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1 TITLE (74 characters with spaces)

2 Indian Ocean Salinity build-up primes Deglacial Ocean Circulation Recovery

3

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13 ABSTRACT (162 words)

14 The Indian Ocean provides a source of salt for North Atlantic deep-water convection
15 sites, via the Agulhas Leakage (AL), and may thus drive changes in the ocean's

16 overturning circulation^{6,7,8}. However, little is known about salt content variability of

17 Indian Ocean and AL waters during past glacial cycles, and how this may influence

18 circulation. Here we show that the glacial Indian Ocean surface salt budget was

19 notably different from the modern, responding dynamically to changes in sea level.

20 Indian Ocean surface salinity increases during glacial intensification peaking in glacial

21 maxima. We find that this is due to rapid land exposure in the Indonesian archipelago

22 induced by glacial sea level lowering, and we suggest a mechanistic link via reduced

23 input of relatively fresh Indonesian throughflow (ITF) waters into the Indian Ocean.

24 Using new climate model results, we show that the release of this glacial Indian Ocean

25 salinity via the Agulhas Leakage during deglaciation can directly impact the Atlantic

26 meridional overturning circulation and global climate.

27

28 Main (2510 words including subheadings)

29 The surface salinity distribution in the modern Indian Ocean differs from the
30 distribution patterns seen in the Atlantic and Pacific Oceans at comparable latitudes
31 (Figure 1). Tropical and subtropical Atlantic and Pacific surface waters are
32 characterised by their enhanced warmth and salinity. This is due to their re-circulation
33 in sunny subtropical gyres with high net-evaporation. The Indian Ocean is largely
34 located in the tropics and sub-tropics; however, modern Indian Ocean surface
35 conditions are notably fresher than comparable latitudes in the Atlantic and Pacific.
36 This is due to the inflow of monsoon-derived and Pacific-origin low salinity surface and
37 thermocline waters from the Indonesian Throughflow (ITF) (Figure 1). Inflow occurs
38 via the Timor, Lombok, and Ombai Straits¹, as well as the Bay of Bengal², and is
39 transported across the tropical Indian Ocean via the South Equatorial Current (SEC)^{3,2,4}.
40 Surface water salinity does increase within the subtropical western Indian Ocean³, but
41 the salt is then partially exported through an active Agulhas Leakage⁵. The addition of
42 Indian Ocean salinity to Atlantic surface waters via the Agulhas Leakage has been
43 proposed as a mechanism to influence global ocean circulation by enhancing the
44 density potential at North Atlantic deep-water convection sites^{6,7,8}. It is therefore
45 possible that changes in the ITF and subsequent Indian Ocean surface salinity could
46 impact global ocean circulation.

47 Here, we present coupled sea surface temperature (SST) from Mg/Ca in the planktonic
48 foraminifer *Globigerinoides ruber* (method after ref.⁹) and oxygen isotope-and SST-
49 based relative salinity reconstructions (method after ref.¹⁰) from western Indian
50 Ocean International Ocean Discovery Program Site U1476 located in the northern
51 entrance of the Mozambique Channel (15°49.25' S; 41°46.12' E; 2166 m) to investigate
52 changes in the western Indian Ocean surface hydrography. This site is strongly
53 influenced by the westward flowing SEC, with a minor contribution of recirculating
54 waters flowing directly from the southern Indian Ocean to Madagascar, and thus
55 tracks the hydrographic conditions of the tropical western Indian Ocean source waters
56 that feed into the Agulhas leakage⁵. Our 1.2 million year (Ma)-long record provides
57 the first evidence for changes in tropical western Indian Ocean hydrography beyond
58 the Last Glacial Maximum (LGM).

59

60 Glacial salinification and warming

61 Our data show that western Indian Ocean surface salinity and temperature structures
62 were significantly different from modern during Pleistocene glacial stages. ED Fig. 1
63 shows that western SEC temperature initially cools during glacial inception from its
64 interglacial high. However during the middle and latter phases of glacial cycles, this
65 cooling trend reverses and surface waters begin to warm. In the absence of other
66 influences, this warming would be expected to cause a decrease in planktic $\delta^{18}\text{O}^{11}$.
67 However, we find planktic $\delta^{18}\text{O}$ continues to increase, suggesting an increase in $\delta^{18}\text{O}_{\text{sw}}$
68 and hence surface salinity. Global growth in ice volume can only account for 50% of
69 the glacial-interglacial difference in $\delta^{18}\text{O}_{\text{sw}}$ throughout the last 1.2Ma (ED Fig. 2d). As
70 such, our data indicate a regional increase in sea surface salinity (as well as
71 temperature) during glacial periods. After correcting for the influence of global ice
72 volume changes (see Methods), our ice volume-corrected $\delta^{18}\text{O}_{\text{sw}}$ ($\delta^{18}\text{O}_{\text{sw-ivc}}$) and SST
73 data show average increases of 0.83‰ ($\pm 0.2\text{‰}$ 2σ) and 4.4°C ($\pm 0.8^{\circ}\text{C}$ 2σ), respectively
74 across 16 glacial cycles (ED Fig. 1). Glacial salinification occurs in 15 out of 16 glacial
75 cycles, with the onset of the glacial increase in $\delta^{18}\text{O}_{\text{sw-ivc}}$ occurring on average 20kyr
76 prior to the glacial termination in $\delta^{18}\text{O}_{\text{benthic}}$ (Figure 2a-d, ED Fig. 1, Methods). To
77 examine the regional consistency of this feature, we stacked SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ records
78 across the Indian Ocean (Figures 1 and 2) by resampling each record and averaging
79 the resulting records using a Gaussian smooth (ED Fig. 3; Methods). The resulting
80 Indian Ocean $\delta^{18}\text{O}_{\text{sw-ivc}}$ and SST stacks show the same patterns of salinification and
81 warming during intensification of glacial conditions (Figure 2a-d), suggesting this is an
82 Indian Ocean-wide phenomenon. The change in water mass properties does not apply
83 to Indian Ocean water source regions, such as the South China Sea (SCS) or the
84 western Pacific Ocean (ED Fig. 5; Methods). It is therefore likely to be connected to
85 dynamics in the Indian Ocean region.

86

87 Salinification not set up by atmosphere

88 Model simulations^{12,13} and data reconstructions^{14,15} show that Indian Ocean
89 temperature and salinity may be influenced by atmospheric circulation and monsoon
90 changes driven by precession. As such, we first examined precession-scale variability
91 within U1476 and stacked $\delta^{18}\text{O}_{\text{sw-ivc}}$ and SST using spectral analysis. We could not find
92 any significant precessional cycle in U1476 or in the stack, but we do identify a
93 significant 100 kyr periodicity in both, though note that caution is necessary when
94 interpreting the spectral analysis for the $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack due to its coverage of only 345
95 kyr. (ED Fig. 6 and 7; Methods). This suggests that insolation-driven monsoonal
96 variability does not drive $\delta^{18}\text{O}_{\text{sw-ivc}}$ and SST in the western Indian Ocean, and only plays
97 a minor role for the whole tropical and subtropical Indian Ocean. The Bay of Bengal^{14,15}
98 and Arabian Sea^{16,17} have been highlighted as parts of the Indian Ocean where
99 monsoonal changes play a key role in surface ocean salinity changes which could
100 influence the subtropical Indian Ocean. However, $\delta^{18}\text{O}_{\text{sw-ivc}}$ records from both
101 locations also show 100 kyr periodicities within the last 1.2Ma (ED Fig. 8 and 9)
102 suggesting a glacial cycle overprint on Bay of Bengal and Arabian Sea surface salinity.
103 In fact, we find the same early salinification process in both the Bay of Bengal (ED Fig.
104 8) and Arabian Sea (ED Fig. 9 k-l) salinity reconstructions. This suggests that glacial
105 salinification is a ubiquitous feature of the Indian Ocean, and points towards a large-
106 scale mechanism that links changes in glacial ice volume to Indian Ocean surface
107 hydrography. Additionally, while some climate model simulations^{12,13} suggest a
108 fresher glacial western Indian surface Ocean in line with a strengthened glacial Indian
109 Ocean dipole compared to modern, our data indicates that the western Indian Ocean
110 was much saltier than modern (ED Fig. 1). Hence, the mechanism for glacial Indian
111 Ocean salinification is likely caused by ocean-intrinsic dynamics, rather than
112 atmospheric changes.

