middle Pleistocene succession of the south-  
764 western part of the Crotone Basin (Calabria, Southern Italy). *Quat. Sci. Rev.* **30**,  
765 1185–1200 (2011). doi:10.1016/j.quascirev.2011.02.008
- 766 57. Giaccio, B. et al. Duration and dynamics of the best orbital analogue to the present  
767 interglacial. *Geology* **43**, 603–606 (2015). doi:10.1130/G36677.1
- 768 58. Sagnotti, L. et al. Extremely rapid directional change during Matuyama-Brunhes  
769 geomagnetic polarity reversal. *Geophys. J. Internat.* **199**, 1110–1124 (2014).  
770 doi:10.1093/gji/ggu287

- 771 59. Sagnotti, L. et al. How fast was the Matuyama–Brunhes geomagnetic reversal? A new  
772 subcentennial record from the Sulmona Basin, central Italy. *Geophys. J. Internat.* **204**,  
773 798–812 (2016). doi:10.1093/gji/ggv486
- 774 60. Simon, Q. et al. Authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio signature of the Matuyama–Brunhes boundary  
775 in the Montalbano Jonico marine succession. *Earth Planet. Sci. Lett.* **460**, 255–267  
776 (2017). doi:10.1016/j.epsl.2016.11.052
- 777 61. Rio, D. et al. Reading Pleistocene eustasy in a tectonically active siliciclastic shelf setting  
778 (Crotona peninsula, southern Italy). *Geology* **24**, 743–746 (1996). doi:10.1130/0091-  
779 7613(1996)024<0743:RPEIAT>2.3.CO;2
- 780 62. Macri, P., Capraro, L., Ferretti, P. & Scarponi, D. A high-resolution record of the  
781 Matuyama-Brunhes transition from the Mediterranean region: The Valle di Manche  
782 section (Calabria, Southern Italy). *Phys. Earth Planet. Inter.* **278**, 1–15 (2018).  
783 doi:10.1016/j.pepi.2018.02.005
- 784 63. Giaccio, B., Hajdas, I., Isaia, R., Deino, A. & Nomade, S. High-precision  $^{14}\text{C}$  and  
785  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of the Campanian Ignimbrite (Y-5) reconciles the time-scales of  
786 climatic-cultural processes at 40 ka. *Sci. Rep.* **7**, 45940 (2017). doi:10.1038/srep45940
- 787 64. Regattieri, E., et al. A last Interglacial record of environmental changes from the  
788 Sulmona Basin (central Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **472**, 51–66  
789 (2017). doi:10.1016/j.palaeo.2017.02.013
- 790 65. Giaccio, B. et al. First integrated tephrochronological record for the last ~190 kyr from  
791 the Fucino Quaternary lacustrine succession, central Italy. *Quat. Sci. Rev.* **158**, 211–234  
792 (2017). doi:10.1016/j.quascirev.2017.01.004
- 793 66. Laurenzi, M. A. & Villa, I.  $^{40}\text{Ar}/^{39}\text{Ar}$  chronostratigraphy of Vico ignimbrites. *Period.*  
794 *Mineral.* **56**, 285–293 (1987)



