

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

3 Bernd Wagner^{1*†}, Hendrik Vogel^{2†}, Alexander Francke^{1,3}, Tobias Friedrich⁴, Timme
4 Donders⁵, Jack H. Lacey⁶, Melanie J. Leng^{6,7}, Eleonora Regattieri^{8,9}, Laura Sadori¹⁰, Thomas
5 Wilke¹¹, Giovanni Zanchetta⁸, Christian Albrecht¹¹, Adele Bertini¹², Nathalie Combourieu-
6 Nebout¹³, Aleksandra Cvetkoska^{5, 11}, Biagio Giaccio¹⁴, Andon Grazhdani¹⁵, Torsten Hauffe¹¹,
7 Jens Holtvoeth¹⁶, Sebastien Joannin¹⁷, Elena Jovanovska¹¹, Janna Just^{1,18}, Katerina Kouli¹⁹,
8 Ilias Kousis²⁰, Andreas Koutsodendris²⁰, Sebastian Krastel²¹, Niklas Leicher¹, Zlatko
9 Levkov²², Katja Lindhorst²¹, Alessia Masi¹⁰, Martin Melles¹, Anna M. Mercuri²³, Sebastien
10 Nomade²⁴, Norbert Nowaczyk²⁵, Konstantinos Panagiotopoulos¹, Odile Peyron¹⁷, Jane M.
11 Reed²⁶, Leonardo Sagnotti²⁷, Gaia Sinopoli¹⁰, Björn Stelbrink¹¹, Roberto Sulpizio^{28,29}, Axel
12 Timmermann^{30,31}, Slavica Tofilovska²², Paola Torri³², Friederike Wagner-Cremer⁵, Thomas
13 Wonik³³, Xiaosen Zhang³⁴

14 ¹Institute of Geology and Mineralogy, University of Cologne, Cologne, Germany.

15 ²Institute of Geological Sciences & Oeschger Centre for Climate Change Research,
16 University of Bern, Bern, Switzerland.

17 ³School of Earth, Atmospheric, and Life Science, University of Wollongong, Wollongong,
18 Australia.

19 ⁴International Pacific Research Center, University of Hawaii at Manoa, Honolulu, Hawaii,
20 USA.

21 ⁵Palaeoecology, Department of Physical Geography, Utrecht University, Utrecht, The
22 Netherlands.

23 ⁶National Environmental Isotope Facility, British Geological Survey, Nottingham, UK.

24 ⁷Centre for Environmental Geochemistry, School of Biosciences, University of Nottingham,
25 UK.

26 ⁸Dipartimento di Scienze della Terra, University of Pisa, Pisa, Italy.

27 ⁹Institute of Earth Sciences and Earth Resources-Italian National Research Council (IGG-
28 CNR), Pisa, Italy.

29 ¹⁰Dipartimento di Biologia Ambientale, Università di Roma "La Sapienza", Rome, Italy.

30 ¹¹Department of Animal Ecology & Systematics, Justus Liebig University Giessen, Giessen,
31 Germany.

32 ¹²Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy.

33 ¹³CNRS UMR 7194, Muséum National d'Histoire Naturelle, Institut de Paléontologie
34 Humaine, Paris, France.

35 ¹⁴Istituto di Geologia Ambientale e Geoingegneria – CNR, Rome, Italy.

36 ¹⁵Faculty of Geology and Mineralogy, University of Tirana, Albania.

37 ¹⁶School of Chemistry, University of Bristol, Bristol, UK.

38 ¹⁷CNRS UMR 5554, Institut des Sciences de l'Evolution de Montpellier, Université de
39 Montpellier, Montpellier, France.

40 ¹⁸Fachbereich Geowissenschaften, Universität Bremen, Bremen, Germany.

41 ¹⁹Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens,
42 Athens, Greece.

43 ²⁰Paleoenvironmental Dynamics Group, Institute of Earth Sciences, Heidelberg University,
44 Heidelberg, Germany.

45 ²¹Institute of Geosciences, Christian-Albrechts-Universität zu Kiel, Kiel, Germany.

46 ²²University Ss Cyril and Methodius, Institute of Biology, Skopje, FYROM.

47 ²³Dipartimento di Scienze della Vita, Laboratorio di Palinologia e Paleobotanica, Università
48 di Modena e Reggio Emilia, Modena, Italy.