113

114 Salinification due to sea level and ITF

115 We find that each Indian Ocean salinification event throughout the last 1.2Ma in the
116 $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack is induced when global mean sea level (GMSL) falls to around -48m (σ
117 = 19m) with respect to average modern sea level (Figure 2e, f). Repeating the analysis
118 using U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ alone yields nearly the same GMSL threshold of -48m (σ = 17m)

119 (ED Fig. 2). This suggests a systematic link between glacial sea level lowering and the
120 Indian Ocean glacial salinification process. The Indonesian archipelago is characterised
121 as a tectonically stable collection of large shallow seas with modern depths of around
122 50m^{18,19}, and has been previously highlighted as an area of major land surface re-
123 organisation as a result of changing sea levels^{20,21}. During glacial periods, falling GMSL
124 causes a shoaling of water depths in the Indonesian archipelago leading to the
125 resurfacing of land if sea levels decrease further than -50m relative to today. To better
126 characterise changes in the sea-land surface distribution as a result of GMSL variability
127 and subsequent water depth changes, we ran a coupled Sea Level-topography model
128 ANICE-SELEN (ref.²²; Methods). The model provides global time-step reconstructions
129 of land-vs-sea maps that are based on dynamical reconstructions of global ice sheet
130 change and consideration of glacio-hydro-isostatic processes. This allows us to assess
131 dynamic regional changes in land exposure and flooding and their relationship to
132 GMSL. Our model results show that the greatest changes in sea-to-land surface area
133 across the Indonesian archipelago occur when GMSL is between -2m to -8m, and -42m
134 to -56m (ED Fig. 10). The shallower of these intervals appears to be linked to the initial
135 exposure of shallow marine geomorphological landforms, such as shallow submarine
136 island channels, estuaries, terraces, shore platforms, sand banks, and coral reefs. Its
137 impact on regional circulation and Indian Ocean surface salinity is therefore small. The
138 deeper interval is directly linked to the abrupt exposure of the Java Straits and North
139 Australian continental shelves. The glacial resurfacing of land due to lower GMSL in
140 the Indonesian Archipelago will have important implications for the outflow dynamics
141 of the ITF. Indeed, we find a close correspondence between GMSL and ITF outflow
142 strength, as reconstructed from $\delta^{13}\text{C}_{\text{benthic}}$ in the Lombok Strait²³ (Figure 2g, h). This
143 suggests that lowering global sea levels causes a reduction in the ITF outflow due to
144 abrupt land surfacing in the Indonesian Archipelago when GMSL falls to -48m relative
145 to today. The Java Straits and North Australian shelves have both been previously
146 hypothesised to influence regional circulation and surface water hydrography^{20,23,24}.
147 The exposure of North Australian shelves may reduce the outflow profile area, and
148 therefore the outflow volume of the ITF^{20,23,24}, while the Java Straits influence the
149 salinity and temperature characteristics of the ITF outflow waters that enter the Indian
150 Ocean^{23,25}. At times of high sea level stands, open Java Straits allow fresh water lenses

151 from the South China Seas (SCS) to enter the centre of the ITF, causing a hydrographic
152 blockage of surface waters²³. As a result, the ITF outflow manifests itself as a
153 predominantly thermocline outflow into the Indian Ocean. In contrast, during times
154 of low sea level (GMSL < -48m relative to today), the closure of the Java Straits restricts
155 the inflow of freshwater lenses, reducing the blockage and allowing a surface water
156 driven ITF outflow^{23,25}. This is important for ITF hydrography, since tropical surface
157 waters can differ strongly from thermocline waters due to evaporation. As such,
158 surface waters in the ITF will likely be saltier and warmer than thermocline waters and
159 will predominantly form the reduced glacial ITF^{23,25}. The salinity increase we observe
160 during glaciation in the tropical and subtropical Indian Ocean is therefore likely linked
161 to a large glacial reduction in and slight salinification of the ITF-sourced fresh water
162 entering the Indian Ocean.

163

164 The other important Indian Ocean gateway

165 In the south west, the Agulhas Leakage (AL) provides a link between the Indian and
166 Atlantic Oceans. Changes in the AL strength can also influence surface hydrography in
167 the Indian and Atlantic Ocean (e.g. refs.^{26,27}). AL strength reconstructions suggest that
168 its volume transport and/or surface temperature and salinity was reduced during
169 glacials within the last 500kyr^{28,29} (Figure 2i-j). This could be linked to northward shifts
170 of the super gyre boundary or the dynamical subtropical front, coupled to changes in
171 Southern Ocean dynamics, which diminish the outflow space for warm and salty
172 waters between the subtropical front and the African continent^{30,31}. It is possible that
173 a weakened AL could enhance the salinification process in the Indian surface Ocean
174 by reducing the outflow of saline waters into the Atlantic and promoting recirculation
175 under net-evaporative conditions in the Indian Ocean. Indeed, published records
176 suggest that the glacial reduction of the AL caused increased recirculation in the
177 southwest Indian Ocean via the Agulhas retroflexion, where high evaporation led to
178 salinification of surface waters²⁶. However, while Figure 3e and 3i-j show that the
179 increases in $\delta^{18}\text{O}_{\text{sw-ivc}}$ were generally initiated during weak AL, in some cycles AL climbs
180 during glacial intensification, while Indian Ocean salinity stays consistently high.
181 Therefore, although the early glacial closure of the AL might have enhanced the initial

182 Indian Ocean salinification process by reducing the outflow of saline waters into the
183 Atlantic, rising AL during glacial intensification would have countered further
184 salinification, and so cannot be the key driving mechanism for the consistent glacial
185 salinification we observe. Instead, we highlight a reduced ITF as the leading driver of
186 glacial Indian Ocean salinification and note that the ITF strength proxy is consistently
187 low during salinification intervals, supporting this idea (Figure 2g).

188

189 A salty Indian Ocean can influence AMOC

190 The high salinity conditions in the glacial Indian Ocean can be traced along the Agulhas
191 current system into the AL in the compiled records (ED Fig. 3c), and thus have the
192 potential to increase salt concentration in the south Atlantic at times when the Indian
193 Ocean is in a salty glacial mode, and the AL is strong. Published AL reconstructions
194 show a resumption of the AL strength at the onset of deglaciations^{28,29} (Figure 2i-j),
195 and notable peaks in salinity are seen in the AL region during deglacial Heinrich stadial
196 events³². Thus, the high salinity conditions prevalent in the Indian Ocean during glacial
197 maxima would lead to an abrupt release of highly salty waters through enhanced AL
198 during deglaciations, especially in Heinrich stadials, with the potential of influencing
199 downstream salt delivery to the Atlantic meridional overturning circulation (AMOC)
200 (Figure 4). Climate model results investigating the modern AL hint towards an
201 influence of salty Indian Ocean waters on the salinity of the Atlantic, and therefore
202 possibly on AMOC⁷. However, little is known about the impact of a salty AL on the
203 AMOC under glacial conditions. Our data show that the salt-potential of the AL is
204 generally highest during glacial maxima, and would remain high during Heinrich stadial
205 events at the onset of deglaciations, when GMSL is still < -50m relative to today, and
206 the AL strength resumes. We therefore tested the influence of enhanced AL salt
207 import on a suppressed AMOC during a Heinrich stadial using the fully-coupled
208 atmosphere-ocean global circulation model COSMOS³³ (Figure 3; Methods). To
209 simulate this, we first equilibrated the model to LGM conditions (black triangle in
210 Figure 3d). We then performed a classic North Atlantic hosing experiment (LGM015)
211 applying 0.15 Sv for 500 years into the so-called Ruddiman Belt (Figure 3) to generate
212 a weakened AMOC under LGM conditions mimicking a Heinrich stadial (see ref.³³). To

213 test the role of an increased AL salt import to the Atlantic, the net result of enhanced
214 deglacial leakage of particularly salty Indian Ocean water, we then conducted two
215 freshwater extraction experiments based on LGM015 by additionally imposing
216 constant high evaporation fluxes over the Agulhas plateau equivalent to 0.05 Sv
217 (LGM015-SA005) and 0.1 Sv (LGM015-SA01) of freshwater extraction. This freshwater
218 extraction occurred while freshwater hosing in the North Atlantic continued. After
219 inducing salinification in the Agulhas plateau area, we see an AMOC recovery in both
220 experiments occurring after ~400 years in LGM015-SA005 and ~250 years in LGM015-
221 SA01, despite the ongoing freshwater hosing (Figure 3). This suggests that enhanced
222 salt import via the AL can have a direct impact on a weakened AMOC and can lead to
223 an AMOC recovery even under a persistent freshwater input in the North Atlantic,
224 which might be expected during deglaciation⁸. Our results further suggest that the
225 elevated amount of salt imported into the South Atlantic has an effect on the response
226 time of the AMOC, with higher salinities leading to faster response times. This
227 underlines that the glacial salinification process in the tropical and subtropical Indian
228 surface Ocean can play an important role for not only the global overturning
229 circulation, but also the shape of deglaciations, depending on the amount of salt
230 harvested throughout the glacial, and the speed of release through the AL. In summary,
231 we highlight the dynamic interplay between different components of the climate
232 system during glacial cycles, showing that falling sea levels during glacial
233 intensification restrict ITF, in turn salinifying the Indian Ocean, which may ultimately
234 trigger abrupt changes in AMOC and shape glacial termination.