- 795 67. Karner, D. B., Marra, F. & Renne, P. R. The history of the Monti Sabatini and Alban  
796 Hills volcanoes: groundwork for assessing volcanic-tectonic hazards for Rome. *J.*  
797 *Volcanol. Geotherm. Res.* **107**, 185–219 (2001). doi: 10.1016/S0377-0273(00)00258-4
- 798 68. Mercer, C. M. & Hodges, K.V. ArAR — A software tool to promote the robust  
799 comparison of K–Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates published using different decay, isotopic, and  
800 monitor-age parameters. *Chem. Geol.* **440**, 148–163 (2016).  
801 doi:10.1016/j.chemgeo.2016.06.020
- 802 69. Blaauw, M. & Christen, J. A. Flexible paleoclimate age-depth models using an  
803 autoregressive gamma process. *Bayes. Analys.* **6**, 457–474 (2011).  
804 doi:10.1214/ba/1339616472
- 805 70. Grant, K. M. et al. Rapid coupling between ice volume and polar temperature over the  
806 past 150,000 years. *Nature* **491**, 744–747 (2012). doi:10.1038/nature11593
- 807 71. Goosse, H. et al. Description of the Earth system model of intermediate complexity  
808 LOVECLIM version 1.2. *Geosci. Model Dev.* **3**, 603–633 (2010). doi:10.5194/gmd-3-  
809 603-2010
- 810 72. Opsteegh, J. D., Haarsma, R. J., Selten, F. M. & Kattenberg A. ECBILT: a dynamic  
811 alternative to mixed boundary conditions in ocean models. *Tellus, Ser. A, Dyn. Meterol.*  
812 *Oceanogr.* **50**, 348–367 (1998). doi:10.3402/tellusa.v50i3.14524
- 813 73. Goosse, H. & Fichefet, T. Importance of ice-ocean interactions for the global ocean  
814 circulation: A model study. *J. Geophys. Res.* **104**, 23337–23355 (1999).  
815 doi:10.1029/1999JC900215
- 816 74. Brovkin, V., Ganopolski, A. & Svirezhev, Y. A continuous climate-vegetation  
817 classification for use in climate-biosphere studies. *Ecol. Modell.* **101**, 251–261 (1997).  
818 doi:10.1016/S0304-3800(97)00049-5

- 819 75. Timmermann, A. et al. obliquity and CO<sub>2</sub> effects on Southern Hemisphere climate during  
820 the past 408 ka. *J. Clim.* **27**, 1863–1875 (2014). doi:10.1175/JCLI-D-13-00311.1
- 821 76. Berger, A. Long-term variations of daily insolation and Quaternary climate change. *J.*  
822 *Atmos. Sci.* **35**, 2362–2367 (1978). doi:10.1175/1520-  
823 0469(1978)035<2362:LTVODI>2.0.CO;2
- 824 77. Lüthi, D. et al. High-resolution carbon dioxide concentration record 650,000-800,000  
825 years before present. *Nature* **453**, 379–382 (2008). doi:10.1038/nature06949
- 826 78. EPICA community members. Eight glacial cycles from an Antarctic ice core. *Nature* **429**,  
827 623–628 (2004). doi:10.1038/nature02599
- 828 79. Ganopolski, A. & Calov, R. The role of orbital forcing, carbon dioxide and regolith in  
829 100 kyr glacial cycles. *Clim. Past*, **7**, 1415–1425 (2011). doi: 10.5194/cp-7-1415-2011
- 830 80. Hammer, O. PAleontological Statistics (PAST) Version 3.21 reference manual, Natural  
831 History Museum, University of Oslo (2018). <https://folk.uio.no/ohammer/past/>
- 832 81. Torrence, C. & Compo, G. P. A practical guide to wavelet analysis. *Bull. Am. Meteorol.*  
833 *Soc.* **79**, 61–78. (1998). doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2
- 834 82. Lindhorst, K. et al. Sedimentary and tectonic evolution of Lake Ohrid  
835 (Macedonia/Albania). *Basin Res.* **27**, 84–101 (2015). doi:10.1111/bre.12063
- 836 83. Melard, G. Algorithm AS 197: A fast algorithm for the exact likelihood of  
837 autoregressive-moving average models. *Appl. Stat.* **33**, 104–114 (1984).  
838 doi:10.2307/2347672
- 839 84. Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A. & Hawkesworth, C. J. Sea-  
840 land oxygen isotopic relationships from planktonic foraminifera and speleothems in the  
841 Eastern Mediterranean region and their implication for paleorainfall during interglacial