49 ²⁴Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212, CEA/CNRS/UVSQ
50 et Université Paris-Saclay, Gif-Sur-Yvette, France.

51 ²⁵Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam,
52 Germany.

53 ²⁶ The Department of Geography, Geology and Environment, University of Hull, Hull, UK.

54 ²⁷Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

55 ²⁸Dipartimento di Scienze della Terra e Geoambientali, University of Bari, Bari, Italy.

56 ²⁹IDPA-CNR, Milan, Italy.

57 ³⁰Center for Climate Physics, Institute for Basic Science, Busan, South Korea

58 ³¹Pusan National University, Busan, South Korea

59 ³²Dipartimento di Scienze della Vita, Laboratorio di Palinologia e Paleobotanica, Università
60 di Modena e Reggio Emilia, Modena, Italy.

61 ³³Leibniz Institute for Applied Geophysics (LIAG), Hannover, Germany.

62 ³⁴Institute of Loess Plateau, Shanxi University, Taiyuan, China.

63

64 *Correspondence to: wagnerb@uni-koeln.de.

65 † these authors contributed equally to this work.

66

67

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 constrained¹. Only a few continental proxy records capable of capturing hydroclimate
73 change cover multiple Northern Hemisphere summer insolation maxima^{2,3} 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 CO₂ 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.

86

87

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 contributors⁴. 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 century¹. 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^{5,6}.

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^{2,7,8,9}. 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^{10,11}, 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^{2,3}. 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^{12,13}. 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^{14,15}. 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^{15,16}. Modelling experiments explain increased winter precipitation by
121 stronger wintertime storm tracks² or air-sea temperature difference, and locally induced
122 convective precipitation that dominate freshwater budget changes on obliquity time scales¹⁷.
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^{7,8,16}. 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 borderlands¹⁸.
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 Ca²⁺ and
138 HCO₃⁻) to the lake and filters particulate matter¹⁹. 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^{18,20}. 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 conditions¹⁹. 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 season²¹. 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) balance¹⁸. 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^{22,23} (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 $5^\circ \times 5^\circ$ 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 stack²⁴ ($r = -0.8737$ 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^{14,15,25}. Iconic records of monsoon strength,
181 such as the Chinese speleothem²⁶, eastern Mediterranean sapropel^{12,13,26} and planktonic
182 foraminifera oxygen isotope records^{14,15,27}, 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 summers¹⁷, and higher sea-surface temperatures (SST)^{16,28}.
188 Reduced NHWI has highest impact on tropical and subtropical latitudes² 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 contrasts², in combination with an
213 increased contrast between warm SST and lower continental air temperatures¹⁷, 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^{17,29}. 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 Mediterranean²,
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 periods¹⁵. During colder and drier glacial periods³ with increased global ice
233 volume, lower atmospheric CO₂ 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 CO₂ 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.

246

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
- 339
- 340

341 **Acknowledgments:** The Hydrobiological Institute in Ohrid (S. Trajanovski and G. Kostoski)
342 and the Hydrometeorological Institute in Tirana (M. Sanxhaku and B. Lushaj) provided
343 logistic support for site surveys and the scientific drilling campaign. Drilling was carried out
344 by Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC). A.
345 Skinner provided logistic and technical advice prior and during drilling operation. The
346 Scientific Collaboration on Past Speciation Conditions in Lake Ohrid (SCOPSCO) drilling
347 project was funded by the International Continental Scientific Drilling Program (ICDP), the
348 German Ministry of Higher Education and Research, the German Research Foundation, the
349 University of Cologne, the British Geological Survey, the INGV and CNR (both Italy), and
350 the governments of the republics of North Macedonia and Albania. V. Scao collected the V5
351 tephra, which was $^{40}\text{Ar}/^{39}\text{Ar}$ dated with funding from LEFE "INTERMED" grant (CNRS-
352 INSU) to S. Nomade.