235

236 MAIN TEXT REFERENCES

- 237 1. Sprintall, J., Wijffels, S. E., Molcard, R., & Jaya, I. (2009). Direct estimates of
238 the Indonesian throughflow entering the Indian Ocean: 2004-2006. *Journal of*
239 *Geophysical Research: Oceans*, 114(7).
240 <https://doi.org/10.1029/2008JC005257>
- 241 2. Sengupta, D., Bharath Raj, G. N., & Shenoi, S. S. C. (2006). Surface freshwater
242 from Bay of Bengal runoff and Indonesian Throughflow in the tropical Indian

- 243 Ocean. *Geophysical Research Letters*, 33(22).
244 <https://doi.org/10.1029/2006GL027573>
- 245 3. Talley, L. D., & Sprintall, J. (2005). Deep expression of the Indonesian
246 Throughflow: Indonesian Intermediate Water in the South Equatorial
247 Current. *Journal of Geophysical Research*, 110(C10), C10009.
248 <https://doi.org/10.1029/2004JC002826>
- 249 4. Gordon, A. L., Ma, S., Olson, D. B., Hacker, P., Ffield, A., Talley, L. D., Wilson,
250 D., & Baringer, M. (1997). Advection and diffusion of Indonesian Throughflow
251 Water within the Indian Ocean South Equatorial Current. *Geophysical*
252 *Research Letters*, 24(21), 2573–2576.
253 [https://doi.org/10.1029/97GL01061@10.1002/\(ISSN\)1944-8007.WOCEEX1](https://doi.org/10.1029/97GL01061@10.1002/(ISSN)1944-8007.WOCEEX1)
- 254 5. Durgadoo, J. V., Rühls, S., Biastoch, A., & Böning, C. W. B. (2017). Indian Ocean
255 sources of Agulhas leakage. *Journal of Geophysical Research: Oceans*, 122(4),
256 3481–3499. <https://doi.org/10.1002/2016JC012676>
- 257 6. Beal, L. M., De Ruijter, W. P. M., Biastoch, A., Zahn, R., Cronin, M., Hermes, J.,
258 Lutjeharms, J., Quartly, G., Tozuka, T., Baker-Yeboah, S., Bornman, T.,
259 Cipollini, P., Dijkstra, H., Hall, I., Park, W., Peeters, F., Penven, P.,
260 Ridderinkhof, H., & Zinke, J. (2011). On the role of the Agulhas system in
261 ocean circulation and climate. In *Nature* (Vol. 472, Issue 7344, pp. 429–436).
262 <https://doi.org/10.1038/nature09983>
- 263 7. Biastoch, A., Böning, C. W., Schwarzkopf, F. U., & Lutjeharms, J. R. E. (2009).
264 Increase in Agulhas leakage due to poleward shift of Southern Hemisphere
265 westerlies. *Nature*, 462(7272), 495–498.
266 <https://doi.org/10.1038/nature08519>
- 267 8. Knorr, G., & Lohmann, G. (2003). Southern ocean origin for the resumption of
268 Atlantic thermohaline circulation during deglaciation. *Nature*.
269 <https://doi.org/10.1038/nature01855>
- 270 9. Gray, W. R., & Evans, D. (2019). Nonthermal Influences on Mg/Ca in
271 Planktonic Foraminifera: A Review of Culture Studies and Application to the
272 Last Glacial Maximum. *Paleoceanography and Paleoclimatology*, 34(3), 306–
273 315. <https://doi.org/10.1029/2018PA003517>

- 274 10. Kiefer, T., McCave, I. N., & Elderfield, H. (2006). Antarctic control on tropical
275 Indian Ocean sea surface temperature and hydrography. *Geophysical*
276 *Research Letters*, 33(24), L24612. <https://doi.org/10.1029/2006GL027097>
- 277 11. Waelbroeck, C., Mulitza, S., Spero, H., Dokken, T., Kiefer, T., & Cortijo, E.
278 (2005). A global compilation of late Holocene planktonic foraminiferal $\delta^{18}\text{O}$:
279 relationship between surface water temperature and $\delta^{18}\text{O}$. *Quaternary*
280 *Science Reviews*, 24(7–9), 853–868.
281 <https://doi.org/10.1016/J.QUASCIREV.2003.10.014>
- 282 12. DiNezio, P. N., Tierney, J. E., Otto-Bliesner, B. L., Timmermann, A.,
283 Bhattacharya, T., Rosenbloom, N., & Brady, E. (2018). Glacial changes in
284 tropical climate amplified by the Indian Ocean. *Science Advances*, 4(12).
285 <https://doi.org/10.1126/sciadv.aat9658>
- 286 13. Thirumalai, K., DiNezio, P. N., Tierney, J. E., Puy, M., & Mohtadi, M. (2019). An
287 El Niño Mode in the Glacial Indian Ocean? *Paleoceanography and*
288 *Paleoclimatology*, 34(8), 1316–1327. <https://doi.org/10.1029/2019PA003669>
- 289 14. Clemens, S. C., Yamamoto, M., Thirumalai, K., Giosan, L., Richey, J. N.,
290 Nilsson-Kerr, K., Rosenthal, Y., Anand, P., & McGrath, S. M. (2021). Remote
291 and local drivers of Pleistocene South Asian summer monsoon precipitation:
292 A test for future predictions. *Science Advances*, 7(23), eabg3848.
293 <https://doi.org/10.1126/sciadv.abg3848>
- 294 15. Nilsson-Kerr, K., Anand, P., Sexton, P. F., Leng, M. J., & Naidu, P. D. (2022).
295 Indian Summer Monsoon variability 140–70 thousand years ago based on
296 multi-proxy records from the Bay of Bengal. *Quaternary Science Reviews*,
297 279, 107403. <https://doi.org/10.1016/J.QUASCIREV.2022.107403>
- 298 16. Ishikawa, S., & Oda, M. (2007). Reconstruction of Indian monsoon variability
299 over the past 230,000 years: Planktic foraminiferal evidence from the NW
300 Arabian Sea open-ocean upwelling area. *Marine Micropaleontology*, 63(3–4),
301 143–154. <https://doi.org/10.1016/J.MARMICRO.2006.11.004>
- 302 17. Kumar K., P., & Ramesh, R. (2017). Revisiting reconstructed Indian monsoon
303 rainfall variations during the last ~25 ka from planktonic foraminiferal $\delta^{18}\text{O}$
304 from the Eastern Arabian Sea. *Quaternary International*, 443, 29–38.
305 <https://doi.org/10.1016/J.QUAINT.2016.07.012>

- 306 18. Hanebuth, T. J. J., & Stattegger, K. (2004). Depositional sequences on a late
307 Pleistocene–Holocene tropical siliciclastic shelf (Sunda Shelf, southeast Asia).
308 *Journal of Asian Earth Sciences*, 23(1), 113–126.
309 [https://doi.org/https://doi.org/10.1016/S1367-9120\(03\)00100-7](https://doi.org/https://doi.org/10.1016/S1367-9120(03)00100-7)
- 310 19. Kudrass, H. R., & Schlüter, H. U. (1994). Development of cassiterite-bearing
311 sediments and their relation to late Pleistocene sea-level changes in the
312 Straits of Malacca. *Marine Geology*, 120(3), 175–202.
313 [https://doi.org/https://doi.org/10.1016/0025-3227\(94\)90058-2](https://doi.org/https://doi.org/10.1016/0025-3227(94)90058-2)
- 314 20. Petrick, B., Martínez-García, A., Auer, G., Reuning, L., Auderset, A., Deik, H.,
315 Takayanagi, H., De Vleeschouwer, D., Iryu, Y., & Haug, G. H. (2019). Glacial
316 Indonesian Throughflow weakening across the Mid-Pleistocene Climatic
317 Transition. *Scientific Reports*, 9(1). [https://doi.org/10.1038/s41598-019-](https://doi.org/10.1038/s41598-019-53382-0)
318 [53382-0](https://doi.org/10.1038/s41598-019-53382-0)
- 319 21. Hanebuth, T. J. J., Voris, H. K., Yokoyama, Y., Saito, Y., & Okuno, J. (2011).
320 Formation and fate of sedimentary depocentres on Southeast Asia’s Sunda
321 Shelf over the past sea-level cycle and biogeographic implications. *Earth-*
322 *Science Reviews*, 104(1), 92–110.
323 <https://doi.org/https://doi.org/10.1016/j.earscirev.2010.09.006>
- 324 22. de Boer, B., Stocchi, P., & van de Wal, R. S. W. (2014). A fully coupled 3-D ice-
325 sheet–sea-level model: algorithm and applications. *Geoscientific Model*
326 *Development*, 7(5), 2141–2156. <https://doi.org/10.5194/gmd-7-2141-2014>
- 327 23. Holbourn, A., Kuhnt, W., & Xu, J. (2011). Indonesian Throughflow variability
328 during the last 140 ka: The timor sea outflow. *Geological Society Special*
329 *Publication*, 355, 283–303. <https://doi.org/10.1144/SP355.14>
- 330 24. Gordon, A. L., Susanto, R. D., & Vranes, K. (2003). Cool Indonesian
331 throughflow as a consequence of restricted surface layer flow. *Nature*,
332 425(6960), 824–828. <https://doi.org/10.1038/nature02038>
- 333 25. Sarr, A. C., Husson, L., Sepulchre, P., Pastier, A. M., Pedoja, K., Elliot, M.,
334 Arias-Ruiz, C., Solihuddin, T., Aribowo, S., & Susilohadi. (2019). Subsiding
335 sundaland. *Geology*, 47(2), 119–122. <https://doi.org/10.1130/G45629.1>