- 842 intervals. *Geochim. Cosmochim. Acta* **67**, 3181–3199 (2003). doi: 10.1016/S0016-  
843 7037(02)01031-1
- 844 85. Zanchetta, G. et al. Aligning and synchronization of MIS5 proxy records from Lake  
845 Ohrid (FYROM) with independently dated Mediterranean archives: implications for  
846 DEEP core chronology. *Biogeosciences*, **13**, 2757–2768 (2016). doi:10.5194/bg-13-2757-  
847 2016
- 848 86. Le Bas, M. J. Le Maitre, R. W. Streckeisen, A. & Zanettin, B. A Chemical Classification  
849 of Volcanic Rocks Based on the Total Alkali-Silica Diagram. *J. Petrol.* **27**, 745–750,  
850 (1986). doi:10.1093/petrology/27.3.745
- 851 87. Wagner, B. et al. The last 40 ka tephrostratigraphic record of Lake Ohrid, Albania and  
852 Macedonia: a very distal archive for ash dispersal from Italian volcanoes. *J. Volcanol.*  
853 *Geotherm. Res.* **177**, 71–80 (2008). doi:10.1016/j.jvolgeores.2007.08.018.
- 854 88. Zanchetta, G. et al. Tephrostratigraphy, chronology and climatic events of the  
855 Mediterranean basin during the Holocene: An overview. *Holocene* **21**, 33–52 (2011).  
856 doi:10.1177/0959683610377531
- 857 89. Siani, G., Sulpizio, R., Paterne, M. & Sbrana, A. Tephrostratigraphy study for the last  
858 18,000 C-14 years in a deep-sea sediment sequence for the South Adriatic. *Quat. Sci.*  
859 *Rev.* **23**, 2485–2500 (2004). doi:10.1016/j.quascirev.2004.06.004.
- 860 90. Albert, P. G. et al. Revisiting the Y-3 tephrostratigraphic marker: a new diagnostic glass  
861 geochemistry, age estimate, and details on its climatostratigraphical context, *Quat. Sci.*  
862 *Rev.* **118**, 105–121 (2015). doi:10.1016/j.quascirev.2014.04.002
- 863 91. Satow, C. et al. A new contribution to the Late Quaternary tephrostratigraphy of the  
864 Mediterranean: Aegean Sea core LC21, *Quat. Sci. Rev.* **117**, 96–112 (2015).  
865 doi:10.1016/j.quascirev.2015.04.005

- 866 92. Giaccio, B. et al. Isotopic (Sr-Nd) and major element fingerprinting of distal tephras: an  
867 application to the Middle-Late Pleistocene markers from the Colli Albani volcano, central  
868 Italy. *Quat. Sci. Rev.* **67**, 190–206 (2013). doi: 10.1016/j.quascirev.2013.01.028
- 869 93. Petrosino, P., Jicha, B. R., Mazzeo, F. C. & Russo Ermolli, E. A high resolution  
870 tephrochronological record of MIS 14–12 in the Southern Apennines (Acerno Basin,  
871 Italy). *J. Volcanol. Geotherm. Res.* **274**, 34–50 (2014).  
872 doi:10.1016/j.jvolgeores.2014.01.014
- 873 94. Marra, F., Karner, D. B., Freda, C., Gaeta, M. & Renne, P. Large mafic eruptions at  
874 Alban Hills Volcanic District (Central Italy): Chronostratigraphy, petrography and  
875 eruptive behavior. *J. Volcanol. Geotherm. Res.* **179**, 217–232 (2009).  
876 doi:10.1016/j.jvolgeores.2008.11.009

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### 879 **Data Availability**

880 Data are available in the main text, in the supplementary materials and in the Pangaea  
881 database at <https://doi.pangaea.de/10.1594/PANGAEA.896848>. Data used for LOVECLIM  
882 are available at <https://climatedata.ibs.re.kr/grav/data/loveclim-784k>.

883

### 884 **Code Availability**

885 Model data produced by the LOVECLIM simulations are available through the data centre of  
886 the IBS Center for Climate Physics: <https://climatedata.ibs.re.kr/grav/data/loveclim-784k>.  
887 Additional data are available upon request made to Tobias Friedrich ([tobiasf@hawaii.edu](mailto:tobiasf@hawaii.edu)).