353

354 **Author Contributions:** B Wagner and H Vogel designed the study and contributed equally.
355 BW initiated and coordinated the SCOPSCO drilling project and drilling campaign. HV
356 conceived major scientific ideas of this study. A Francke (sedimentology, chronology), T
357 Friedrich (LOVECLIM modelling), T Donders (palynology), J Lacey (isotope geochemistry),
358 and L Sadori (palynology) contributed and oversaw key datasets used in the study. They
359 coordinated together with F Cremer-Wagner, M Leng, E Regattieri, T Wilke and G Zanchetta
360 discussion and interpretations of proxy data groups and model results. Specific data were
361 provided by A Bertini (pollen, MIS 19–21, MIS 25–28, MIS 42–43), N Combourieu-Nebout
362 (pollen, MIS 1–4, MIS 8, MIS 14–15), B Giaccio (tephrostratigraphy), S Joannin (pollen,
363 MIS 1–4, MIS 13–16, MIS 30), J Just (paleomagnetic data), K Kouli (pollen, MIS 6–8, MIS
364 10, MIS 16–19, MIS 28–30, MIS 33), I Kousis (pollen, MIS 11–12, MIS 15), A
365 Koutsodendris (pollen, MIS 11–12, MIS 15), N Leicher (tephrostratigraphy), A Masi (pollen,

366 MIS 5–6, MIS 20–25, MIS 31–32), A M Mercuri (pollen, MIS 6, MIS 34), S Nomade
367 (tephrochronology), N Nowaczyk (paleomagnetic data), K Panagiotopoulos (pollen, MIS 7–8,
368 MIS 35–43), O Peyron (pollen, MIS 1–4, MIS 13–16, MIS 30), L Sagnotti (paleomagnetic
369 data), G Sinopoli (pollen, MIS 5–6), R Sulpizio (tephrostratigraphy) and P Torri (pollen MIS
370 6, MIS 34). S Krastel, K Lindhorst, and T Wonik coordinated the seismic survey of Lake
371 Ohrid, the selection of the coring location and the geophysical measurements needed for core
372 correlation. A Grazhdani, M Melles, J Reed, and Z Levkov contributed to the conception of
373 the work. A Cvetkoska, J Holtvoeth, E Jovanvoska, S Tofilovska, and X Zhang provided
374 micropaleontological and organic geochemistry data, which confirmed that the sediment
375 succession from the DEEP site covers the entire history of Lake Ohrid. A Timmermann
376 provided model infrastructure and resources. All authors contributed to the discussion and
377 interpretation of the data and provided comments and suggestions to the manuscript.

378

379 **Author Information:** Reprints and permissions information is available at
380 www.nature.com/reprints. Authors declare no competing interests. Correspondence and
381 requests for materials should be addressed to wagnerb@uni-koeln.de. Data are available in
382 the main text, in the supplementary materials and in the Pangaea database at
383 <https://doi.pangaea.de/10.1594/PANGAEA.896848>. Data used for LOVECLIM are available
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 record²⁰ (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)^{12,13,27}; **(b)** Chinese Speleostack $\delta^{18}\text{O}$ ²⁶ in
400 ‰ relative to VPDB; **(c)** Medstack $\delta^{18}\text{O}$ planktonic²⁸ 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 circle³⁰; **(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 percentages³ **(k)** and LR04 benthic $\delta^{18}\text{O}$ stack²⁵ 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 (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 (m s^{-1} , vectors)

417 associated with precipitation maxima shown in (a).

418

419

420

421

422

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⁻¹ with increasing altitude and occurs primarily during winter months³¹. 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 present³².

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 m³³. 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)³³. 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% H₃PO₄ 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 LN₂-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⁻¹ (reciprocal centimetres) for the wavenumber range from 3,750
472 to 520 cm⁻¹ 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⁻¹). Peak areas diagnostic for symmetric stretching of SiO₄ in

475 quartz (778 and 798 cm^{-1}), and representative for relative abundance^{34,35} 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 in³⁶. 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 taxon³⁶. Deciduous oak abundances represent the combined percentages of *Quercus robur* and
487 *Q. cerris* types³⁷, which is commonly used as an indicator for mid-elevation, relatively humid
488 forest across the Mediterranean^{38,39,40,41}.

489

490 **Isotope analysis**

491 Oxygen and carbon isotopes were analysed on bulk carbonate (calcite)⁴² 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 μm fraction washed with deionized water, dried at 40°C, and then ground
496 to a fine powder in an agate mortar. CO₂ was evolved from 10 mg CaCO₃ powders by
497 reaction with anhydrous H₃PO₄ overnight inside a vacuum at a constant temperature of 25°C.
498 The liberated CO₂ 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 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 signal⁴³, 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^{44,45,46}. 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 ⁴⁴.