- 336 26. Simon, M. H., Arthur, K. L., Hall, I. R., Peeters, F. J. C., Loveday, B. R., Barker,
337 S., Ziegler, M., & Zahn, R. (2013). Millennial-scale Agulhas Current variability
338 and its implications for salt-leakage through the Indian-Atlantic Ocean
339 Gateway. *Earth and Planetary Science Letters*, *383*, 101–112.
340 <https://doi.org/10.1016/j.epsl.2013.09.035>
- 341 27. Dickson, A. J., Leng, M. J., Maslin, M. A., Sloane, H. J., Green, J., Bendle, J. A.,
342 Mcclymont, E. L., Pancost, R. D., Dickson, C. :, Leng, M. J., Maslin, M. A.,
343 Sloane, H. J., Green, J., Bendle, J. A., Mcclymont, E. L., & Pancost, R. D. (2010).
344 Atlantic overturning circulation and Agulhas leakage influences on southeast
345 Atlantic upper ocean hydrography during marine isotope stage 11.
346 *Paleoceanography*, *25*(3). <https://doi.org/10.1029/2009PA001830>
- 347 28. Peeters, F. J. C., Acheson, R., Brummer, G. J. A., De Ruijter, W. P. M.,
348 Schneider, R. R., Ganssen, G. M., Ufkes, E., & Kroon, D. (2004). Vigorous
349 exchange between the Indian and Atlantic oceans at the end of the past five
350 glacial periods. *Nature*, *430*(7000), 661–665.
351 <https://doi.org/10.1038/nature02785>
- 352 29. Caley, T., Giraudeau, J., Malaizé, B., Rossignol, L., & Pierre, C. (2012). Agulhas
353 leakage as a key process in the modes of Quaternary climate changes.
354 *Proceedings of the National Academy of Sciences of the United States of*
355 *America*, *109*(18), 6835–6839. <https://doi.org/10.1073/pnas.1115545109>
- 356 30. Bard, E., & Rickaby, R. E. M. (2009). Migration of the subtropical front as a
357 modulator of glacial climate. *Nature*, *460*(7253), 380–383.
358 <https://doi.org/10.1038/nature08189>
- 359 31. De Boer, A. M., Graham, R. M., Thomas, M. D., and Kohfeld, K. E. (2013). The
360 control of the Southern Hemisphere Westerlies on the position of the
361 Subtropical Front. *J. Geophys. Res. Oceans*, *118*, 5669– 5675,
362 <https://doi.org/10.1002/jgrc.20407>
- 363 32. Marino, G., Zahn, R., Ziegler, M., Purcell, C., Knorr, G., Hall, I. R., Ziveri, P., &
364 Elderfield, H. (2013). Agulhas salt-leakage oscillations during abrupt climate
365 changes of the Late Pleistocene. *Paleoceanography*, *28*(3), 599–606.
366 <https://doi.org/10.1002/palo.20038>

367 33. Zhang, X., Lohmann, G., Knorr, G., & Xu, X. (2013). Different ocean states and
 368 transient characteristics in Last Glacial Maximum simulations and
 369 implications for deglaciation. *Climate of the Past*, 9(5), 2319–2333.

370 <https://doi.org/10.5194/cp-9-2319-2013>

371

372 FIGURE LEGENDS

373 Fig. 1 Geographic and hydrographic context of study sites

374 Modern ocean surface salinity distribution³⁴ and GEBCO2014 bathymetry³⁵ plotted
 375 using Ocean Data view³⁶, and orange-to-blue salinity scale, where white represents
 376 mean ocean water ~35 psu, with key surface circulation patterns and study sites.
 377 Fresher and saltier water mass pathways are indicated with blue and orange arrows,
 378 respectively. Location numbers as follows: pink star ④ U1476 (this study); pink circles
 379 ① ODP1087^{29, 37}, ② Agulhas Bank Splice (ABS)³⁸, ③ MD96-2048³⁹, ④ U1476 (this
 380 study), ⑤ WIND28K¹⁰, ⑥ TY93-929/P⁴⁰, ⑦ MD90-0963^{41,42}, ⑧ GeoB10038-4⁴³, ⑨
 381 MD01-2378^{44,45}, ⑩ ODP1146⁴⁶, ⑪ ODP806⁴⁷. Sites ② – ⑨ are used in our Indian
 382 Ocean data stacks. Abbreviations include Agulhas counter current (CC), South China
 383 Sea (SCS), Indonesian throughflow (ITF), and west Pacific warm pool (WPWP).

384

385 Fig. 2 Records of Indian Ocean surface salinification and warming compared to 386 changes in Indonesian throughflow and sea level

387 (a) Sea surface temperature (SST) stack (z-scores relative to mean and $\sigma = 1$) for the
 388 Indian Ocean (bold orange line, from 0 - 790 ka) with upper and lower 95th percentile
 389 indicated by orange shaded envelope, and prior to 790 ka, SST data exclusively from
 390 U1476 SST (thin orange line; this study). (b), (d) LR04 benthic $\delta^{18}\text{O}^{48}$ with inverted y-
 391 axes (grey line). (c), (e) Ice volume-corrected $\delta^{18}\text{O}_{\text{sw}}$ stack (z-scores) for the Indian
 392 surface Ocean (bold green line from 0 – 345 ka) with upper and lower 95th percentile
 393 indicated by green shaded envelope, and prior to 345 ka, ice volume-corrected $\delta^{18}\text{O}_{\text{sw}}$
 394 data exclusively from U1476 (thin green line; this study). Green diamonds in (e)
 395 indicate the onset of glacial $\delta^{18}\text{O}_{\text{sw-ivc}}$ increase within each glacial cycle. (f), (h) global

396 mean sea level⁴⁹ (GMSL, pink line), in (f) with GMSL at onset of $\delta^{18}\text{O}_{\text{sw-ivc}}$ increases
 397 (green diamonds in (e)), horizontal dashed pink line is the average value of all pink
 398 circles. (g) Detrended Indonesian throughflow (ITF) outflow strength proxy²³ (blue
 399 line). (i) Agulhas Leakage proxy using Agulhas Leakage Fauna (ALF) counts²⁸ (light grey
 400 area). (j) Agulhas Leakage proxy using *G. menardii* counts²⁹ (dark grey spikes). Intervals
 401 of rising $\delta^{18}\text{O}_{\text{sw-ivc}}$ -stack prior to each glacial termination are indicated with vertical
 402 grey bars. Glacial terminations are labelled at the top, and indicated with dashed
 403 vertical lines.

404

405 Fig. 3 Role of intrusion of salinification Indian water mass in deglacial AMOC strength

406 (a) Sea surface salinity anomaly between the normal LGM background experiment
 407 (LGM) which is equivalent to the LGM-W experiment in ref.³³, and the Heinrich-stadial
 408 experiment including North Atlantic freshwater hosing (LGM015). (b) and (c) sea
 409 surface salinity anomaly between the Heinrich-stadial background setting (experiment
 410 LGM015) and anomalies of saltwater hosing experiments equivalent to removal of 0.1
 411 Sv freshwater (LGM015-SA01), and 0.05 Sv freshwater (LGM015-SA005). The average
 412 in (b), and (c) respectively, was calculated from the 160th to 210th, and 290th to 340th,
 413 model year window. Green and purple rectangles in (a) indicate freshwater hosing and
 414 freshwater extraction (“saltwater hosing”) in the North and South Atlantic. (d) and (e)
 415 time series of AMOC indices and Agulhas Leakage salinity (average in 5° E ~ 20° E and
 416 30° S ~ 40° S). AMOC index from the LGM background climate run (no freshwater
 417 hosing), indicated with a black arrow marker (~18 Sv). The AMOC index is defined as
 418 the maximum value of the stream function below the water depth of 500 m north of
 419 45° N in the North Atlantic. The map was plotted using the numerical computing
 420 environment and programming language Matlab developed by MathWorks. PMIP3
 421 LGM topography/bathymetry were taken from ref³³ according to the PMIP protocol⁵⁰.