888

### 889 **Extended Data Legends**

890 **Extended Data Figure 1 | Map of Lake Ohrid and its surrounding area.** Geology,  
891 topography, and bathymetry compiled from<sup>19,82</sup> and geological maps of Albania and North  
892 Macedonia. The lake is located at an altitude of 693 m a.s.l. and has a maximum water depth  
893 of 293 m. The water depth at the DEEP drill site is 240 m.

894

895 **Extended Data Figure 2 | Correlation of tephra layers at the DEEP site with tephra**  
896 **layers found in mid-distal records.** Bi-oxide plots of (a) CaO vs. FeO<sub>total</sub>, (b) CaO vs.  
897 Al<sub>2</sub>O<sub>3</sub>, (c) CaO vs. TiO<sub>2</sub>, (d) Na<sub>2</sub>O vs. K<sub>2</sub>O, and (e) total alkali vs. silica (TAS) diagram<sup>86</sup>  
898 show the correlation of OH-DP-2669 with the tephra layers SC1-35.30/SUL2-1/V5 and the  
899 differences to the Parmenide ash. Bi-oxide plots of (f) CaO vs. FeO<sub>total</sub>, (g) CaO vs. Al<sub>2</sub>O<sub>3</sub>, (h)  
900 CaO vs. TiO<sub>2</sub>, (i) Na<sub>2</sub>O vs. K<sub>2</sub>O, and (k) TAS diagram show the correlation of OH-DP-2898  
901 with tephra SUL2-22 and the differences to SUL2-23, -27, -31, V4, V3, and the Pitagora ash.  
902 Error bars of the Parmenide Ash refer to<sup>54</sup>. Tephra ages, geochemical data, tephrostratigraphic  
903 discussion and references are provided in Extended Data Tables 1 and 2 and in Methods.

904

905 **Extended Data Figure 3 | Lake Ohrid LOVECLIM simulation data and sedimentary**  
906 **paleoclimate and paleoenvironment proxies.** (a) Simulated surface-air temperature (SAT)  
907 for the Lake Ohrid grid cell from the LOVECLIM simulation; (b) simulated precipitation  
908 amount for the Lake Ohrid grid cell from the LOVECLIM simulation; (c) Lake Ohrid total  
909 organic carbon (TOC) concentrations; (d) Lake Ohrid  $\delta^{13}\text{C}$  endogenic calcite in ‰ relative to  
910 VPDB; (e) Lake Ohrid  $\delta^{18}\text{O}$  endogenic calcite in ‰ relative to VPDB; (f) Lake Ohrid relative  
911 sedimentary quartz content; (g) Lake Ohrid K intensities in kilo counts and displayed using a  
912 11pt running mean; (h) Lake Ohrid ratio of Ca/K intensities displayed using a 11 pt running  
913 mean; (i) Lake Ohrid Ca intensities in kilo counts and displayed using a 11 pt running mean;  
914 (k) Lake Ohrid total inorganic carbon (TIC) concentrations; (l) Lake Ohrid deciduous oaks  
915 pollen percentages; (m) Lake Ohrid arboreal pollen excluding *Pinus* pollen (AP-P)

916 percentages; red and white diamonds indicate the position of radiometrically dated tephra  
917 layers, blue and white diamonds the position of reversals of Earth's magnetic field in the Lake  
918 Ohrid sediment record. (b), (d), (e), (K), (l) and (m) are from Fig. 2.