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 CO₂
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}Ar , ^{37}Ar , ^{38}Ar , ^{39}Ar and ^{40}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 1.1891Ma⁴⁷ and
538 the total decay constant of⁴⁸. 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 298.56⁴⁹.

541 Tephra OH-DP-2669 is a 2.5 cm thick, yellowish layer with sharp upper and lower
542 boundaries comprising up to 500 μm 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 ka⁴⁴; 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^{50,51} 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^{52,53}. 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: SiO₂ >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 $722.8\pm 2.4\text{ ka}^{50}$ and $719.5\pm 12.6\text{ ka}^{53}$,
553 respectively.
554 The previous proposed correlation of SUL2-1/V5 with the Parmenide ash found in the
555 Crotone basin^{50,52} is not considered here due to a slightly younger $^{40}\text{Ar}/^{39}\text{Ar}$ age of the
556 Parmenide ash ($710\pm 5\text{ ka}$)^{54,55,56} 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 conditions²⁰. 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, TiO₂ 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 20⁵⁷. SUL2-22 is also
568 geochemically indistinguishable from OH-DP-2898 and shares a similar stratigraphic position
569 below the M/B boundary^{58,59} and at the transition from MIS 20 to MIS 19⁵⁷. 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 $773.9\pm 1.3\text{ ka}$ of V4⁵², quasi-synchronous position during the ¹⁰Be peak or M/B
573 transition⁶⁰. Also a correlation of OH-DP-2898/SUL2-22 with tephra V3 of the MJS
574 ($801.2\pm 19.5\text{ ka}$) 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 ⁶⁰. The Pitagora ash from the Crotone basin is found in a similar magneto- and
577 climatostratigraphic position^{55,61,62}, 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 ± 1.9 ka⁵⁸ 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)⁶³ and tephra layers OH-DP-0404/POP2 and OH-DP-0435/X-6, based on new results
583 from the Sulmona section⁶⁴. The tephrostratigraphy of the Fucino record⁶⁵ improved and
584 reassessed the correlations established for OH-DP-0617 and OH-DP-0624⁴⁴. $^{40}\text{Ar}/^{39}\text{Ar}$ dating
585 of TF-17, correlated to OH-DP-0624, yielded a much more precise age of 158.8 ± 3.0 ka,
586 which replaced the age of Vico B/OH-DP-0617 (162 ± 6 ka)⁶⁶.

587 Furthermore, the correlation of cryptotephra OH-DP-1700.6 with the Vico β eruption⁴⁵
588 provided a new chronological tie-point at 410 ± 2 ka⁶⁷. The previously established correlation
589 of tephra layer OH-DP-1955 with tephra layer SC-5 from the Mercure basin⁴⁴ was rejected in
590 the light of its large uncertainty (± 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 xenocrysts⁵⁸ yielded a new age of 715.02 ± 5.4 ka (Extended
594 Data Table 1) using the decay constant of⁴⁸ and an age of 1.1891 Ma for the ACs-2 flux
595 standard⁴⁷. Our new $^{40}\text{Ar}/^{39}\text{Ar}$ age of V5 (716.2 ± 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 ArAR⁶⁸ 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 record²⁰, the chronology
602 of the DEEP site sediment succession down to 447.12 mcd uses tephrochronological data^{44,45},
603 ⁴⁶ as 1st-order tie points and tuning of climate-sensitive proxy data (TOC; ~ 480 yr resolution)

604 against orbital parameters as 2nd-order tie points considering that maxima in TIC represent
605 interglacial periods^{19,20}. 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 March²⁰. These perihelion
608 passages in March correspond to the inflection points of increasing local summer insolation
609 (21st 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 sediments²⁰.
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 2nd-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 2.2⁶⁹,
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 site³³. An error of ±2,000 years was applied
623 to the 2nd-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 We²⁰ evaluated the DEEP site's chronology against the 0-160 ka U/Th dated Soreq
628 Cave speleothem record⁷⁰ 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 record³ 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 model⁷¹. The
637 atmospheric component of LOVECLIM is the spectral T21, three-level model ECBilt⁷² 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 model⁷³.