422

423 Fig. 4 Proposed links between sea-level induced changes in the Indonesian
 424 throughflow, Indian surface ocean salinity, and efficiency of Agulhas leakage

425 (a) During interglacials and glaciation, when sea level (SL) is higher than -50 m relative
426 to today, the Indonesian archipelago is submerged leading to a strong Indonesian
427 throughflow (ITF) and import of fresher waters into the Indian Ocean (IO) along the
428 South Equatorial Current (SEC). This coincides with a moderately efficient Agulhas
429 Leakage (AL) south of Africa where the subtropical front (SF) is located further south.
430 (b) During the latter half of the glacial cycle, Indonesian archipelago channels and
431 shallow seas are exposed due to SL lower than -50m relative to today, reducing the
432 ITF and minimising the import of fresher waters into the IO. This coincides with
433 equatorward-shifted glacial SF conditions and a reduced glacial AL. (c) During the
434 onset of deglaciations, the ITF is still reduced because the Indonesian archipelago is
435 still exposed (SL lower than -50m relative to today). However, poleward shift of the SF
436 causes a resumption of the AL which releases highly salty Indian Ocean waters into
437 the South Atlantic. Note all colour bars and patterns are for descriptive purposes only.
438 Top and side panels were plotted using Ocean Data view³⁶ and bathymetry³⁵,
439 respectively.

440

441 METHODS (2754 words including subheadings)

442 Age model

443 The age model for U1476 was taken from ref.⁵¹ who aligned U1476 $\delta^{18}\text{O}_{\text{benthic}}$ to the
444 $\delta^{18}\text{O}_{\text{benthic}}$ probability stack⁵².

445

446 SST and relative salinity derivation

447 *Globigerinoides ruber* (*G. ruber*) samples were picked from U1476, then crushed and
448 homogenised. An aliquot of 5 foraminifera was analysed for $\delta^{18}\text{O}$ on a MAT253 with a
449 Kiel IV preparation device at Cardiff University. The remaining samples were cleaned
450 and dissolved in a fume hood equipped with HEPA filters under clean laboratory
451 conditions according to ref.³⁹. Analysis of Mg/Ca was conducted partially on a Thermo
452 Element XR at Cardiff University, partially on an Agilent Triple Quadrupole at the
453 University of St. Andrews. The instruments were cross-calibrated using the same in-

454 house standard. In both institutions, long term reproducibility of in-house standards
455 yielded RSDs of 1-3 %.

456 SST were calculated from *G. ruber* Mg/Ca using the transfer function and R-script from
457 ref.⁹

$$458 \quad \frac{Mg}{Ca} = e^{0.060(\pm 0.008)xT + 0.033(\pm 0.022)xS - 0.83(\pm 0.73)x(pH-8) - 1.07(\pm 0.80)}$$

459 where T is sea surface temperature, S is salinity, and pH is the negative decadic
460 logarithm of H⁺ ions. The method⁹ allows for the influence of pH and salinity on Mg/Ca,
461 and calculates SST and pH iteratively using Mg/Ca and Antarctic ice core *p*CO₂⁵³. This
462 underlies the assumption that the core site has been at CO₂ equilibrium, or constant
463 disequilibrium throughout the record⁹. Global ocean salinity and alkalinity are
464 calculated from the LR04 benthic δ¹⁸O stack⁴⁸ at each time step with modern salinity
465 assumed as 35 psu and modern alkalinity at 2300 μmol/kg⁹. For Late Pleistocene
466 records, *p*CO₂ can be taken from ice core measurements⁵³. Our data exceeds the
467 maximum length of the ice core by several thousand years. We therefore scale the
468 LR04 benthic δ¹⁸O stack⁴⁸ to the ice core *p*CO₂ record⁵³ (see ED Fig. 2a, b) to provide
469 an estimate of CO₂ change and assign a conservative uncertainty of ±40 μatm (2 σ)⁹.
470 SST uncertainties are calculated using Monte-Carlo propagation analysis which
471 accounts for errors on Mg/Ca measurement, SST-equation-calibration errors, salinity
472 errors prescribed as ±1 psu (2 σ), LR04 age model errors prescribed as 4 kyr, alkalinity
473 uncertainty prescribed as -25 to +75 μmol/kg about the modern value using a flat
474 probability distribution⁹.

475 Ice volume-corrected seawater δ¹⁸O (δ¹⁸O_{sw-ivc}) has been previously used as a proxy for
476 changes in relative seawater salinity in the surface Indian Ocean (e.g. ref.¹⁰). We
477 therefore correct our δ¹⁸O_{carbonate} according to

$$478 \quad \delta^{18}O_{sw-ivc} = \delta^{18}O_{carbonate} - \delta^{18}O_{temperature} - \delta^{18}O_{ice\ volume}$$

479 to reflect local δ¹⁸O_{sw} and interpret the results as changes in relative salinity.
480 δ¹⁸O_{temperature} was calculated from Mg/Ca-based temperatures and δ¹⁸O_{*G. ruber*} using the
481 transfer function of ref.⁵⁴ for Indian Ocean planktonic foraminifera with a correction
482 factor of +0.20⁵⁵. Analytical errors from δ¹⁸O_{carbonate} and Monte-Carlo-errors from SST

483 were propagated through the calculation. To determine the best correction curve for
 484 $\delta^{18}\text{O}_{\text{ice volume}}$ across the last 1.2Ma, we tested the impact of 4 different sea level
 485 reconstructions on the resulting $\delta^{18}\text{O}_{\text{sw-ivc}}$ (ED Fig. 4). Reconstructions of $\delta^{18}\text{O}_{\text{ice volume}}$
 486 from ref.⁴⁹ based on the LR04 stack⁴⁸ gave representative results over the last ~500
 487 kyr where different sea level reconstructions can be readily compared and also
 488 extends for the ~1.2 Myr duration of our record, and was therefore used to determine
 489 $\delta^{18}\text{O}_{\text{sw-ivc}}$. In Figures 2 and ED Fig. 2, we compare the U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ record to GMSL
 490 and the change in land/sea area in the Indonesian archipelago both of which are based
 491 on calculations using the U1476 $\delta^{18}\text{O}_{\text{benthic}}$ record⁵¹. Using $\delta^{18}\text{O}_{\text{ivc}}$ from ref.⁴⁹ as a
 492 correction factor may lead to age model uncertainties when comparing U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$
 493 ivc to U1476 $\delta^{18}\text{O}_{\text{benthic}}$ ⁵¹, and -related results. We therefore also corrected the U1476
 494 $\delta^{18}\text{O}_{\text{sw-ivc}}$ record with $\delta^{18}\text{O}_{\text{ivc}}$ modelled in ANICE using U1476 $\delta^{18}\text{O}_{\text{benthic}}$ ⁵¹. The resulting
 495 age model differences are minimal. For example, when correcting U1476 $\delta^{18}\text{O}_{\text{sw}}$ with
 496 U1476 $\delta^{18}\text{O}_{\text{ivc}}$, salinification occurs at GMSL of -45 m ($\sigma = 17$ m) relative to today which
 497 is nearly the same as calculated for the $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack and U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ corrected
 498 using $\delta^{18}\text{O}_{\text{ivc}}$ from ref.⁵¹.

499 To analyse the lead-lag time between our $\delta^{18}\text{O}_{\text{sw-ivc}}$, and SST data with $\delta^{18}\text{O}_{\text{benthic}}$ ⁵¹,
 500 we performed a cross spectral analysis **using the ARAND software package (new ref)**
 501 between $\delta^{18}\text{O}_{\text{sw-ivc}}$, or SST, and $\delta^{18}\text{O}_{\text{benthic}}$ ⁵¹. Both records were first clipped to 1350
 502 ka, then subsampled to 1 kyr. The resulting cross spectral analysis calculated an
 503 average lead time of 18 kyr in the $\delta^{18}\text{O}_{\text{sw-ivc}}$, and 14 kyr in SST to $\delta^{18}\text{O}_{\text{benthic}}$ at the 95 %
 504 confidence interval in the 100-ka periodicity. The phasing results show that both
 505 $\delta^{18}\text{O}_{\text{sw-ivc}}$ and SST lead $\delta^{18}\text{O}_{\text{benthic}}$ at the 95 % confidence interval.