919

920 **Extended Data Figure 4 | Data analysis.** Continuous wavelet transform results for  
921 percentages of total inorganic carbon (TIC; **a**) and deciduous oak pollen (**b**) time series from  
922 Ohrid DEEP where colour represents the signal amplitude at a given time and spectral period  
923 (yellow highest, red lowest power). Black contour is the 5% significance level (chi-squared  
924 test according to <sup>81</sup>) against a red-noise background spectrum with autocorrelation coefficient  
925 of 0.95, estimated through an autoregressive–moving-average (ARMA) model implemented  
926 in PAST (<sup>80</sup> based on <sup>83</sup>). Thick grey line indicates the “cone of influence” outside of which  
927 boundary effects can influence the results. Least squares regression (red line) between band  
928 pass-filtered 18-25 ky component of (**c**) % TIC and (**d**) the % deciduous oak against  
929 precession at 1 ky resolution. Blue lines indicate 95% bootstrapped (n=1999) confidence  
930 intervals. Results show significant negative relationships for both proxies, with a stronger  
931 response (steeper slope) of the deciduous oaks. Partial least squares regression (PLSR) using  
932 TIC and deciduous oaks as predictive variables and LOVECLIM (**e**) temperature and (**f**)  
933 precipitation output data as observations. PLSR was performed using SIMCA 14 (Sartorius  
934 Stedim Biotech). All datasets were filtered using a frequency centred at 0.05 and a bandwidth  
935 of 0.02 prior to multivariate statistical analysis to accommodate for slight offsets in age  
936 differences between proxy and simulation data. Results show highly significant positive  
937 correlations of simulated temperatures (e) and of simulated precipitation (f) data to proxy  
938 data, with a higher sensitivity of TIC and deciduous oaks towards changes in precipitation  
939 compared to temperature.

940

941 **Extended Data Figure 5 | Lake Ohrid precipitation indicators and global monsoon**  
942 **records during MIS 5. (a)** Ages of sapropels and humid phases in the Eastern Mediterranean  
943 based on Soreq Cave speleothem  $\delta^{18}\text{O}$  data and U/Th chronology<sup>84</sup>; **(b)** simulated  
944 precipitation amount for the Lake Ohrid grid cell from the LOVECLIM simulation; **(c)** Lake  
945 Ohrid deciduous oaks pollen percentage; **(d)** Lake Ohrid total inorganic carbon (TIC)  
946 concentrations; **(e)** Chinese Speleostack  $\delta^{18}\text{O}^{25}$  in ‰ relative to VPDB; red and white  
947 diamonds indicate the position of radiometrically dated tephra layers in the Lake Ohrid  
948 record. The chronology of the MIS 5 interval in the Lake Ohrid DEEP site record is based on  
949 <sup>85</sup>.

950

951 **Extended Data Figure 6 | Simulated Lake Ohrid precipitation for full-forcing run and**  
952 **sensitivity simulations. (a)** Lake Ohrid precipitation ( $\text{cm yr}^{-1}$ ) for full-forcing simulation  
953 (black) and a simulation using only orbital forcing under a warm background climate (red).  
954 **(b)** Black line as in (a) and a simulation using only orbital forcing under a cold background  
955 climate (blue). **(c)** Black line as in (a) and a simulation using full-forcing except for a constant  
956 preindustrial NH ice sheet. **(d)** Black line as in (a) and a simulation using full-forcing except  
957 for constant preindustrial GHG concentrations. Please note that the sensitivity simulations  
958 only cover the last 408 kyr. Please see Methods for details on the sensitivity simulations.

959

960 **Extended Data Figure 7 | NOAA reanalysis data for the Mediterranean region. (a)**  
961 Reconstructed precipitation ( $\text{cm yr}^{-1}$ ) for the Lake Ohrid reanalysis grid cell. Data based on  
962 monthly means. Dashed line indicates two standard deviations above the mean. **(b)** Composite  
963 anomalies of 850 hPa geopotential height (m) associated with Lake Ohrid precipitation  
964 maxima shown in (a) and referring to the months shown in (c). **(c)** Monthly distribution of  
965 precipitation maxima shown in (a).

966

967 **Extended Data Figure 8 | Mean seasonal cycle of Lake Ohrid precipitation - model**  
968 **simulation and NOAA reanalysis data. (a)** Mean seasonal cycle of simulated Lake Ohrid  
969 precipitation (cm yr<sup>-1</sup>) for all model years (green) and model years with annual-mean  
970 precipitation exceeding two standard deviations (magenta). Please see also Fig. 3a. **(b)** Mean  
971 seasonal cycle of Lake Ohrid precipitation (cm yr<sup>-1</sup>) derived from NOAA reanalysis data  
972 (blue) and simulated for the 1–0 kyr period (red). The annual means were removed for better  
973 comparison and are provided in the panel.