641 Atmosphere and ocean components are coupled through the exchange of freshwater and heat
642 fluxes. The vegetation model VECODE⁷⁴ 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 in⁷⁵. The orbital forcing was
647 calculated according to⁷⁶. Atmospheric GHG concentrations were prescribed according to
648 reconstructions from EPICA Dome C for CO₂⁷⁷ as well as CH₄ and N₂O⁷⁸. 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 to⁷⁹. 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 in⁷⁵ and uses a higher climate

654 sensitivity resulting in a better representation of the glacial-interglacial surface temperature
655 amplitude²³.

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 CO₂ concentration of
668 280 ppm, whereas the second simulation uses a constant atmospheric CO₂ 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 software⁸⁰ following the
677 approach by ⁸¹. 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 solution³⁰.

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}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}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 CO₂ 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

877

878

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).

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^{19,82} 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_{total}, **(b)** CaO vs.
897 Al₂O₃, **(c)** CaO vs. TiO₂, **(d)** Na₂O vs. K₂O, and **(e)** total alkali vs. silica (TAS) diagram⁸⁶
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_{total}, **(g)** CaO vs. Al₂O₃, **(h)**
900 CaO vs. TiO₂, **(i)** Na₂O vs. K₂O, 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 to⁵⁴. 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 11 pt 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 ⁸¹) 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 (⁸⁰ based on ⁸³). 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 chronology⁸⁴; **(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 ⁸⁵.

950

951 **Extended Data Figure 6 | Simulated Lake Ohrid precipitation for full-forcing run and**
952 **sensitivity simulations. (a)** Lake Ohrid precipitation (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 (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⁻¹) 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⁻¹) 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

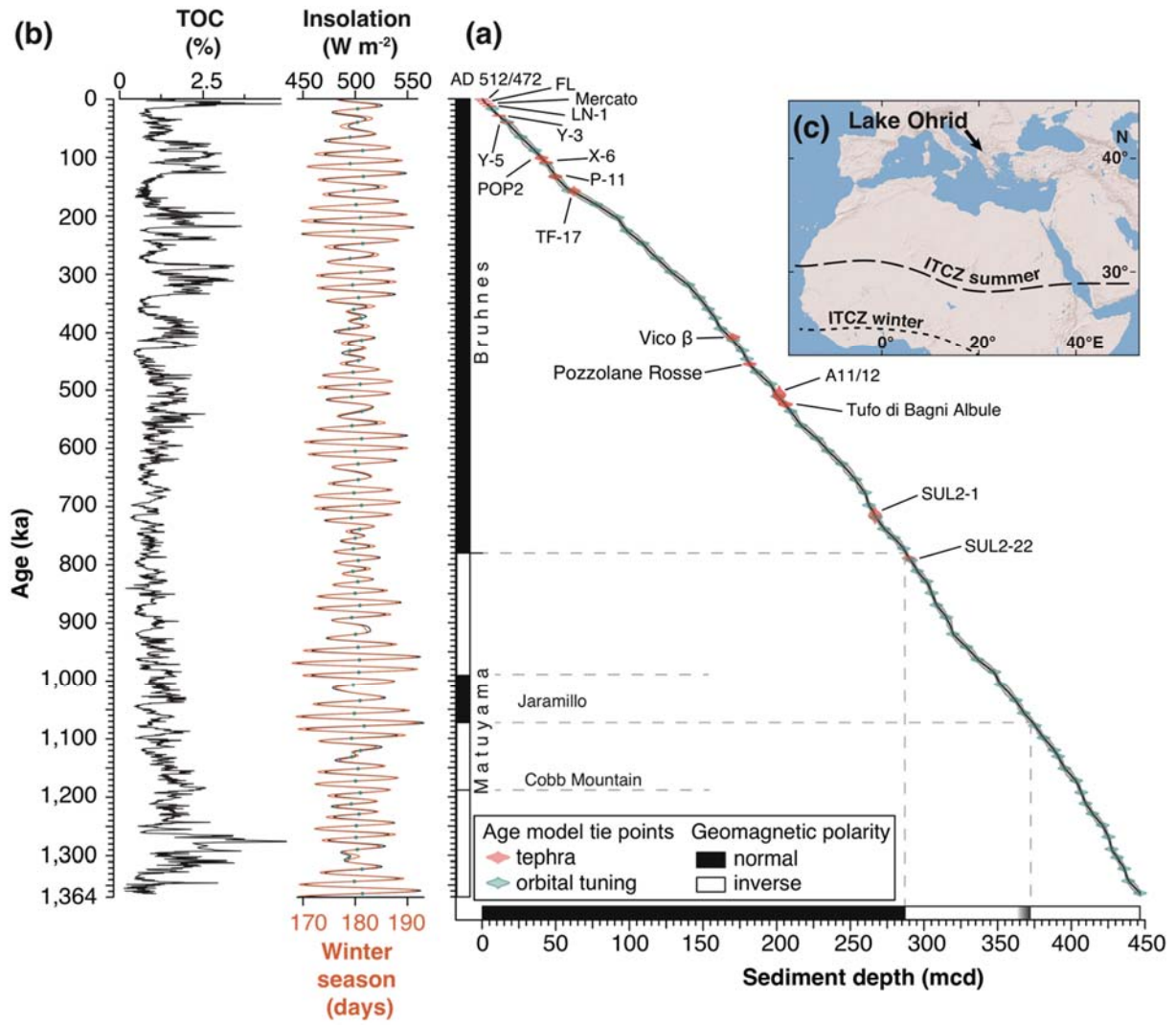
975 **Extended Data Table 1 | Selected tephra layers from Lake Ohrid and their correlation**
976 **with tephra layers of other records.** ⁴⁰Ar/³⁹Ar ages from literature were recalculated using a
977 decay constant⁷³ and Alder Creek sanidine (ACs-2) at 1.1891 Ma⁷⁴ or Fish Canyon sanidine
978 (FCs) at 28.294 Ma⁷³. 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 ⁵¹;
983 SC1-35.50 from ⁵⁰; V5, V4, V3, Pitagora ash from ⁵² and the Parmenide ash from ⁵⁴. \bar{x} =
984 mean; S = standard deviation; n= number of analysis.