506

507 SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack formation

508 The data for the SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ stacks was taken from 8 cores spread across the
 509 Indian Ocean. We included all cores covering at least the Holocene and LGM at 3 - 4
 510 kyr resolution which represent open ocean environments (i.e. to avoid coastal
 511 influences), and were able to provide: Mg/Ca- or alkenone-based SST data for the SST
 512 stack; Mg/Ca-based SST, and surface foraminifera-based $\delta^{18}\text{O}$ for the $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack.
 513 The resulting stacks include the following cores: Agulhas Bank Slice (ABS) (Mg/Ca_G.
 514 *bulloides*, $\delta^{18}\text{O}_{G. bulloides}$)³⁸, MD96-2048 (SST_{Alkenone}, $\delta^{18}\text{O}_{C. wuellerstorfi}$)³⁹, U1476 (Mg/Ca_G. *ruber*

515 and $\delta^{18}\text{O}_{G.ruber}$, this study; $\delta^{18}\text{O}_{C.wuellerstorfi}$ ⁵¹), WIND 28K ($\text{Mg}/\text{Ca}_{G.ruber}$, $\delta^{18}\text{O}_{G.ruber}$, $\delta^{18}\text{O}_{C.wuellerstorfi}$)¹⁰, TY93-929/P ($\text{Mg}/\text{Ca}_{G.ruber}$, $\delta^{18}\text{O}_{G.ruber}$)⁴⁰, MD90-0963 ($\text{SST}_{\text{Alkenone}}$, $\delta^{18}\text{O}_{G.ruber}$)^{41,42}, GeoB10038-4 ($\text{Mg}/\text{Ca}_{G.ruber}$, $\delta^{18}\text{O}_{G.ruber}$, $\delta^{18}\text{O}_{C.wuellerstorfi}$)⁴³, and MD01-2378 ($\text{Mg}/\text{Ca}_{G.ruber}$, $\delta^{18}\text{O}_{G.ruber}$)^{44,45}. We first re-calculated SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ data from all
519 cores using the same method as described in the methods above for U1476 to ensure
520 methodological consistency. The SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ stacks were then created by
521 splicing the records together and resampling by replacement within a moving 15 kyr
522 window centred on each real data point. The probability of selecting each data point
523 within the window was adjusted using two weights. The first uses a gaussian function
524 ($\sigma = 3$ kyr) to weight each point based on its distance from the centre of the window,
525 thus favouring closer data. The second weight is inversely proportional to the relative
526 representation of a given component record within the sampling window, thus acting
527 to mitigate sampling bias. The resampling was performed throughout the spliced
528 record 1000 times to produce a smoothed stack with 95% confidence intervals. Figure
529 2 in the main manuscript shows z-scores of the stacks.

530 We also incorporate age model uncertainties into the stack uncertainty. Because each
531 of the component records used in the stack use a combination of radiocarbon and
532 $\delta^{18}\text{O}$ alignment, we take a simple conservative approach and apply a 4 kyr
533 uncertainty⁴⁸ to the age models based on the estimated uncertainty for $\delta^{18}\text{O}$
534 alignment. This uncertainty was incorporated into the stack by adapting the method
535 of ref.⁵⁶, which involves applying an age shift of -2, -1, 0, +1, or +2 kyr (chosen with
536 equal probability) independently to each record during the construction of each of the
537 1000 synthetic records. $\delta^{18}\text{O}$ data are shown from each core alongside LR04⁴⁸ in ED
538 Fig. 3a and demonstrate a close alignment of age models for these cores on glacial-
539 interglacial timescales.

540

541 Alternative hypothesis testing

542 To test whether the salinification process is also evident in Indian Ocean source waters,
543 we additionally analysed SST core data from the western Pacific warm pool
544 (ODP806)⁴⁷ and the South China Sea (ODP1146)⁴⁶ for lead-lag against their respective

545 $\delta^{18}\text{O}_{\text{benthic}}$ using cross spectral analysis. For the analysis, SST and $\delta^{18}\text{O}_{\text{benthic}}$ data from
546 the cores was clipped to 6 - 1168 ka, then subsampled at 1 kyr. The cross spectral
547 analysis was conducted between the SST data and their respective $\delta^{18}\text{O}_{\text{benthic}}$ from the
548 same core using the resampled data. Neither core ODP806⁴⁷ or ODP1146⁴⁶ showed a
549 significant SST lead at the 95 % confidence interval.

550 We also used spectral analysis to test whether insolation or monsoon dynamics drive
551 our records. For this purpose, we used U1476, our calculated Indian Ocean surface
552 $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack, and ocean sediment core U1446 from the Bay of Bengal¹⁴. We find no
553 significant peak in the precession band for U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ and the Indian Ocean
554 $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack (ED Fig. 8), and no visual correlation between U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ and 15°
555 S July insolation⁵⁷ or African⁵⁸, Indian⁵⁹ or Southeast Asian⁶⁰ monsoonal proxies (ED
556 Fig. 9 c-j). As already pointed out by the authors, there is a significant precession peak
557 for U1446¹⁴ (ED Fig. 8). However, the most significant peak occurs in the 100 kyr
558 periodicity in all records (ED. Figs. 6 - 8). We therefore conclude that insolation and
559 monsoonal changes do not influence U1476 and that the monsoon signal in Indian
560 Ocean salinity records is overprinted by an ice volume signal to different degrees.

561

562 ANICE-SELEN sea level-topography model

563 Simulations of local relative sea level around the Indonesian archipelago were
564 executed using the coupled ice sheet – topography model ANICE-SELEN^{22,61}. The 3D
565 ice-sheet model ANICE produces a paleo-GMSL record and, in this study, is forced with
566 U1476 $\delta^{18}\text{O}_{\text{benthic}}$ data, which acts as a proxy for global ice sheet volume^{62,63} while also
567 minimising age model uncertainty in comparisons of model output to our data.
568 Additional inputs of present-day meteorological information, basal and ice sheet
569 height topography for Greenland and Antarctica, and higher resolution topography for
570 currently ice-free Eurasia and North America⁶¹ allow it to solve the ice sheet mass
571 balance for four global ice sheets Greenland, Antarctica, Eurasia, and North America
572 on a 2D grid⁶¹. This is achieved by decomposing the $\delta^{18}\text{O}_{\text{benthic}}$ record into its ice
573 volume and deep-water temperature components using an inverse approach,
574 modelling from the past into the present day⁶¹, where information from the $\delta^{18}\text{O}_{\text{benthic}}$

575 data determines the mass balance, and in return mass balance results influence the
576 modelled $\delta^{18}\text{O}$. The approach assumes that changes in Northern hemisphere (NH) mid
577 latitude-to-subpolar surface-air temperature anomalies (ΔT_{NH}) are strongly related to
578 changes in ice volume and deep-water formation. Changes in ΔT_{NH} are derived from
579 the difference between modelled $\delta^{18}\text{O}$ at time t , and foraminiferal $\delta^{18}\text{O}_{\text{benthic}}$ at time t
580 + 100 years⁶¹. Bedrock deformations due to changes in ice volume and resulting
581 influences on GMSL are considered by allowing a downward deflection of the flat
582 elastic lithosphere into a viscous asthenosphere as a result of pressure exerted from
583 above. The SELEN model solves the sea level equation (SLE) accounting for glacial-
584 hydro-isostatic adjustment on a global mesh²². In the coupled ANICE-SELEN version,
585 ANICE's ice sheet thickness information, in addition to initial topography information
586 which we assume to be present-day topography in this study, is used to calculate local
587 sea level stands at each GMSL time step as a result of glacial-hydro-isostatic
588 adjustment²². Any time lags in isostatic adjustment are accounted for by predicting
589 the effect of sea level change within the next 15 time-steps (around 15 000 years).
590 This information is also returned to ANICE, leading to a more accurate prediction of
591 ice sheet height in the four regional ice sheet models. During times of transient ice
592 sheet height changes, the predicted effect is continuously updated and considers the
593 influence of previous multiple time-steps on the time-step currently calculated²². In
594 the end, ANICE-SELEN exports two important variables which involve (i) a
595 reconstruction of GMSL as time transient curve, and (ii) a reconstruction of the local
596 sea level changes as geospatial maps which are made up of land and ocean pixels.

597 To gain understanding of the land surfacing and flooding rates around the Indonesian
598 archipelago across the Middle to Late Pleistocene (ED Fig. 10), we began running
599 ANICE from $t = 1.4$ Ma, then started the coupling process at 1.35 Ma with a 100 kyr
600 spin-up period (about 3 glacial cycles) to equilibrate the time-lag in isostatic
601 adjustment. To increase model-run efficiency, we disconnected SELEN after 10 glacial
602 cycles at 0.65 Ma, and ended ANICE modelling at $t = 0$ Ma. We extracted 598 global
603 topography maps from the period between 1250 ka and 651 ka at a temporal
604 resolution of 1 kyr and a spatial resolution of 1 pixel per ~ 5000 km². Each topography
605 map is linked to a period of time, where a GMSL value is calculated from ANICE. Since

606 the tectonics and geomorphology of the Indonesian Archipelago appear relatively
 607 constant across the last 1.2 Ma^{18,19}, we assume that any correlations between changes
 608 in the land-ocean ratio and GMSL should also be valid for younger glacial cycles. To
 609 calculate changes in above-sea level topography, all maps were processed in Python
 610 and cut to the same size, zooming in on the Indonesian archipelago (ED Fig. 10a). Each
 611 pixel was given a value of 0, or 1, for ocean, or land, respectively. Then, all pixels of
 612 the same value were counted up, and land-to-ocean ratios were calculated for each
 613 map as

$$614 \quad R_{land-ocean} = \frac{\sum Pixel_{land}}{\sum Pixel_{ocean}}$$

615 Changes in the land-to-ocean ratio with respect to GMSL [m] were calculated as

$$616 \quad \Delta R_{land-ocean} = \frac{R_{land-ocean}(GMSL(t+1)) - R_{land-ocean}(GMSL(t))}{GMSL(t+1) - GMSL(t)}$$

617 To identify trends in the sea/land ratio linked to regionally rising and falling sea level,
 618 we analysed peaks and troughs in the global mean sea level curve and defined the
 619 time between a peak and a trough as “falling”, and between a trough and a peak as
 620 “rising”. The land-ocean ratios corresponding to the different time slices were then
 621 sorted into ratios during rising, and ratios during falling GMSL, to understand the
 622 dynamics of sea/land changes that occur during rising GMSL and falling GMSL,
 623 respectively (see ED Fig. 10).