974

975 **Extended Data Table 1 | Selected tephra layers from Lake Ohrid and their correlation**  
976 **with tephra layers of other records.** <sup>40</sup>Ar/<sup>39</sup>Ar ages from literature were recalculated using a  
977 decay constant<sup>73</sup> and Alder Creek sanidine (ACs-2) at 1.1891 Ma<sup>74</sup> or Fish Canyon sanidine  
978 (FCs) at 28.294 Ma<sup>73</sup>. Tephra ages in bold are used for age-depth modelling in Fig. 1. Age  
979 uncertainties are provided according to the original reference (Reference age).

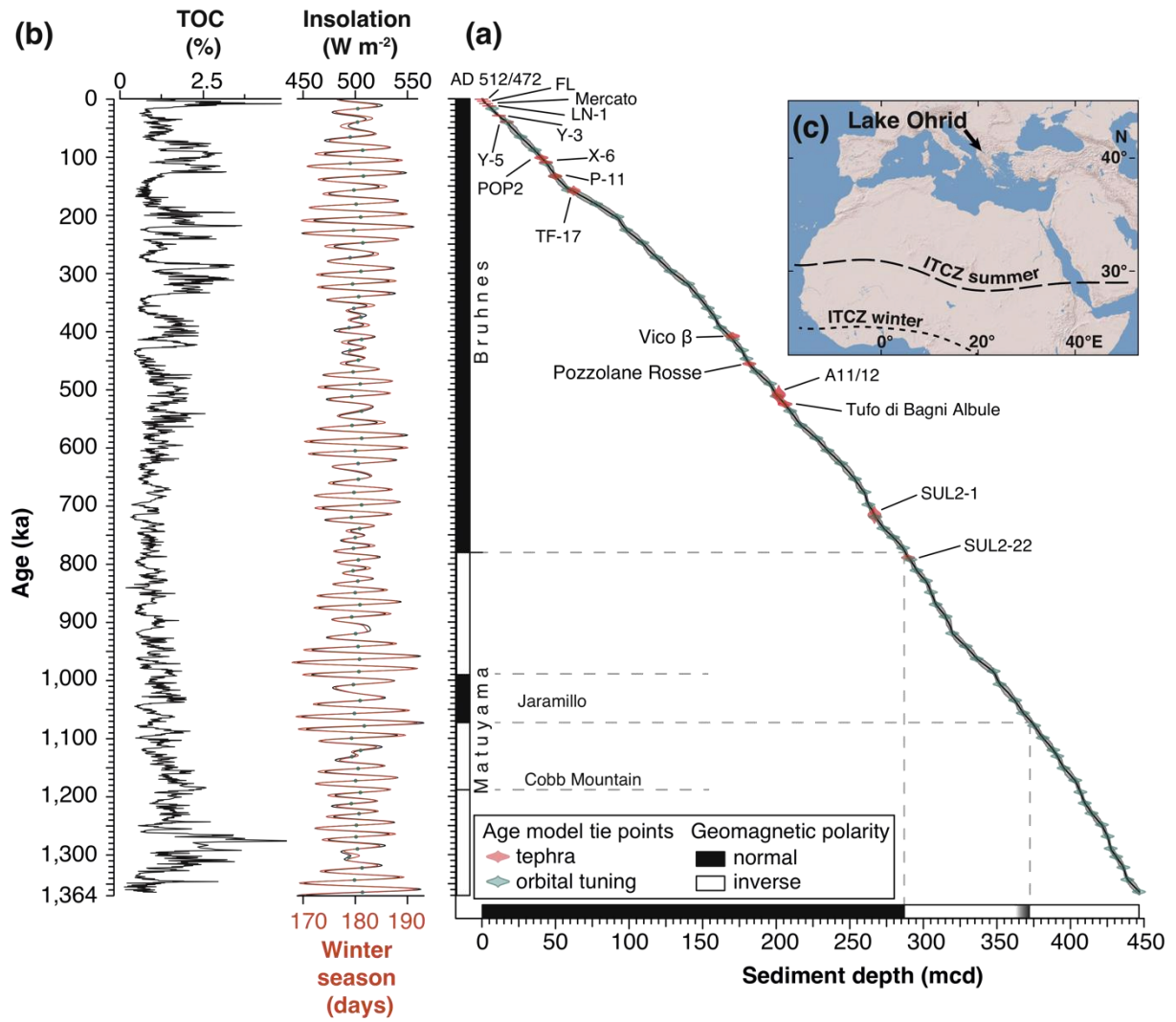
980

981 **Extended Data Table 2 | Average compositions of OH-DP-2669 and OH-DP-2898 and**  
982 **potential equivalent correlations.** Data of SUL2-1, SUL2-22, SUL2-23, SUL2-27 from <sup>51</sup>;  
983 SC1-35.50 from <sup>50</sup>; V5, V4, V3, Pitagora ash from <sup>52</sup> and the Parmenide ash from <sup>54</sup>.  $\bar{x}$  =  
984 mean; S = standard deviation; n= number of analysis.