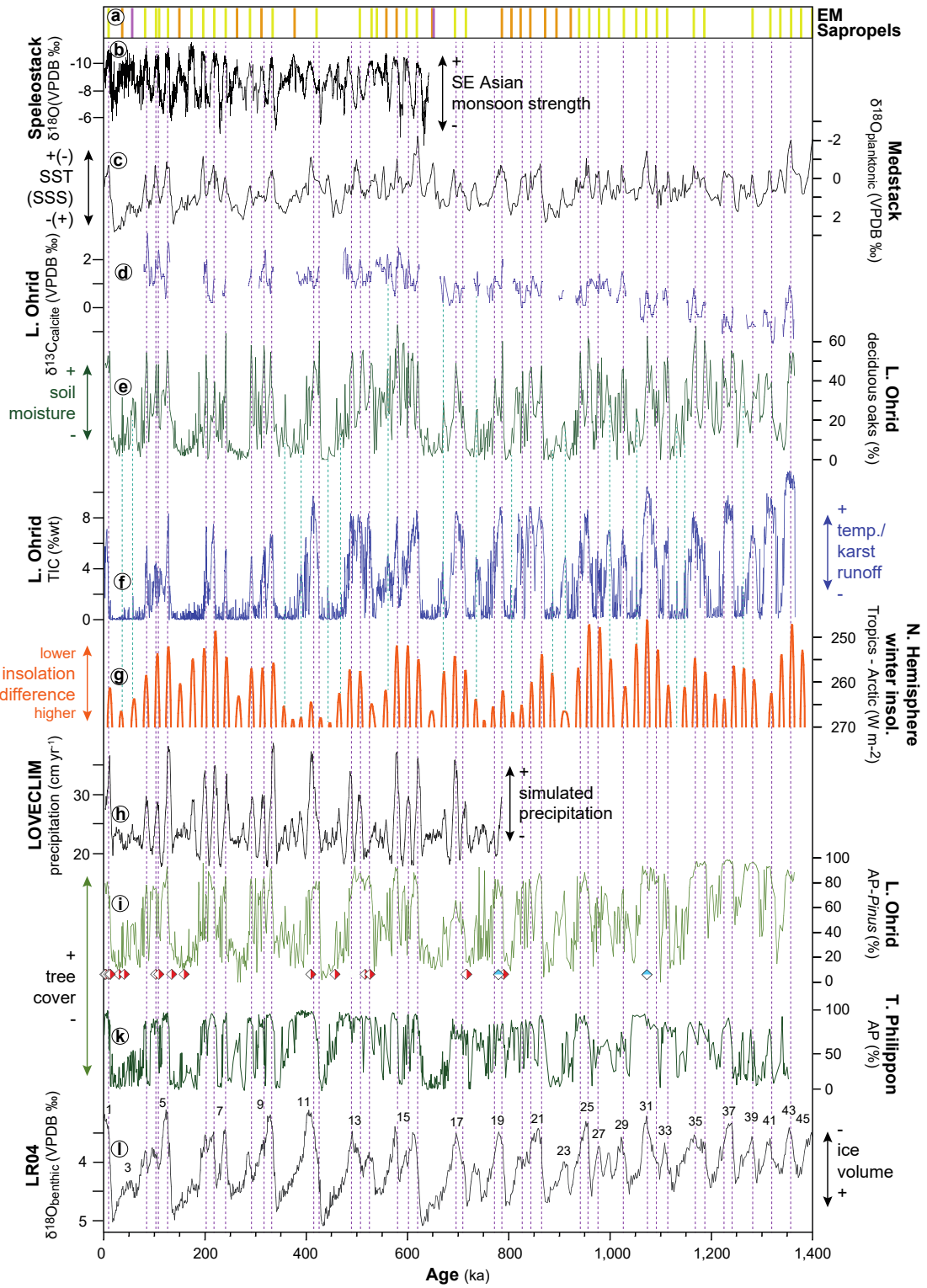
985

986 **Fig. 1**
 987



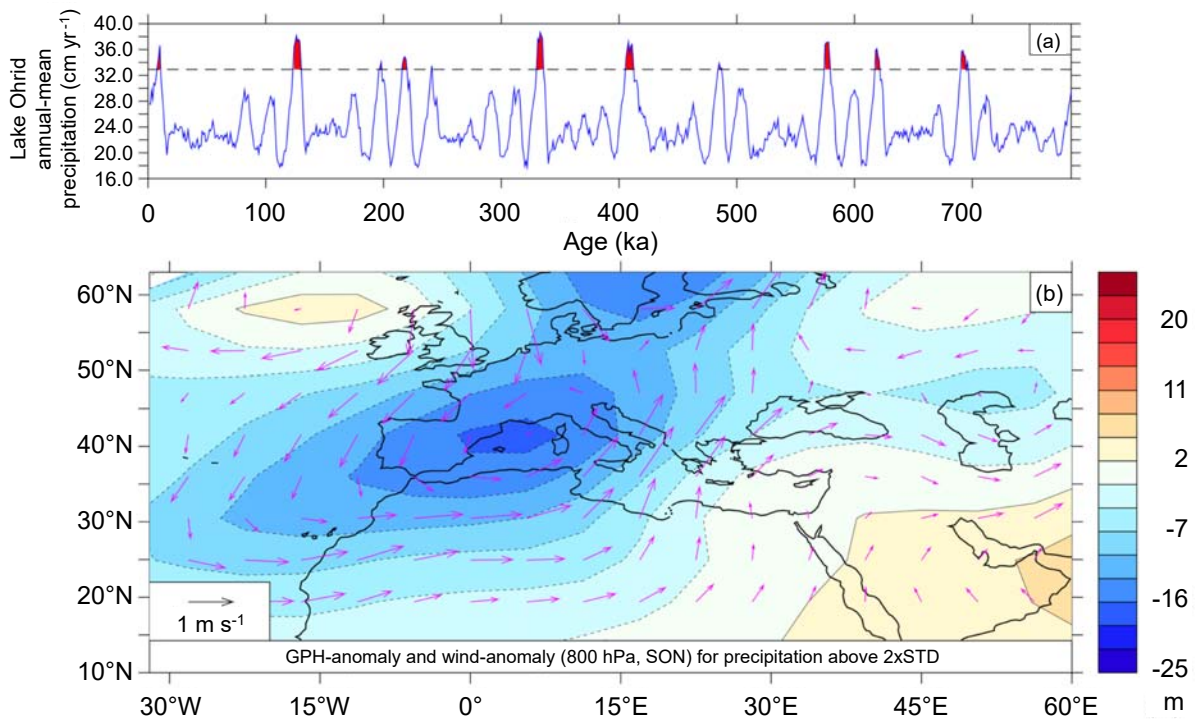
988
 989

990 Fig. 2
 991



992
 993
 994

995 **Fig. 3**
996



997