624

625 Salinity influence on AMOC in COSMOS

626 Four ocean circulation experiments were conducted in the comprehensive climate
 627 model COSMOS³³. These include the LGM (no freshwater hosing) control experiment,
 628 the LGM015 (freshwater hosing into the North Atlantic) experiment, the LGM015-
 629 SA01 (freshwater extraction in the South Atlantic equivalent to “saltwater hosing” in
 630 addition to freshwater hosing in the North Atlantic) experiment, and the LGM015-
 631 SA005 (weaker freshwater extraction in the South Atlantic equivalent to “saltwater
 632 hosing” in addition to freshwater hosing in the North Atlantic) experiment. Glacial
 633 state control settings are taken from the LGM-W experiment from ref.³³ which

634 currently provide the closest match with proxy data We allowed the model to run until
635 the glacial control settings were equilibrated (LGM experiment). Since deglaciations
636 begin with Heinrich events during which the AMOC is strongly suppressed, we
637 perturbed the equilibrium state glacial ocean circulation by imposing a constant 0.1Sv
638 Sv freshwater perturbation over the ice-rafted debris belt in the North Atlantic for 500
639 years (LGM015) (Figure 3) representative of a 10 m/kyr GMSL rise (see also ref.³³). We
640 then investigated effects of additional salinity perturbations on the Agulhas plateau
641 by removing freshwater from the region through enhanced evaporation. Two salt-
642 water perturbation experiments with evaporation equivalent of the removal of 0.05Sv
643 (LGM015-SA005) and 0.1 Sv (LGM015-SA01) freshwater, representing 1/3 and 2/3 of
644 the freshwater hosing force, were integrated for 800 years based on LGM015 (i.e.
645 under the background climate of persistent freshwater input in the North Atlantic)
646 (Figure 3). In addition, LGM015 is continued for additional 800 years to provide a
647 control run for AMOC changes in LGM015-SA005 and LGM015-SA01. We plot AMOC
648 variability as the AMOC index in Figure 3. Here, we define the AMOC index as the
649 maximum value of the stream function below the water depth of 500m north of 45°
650 N in the North Atlantic in depth-space, effectively representing changes in the rate of
651 North Atlantic deep-water formation and AMOC.

652

653 DATA AVAILABILITY

654 The geochemical datasets produced in this study are freely available at the data
655 repository Pangea.

656

657 CODE AVAILABILITY

658 Python code was used to calculate the stacks, and analyse the ANICE-SELEN image
659 outputs. Both are freely available on Zenodo, for stack calculation
660 (<https://zenodo.org/record/7478552>; DOI: 10.5281/zenodo.7478552), and ANICE-
661 SELEN image processing (<https://zenodo.org/record/7471500>; DOI
662 10.5281/zenodo.7471500).

663

664 ADDITIONAL REFERENCES

- 665 34. Lauvset, S. K., Lange, N., Tanhua, T., Bittig, H. C., Olsen, A. C., Kozyr, A.,
666 Àlvarez, M., Becker, S., Brown, P. J., Carter, B. R., Cotrim da Cunha, L.,
667 Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Jeansson, E.,
668 Jutterström, S., Jones, S. D., Karlsen, M. K., Lo Monaco, C., Michaelis, P.,
669 Murata, A., Pérez, F. F., Pfeil, B., Schirnack, C., Steinfeldt, R., Suzuki, T.,
670 Tilbrook, B., Velo, A., Wanninkhof, R., Woosley, R. J., and Key, R. M.
671 (2021). An updated version of the global interior ocean biogeochemical data
672 product, GLODAPv2.2021. *Earth System Sciences Data Discussion*, 1-32.
673 <https://doi.org/10.5194/essd-2021-234>
- 674 35. Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E.,
675 Rovere, M., Chayes, D., Ferrini, V., & Wigley, R. (2015). A new digital
676 bathymetric model of the world's oceans. *Earth and Space Science*, 2(8), 331–
677 345. <https://doi.org/10.1002/2015EA000107>
- 678 36. Schlitzer, Reiner, Ocean Data View, <https://odv.awi.de>, 2021
- 679 37. Pierre, C., Saliège, J. F., Urrutiaguer, M. J., & Giraudeau, J. (2001). *Stable*
680 *isotope record of benthic and planktonic foraminifera from ODP Site 175-1087*
681 *in the southern Cape Basin, Atlantic Ocean*. PANGAEA.
682 <https://doi.org/10.1594/PANGAEA.701338>
- 683 38. Martinez-Mendez, G., Zahn, R., Hall, I. R., Peeters, F. J. C., Pena, L. D., Cacho,
684 I., & Negre, C. (2010). Contrasting multiproxy reconstructions of surface
685 ocean hydrography in the Agulhas Corridor and implications for the Agulhas
686 Leakage during the last 345,000 years. *Paleoceanography*, 25(4).
687 <https://doi.org/10.1029/2009PA001879>
- 688 39. Caley, T., Kim, J.-H., Malaizé, B., Giraudeau, J., Laepple, T., Caillon, N.,
689 Charlier, K., Rebaubier, H., Rossignol, L., Castañeda, I. S., Schouten, S., &
690 Sinninghe Damsté, J. S. (2011). High-latitude obliquity as a dominant forcing
691 in the Agulhas current system. *Climate of the Past*, 7(4), 1285–1296.
692 <https://doi.org/10.5194/cp-7-1285-2011>
- 693 40. Barker, S., Greaves, M., & Elderfield, H. (2003). A study of cleaning

- 694 procedures used for foraminiferal Mg/Ca paleothermometry. *Geochemistry,*
695 *Geophysics, Geosystems*, 4(9), n/a-n/a.
696 <https://doi.org/10.1029/2003GC000559>
- 697 41. Rostek, F., Bard, E., Beaufort, L., Sonzogni, C., & Ganssen, G. (1997). Sea
698 surface temperature and productivity records for the last 240 kyr on the
699 Arabian Sea. *Deep-Sea Research Part II: Topical Studies in Oceanography*,
700 44(6–7), 1461–1480. [https://doi.org/10.1016/S0967-0645\(97\)00008-8](https://doi.org/10.1016/S0967-0645(97)00008-8)
- 701 42. Bassinot, F. C., Beaufort, L., Vincent, E., Labeyrie, L. D., Rostek, F., Müller, P.
702 J., Quidelleur, X., & Lancelot, Y. (1994). Coarse fraction fluctuations in pelagic
703 carbonate sediments from the tropical Indian Ocean: A 1500-kyr record of
704 carbonate dissolution. *Paleoceanography*, 9(4), 579–600.
705 <https://doi.org/10.1029/94PA00860>
- 706 43. Mohtadi, M., Lückge, A., Steinke, S., Groeneveld, J., Hebbeln, D., & Westphal,
707 N. (2010). Late Pleistocene surface and thermocline conditions of the eastern
708 tropical Indian Ocean. *Quaternary Science Reviews*, 29(7), 887–896.
709 <https://doi.org/https://doi.org/10.1016/j.quascirev.2009.12.006>
- 710 44. Xu, J., Holbourn, A., Kuhnt, W., Jian, Z., & Kawamura, H. (2008). Changes in
711 the thermocline structure of the Indonesian outflow during Terminations I
712 and II. *Earth and Planetary Science Letters*, 273(1–2), 152–162.
713 <https://doi.org/10.1016/j.epsl.2008.06.029>
- 714 45. Zuraida, R., Holbourn, A., Nürnberg, D., Kuhnt, W., Dürkop, A., & Erichsen, A.
715 (2009). Evidence for Indonesian Throughflow slowdown during Heinrich
716 events 3 to 5. *Paleoceanography*, 24(2), n/a-n/a.
717 <https://doi.org/10.1029/2008PA001653>
- 718 46. Herbert, T. D., Peterson, L. C., Lawrence, K. T., & Liu, Z. (2010). Tropical ocean
719 temperatures over the past 3.5 million years. *Science*, 328(5985), 1530–1534.
720 <https://doi.org/10.1126/science.1185435>
- 721 47. De Garidel-Thoron, T., Rosenthal, Y., Bassinot, F., & Beaufort, L. (2005). Stable
722 sea surface temperatures in the western Pacific warm pool over the past 1.75
723 million years. *Nature*, 433(7023), 294–298.
724 <https://doi.org/10.1038/nature03189>
- 725 48. Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57