985

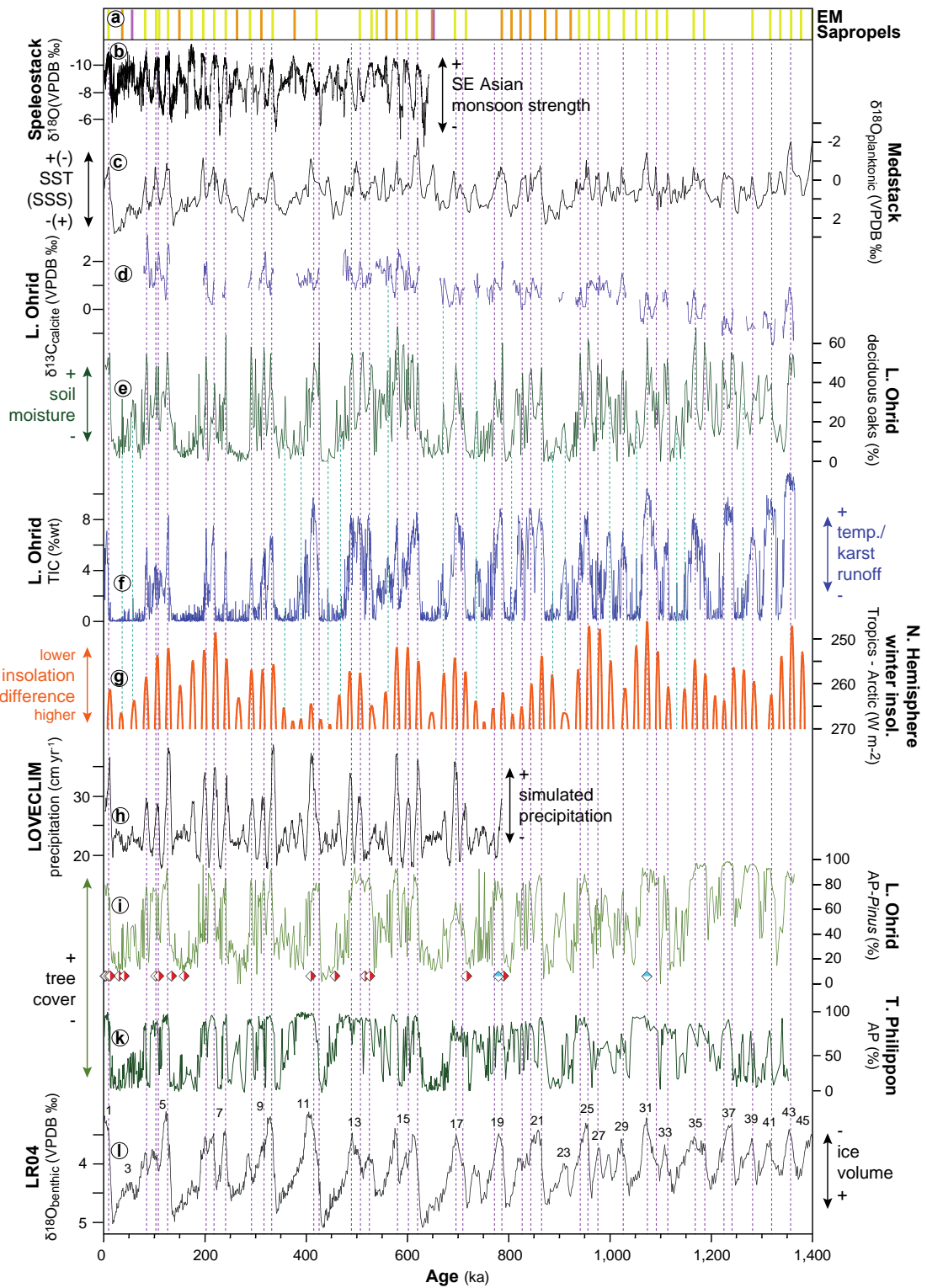


986 **Fig. 1**  
 987



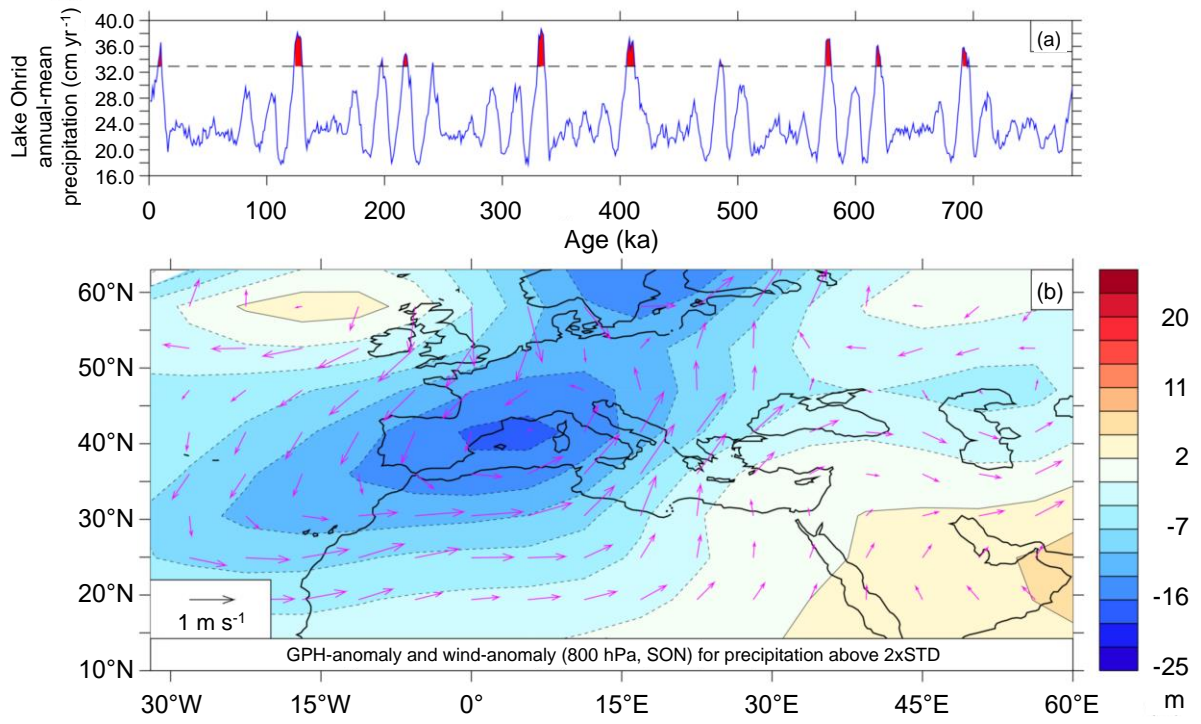
988  
 989

990 Fig. 2  
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995 **Fig. 3**  
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997