- 726 globally distributed benthic δ 18O records. *Paleoceanography*.
727 <https://doi.org/10.1029/2004PA001071>
- 728 49. de Boer, B., Lourens, L. J., & Van De Wal, R. S. W. (2014). Persistent 400,000-
729 year variability of Antarctic ice volume and the carbon cycle is revealed
730 throughout the Plio-Pleistocene. *Nature Communications*, 5.
731 <https://doi.org/10.1038/ncomms3999>
- 732 50. Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte,
733 V., Abe-Ouchi, A., Otto-Bliesner, B., & Zhao, Y. (2012). Evaluation of climate
734 models using palaeoclimatic data. *Nature Climate Change* 2012 2:6, 2(6),
735 417–424. <https://doi.org/10.1038/nclimate1456>
- 736 51. Howell, P., Piasias, N., J. Ballance, J. Baughman, and L. Ochs, 2006. ARAND.
737 <https://github.com/jesstierney/arand>.
- 738 52. van der Lubbe, H. J. L., Hall, I. R., Barker, S., Hemming, S. R., Baars, T. F., Starr,
739 A., Just, J., Backeberg, B. C., & Joordens, J. C. A. (2021). Indo-Pacific Walker
740 circulation drove Pleistocene African aridification. *Nature* 598, 618-623.
741 <https://doi.org/10.1038/s41586-021-03896-3>
- 742 53. Ahn, S., Khider, D., Lisiecki, L. E., & Lawrence, C. E. (2017). A probabilistic
743 Pliocene–Pleistocene stack of benthic δ 18O using a profile hidden Markov
744 model. *Dynamics and Statistics of the Climate System*, 2(1).
745 <https://doi.org/10.1093/climsys/dzx002>
- 746 54. Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F.,
747 Fischer, H., Kipfstuhl, S., & Chappellaz, J. (2015). Revision of the EPICA Dome
748 C CO₂ record from 800 to 600 kyr before present. *Geophysical Research*
749 *Letters*, 42(2), 542–549. <https://doi.org/10.1002/2014GL061957>
- 750 55. Bouvier-Soumagnac, Y., & Duplessy, J.-C. (1985). Carbon and oxygen isotopic
751 composition of planktonic foraminifera from laboratory culture, plankton
752 tows and Recent sediment; implications for the reconstruction of
753 paleoclimatic conditions and of the global carbon cycle. *Journal of*
754 *Foraminiferal Research*, 15(4), 302–320.
755 <http://dx.doi.org/10.2113/gsjfr.15.4.302>
- 756 56. Pearson, P. N. (2012). Oxygen Isotopes in Foraminifera: Overview and
757 Historical Review. *The Paleontological Society Papers*, 18, 1–38.

- 758 <https://doi.org/10.1017/s1089332600002539>
- 759 57. Spratt, R. M., & Lisiecki, L. E. (2016). A Late Pleistocene sea level stack.
760 *Climate of the Past*, 12(4), 1079–1092. [https://doi.org/10.5194/cp-12-1079-](https://doi.org/10.5194/cp-12-1079-2016)
761 [2016](https://doi.org/10.5194/cp-12-1079-2016)
- 762 58. Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., & Levrard, B.
763 (2004). A long-term numerical solution for the insolation quantities of the
764 Earth. *Astronomy & Astrophysics*, 428(1), 261–285.
765 <https://doi.org/10.1051/0004-6361:20041335>
- 766 59. Johnson, T. C., Werne, J. P., Brown, E. T., Abbott, A., Berke, M., Steinman, B.
767 A., Halbur, J., Contreras, S., Grosshuesch, S., Deino, A., Scholz, C. A., Lyons, R.
768 P., Schouten, S., & Damsté, J. S. S. (2016). A progressively wetter climate in
769 southern East Africa over the past 1.3 million years. *Nature*, 537(7619), 220–
770 224. <https://doi.org/10.1038/nature19065>
- 771 60. Kathayat, G., Cheng, H., Sinha, A., Spötl, C., Edwards, R. L., Zhang, H., Li, X., Yi,
772 L., Ning, Y., Cai, Y., Lui, W. L., & Breitenbach, S. F. M. (2016). Indian monsoon
773 variability on millennial-orbital timescales. *Scientific Reports*, 6(1), 24374.
774 <https://doi.org/10.1038/srep24374>
- 775 61. Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S., Kelly, M.,
776 Kathayat, G., Wang, X., Li, X., Kong, X., Wang, Y., Ning, Y., & Zhang, H. (2016).
777 The Asian monsoon over the past 640,000 years and ice age terminations.
778 *Nature*, 534(7609), 640–646. <https://doi.org/10.1038/nature18591>
- 779 62. de Boer, B., van de Wal, R. S. W., Lourens, L. J., Bintanja, R., & Reerink, T. J.
780 (2013). A continuous simulation of global ice volume over the past 1 million
781 years with 3-D ice-sheet models. *Climate Dynamics*, 41(5), 1365–1384.
782 <https://doi.org/10.1007/s00382-012-1562-2>
- 783 63. Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I. N., Hodell,
784 D., & Piotrowski, A. M. (2012). Evolution of ocean temperature and ice
785 volume through the mid-Pleistocene climate transition. *Science*, 337(6095),
786 704–709. <https://doi.org/10.1126/SCIENCE.1221294/>
- 787 64. Shackleton, N. J. (1987). Oxygen isotopes, ice volume and sea level.
788 *Quaternary Science Reviews*, 6(3–4), 183–190. [https://doi.org/10.1016/0277-](https://doi.org/10.1016/0277-3791(87)90003-5)
789 [3791\(87\)90003-5](https://doi.org/10.1016/0277-3791(87)90003-5)

- 790 65. Grant, K. M., Rohling, E. J., Bronk Ramsey, C., Cheng, H., Edwards, R. L.,
791 Florindo, F., Heslop, D., Marra, F., Roberts, A. P., Tamisiea, M. E., & Williams,
792 F. (2014). Sea-level variability over five glacial cycles. *Nature Communications*
793 *2014 5:1*, 5(1), 1–9. <https://doi.org/10.1038/ncomms6076>
- 794 66. Wang, P., Tian, J., & Lourens, L. J. (2010). Obscuring of long eccentricity
795 cyclicity in Pleistocene oceanic carbon isotope records. *Earth and Planetary*
796 *Science Letters*, 290(3–4), 319–330.
- 797 67. U.K. Met Office (2010). Cartopy: A cartographic python library with a
798 matplotlib interface. *Exeter, Devon*.
- 799 68. Natural Earth (2015). Free vector and raster map data. Available at
800 www.naturalearthdata.com

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817 S.N. collected, analysed and interpreted the data. S.N. wrote the paper, with support
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826

827 AUTHOR INFORMATION

828 *Competing interests*

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833

834 EXTENDED DATA LEGENDS

835 Extended Data Fig. 1 U1476 sea surface hydrography reconstructions in comparison
836 to U1476 benthic oxygen isotopes

837 (a), (c), and (f) benthic foraminifera $\delta^{18}\text{O}^{51}$ on inverted y-axes (light blue lines), (b)
838 planktonic $\delta^{18}\text{O}_{\text{carbonate}}$ from *G. ruber* on inverted y-axis (green line; this study), (d)
839 planktonic Mg/Ca with log-scale y-axis and (e) calculated SSTs (red line; this study)
840 with Monte-Carlo propagated errors including analysis, age model, and equation
841 calibration errors plotted as red shaded envelope, (g) calculated ice-volume corrected
842 $\delta^{18}\text{O}_{\text{sw-ivc}}$ for the surface ocean as proxy for salinity, derived from the $\delta^{18}\text{O}_{G. ruber}$ and
843 SST records (dark green; this study) with propagated errors including Monte-Carlo SST-,
844 and $\delta^{18}\text{O}_{G. ruber}$ -analysis errors plotted as dark green shaded envelope. The centre of
845 each deglaciation is indicated by dashed vertical lines and labelled T1 to T16. Note the
846 increases in SST and $\delta^{18}\text{O}_{\text{sw-ivc}}$ during glacial periods (grey shaded bars).

847

848 Extended Data Fig. 2 Derivation and alternative derivations of the newly presented
849 climate proxies

850 (a) Atmospheric CO₂ from Antarctic ice cores⁵³ (pink) and calculated using linear
851 transfer from the LR04 benthic $\delta^{18}\text{O}$ stack⁴⁸ (dark red), which is plotted in (b). (c)
852 Resulting SST calculations using the method of ref.⁹ with ice core CO₂⁵³ (pink), and
853 LR04⁴⁸-based CO₂ (dark red). (d) Difference between $\delta^{18}\text{O}$ of global ice volume⁴⁹ (blue)
854 and U1476 seawater (this study) prior to the ice volume correction (green). The large
855 difference suggests that there is a substantial local salinity signal which cannot be
856 explained by whole ocean changes. (e) Age model comparison using benthic $\delta^{18}\text{O}$ for
857 all sites in Fig. 2 (this study and refs^{23,28,29}). (f) U1476 salinity proxy (dark green; this
858 study); dark green diamonds highlight times of salinification onset, and (g) GMSL⁴⁹
859 (pink) highlighting sea level stands at times of salinification onset in pink dots. The
860 analysis corresponds to Fig. 2e, f, and results in the same average GMSL stand (dashed
861 pink line) at which salinification occurs. Deglaciations are plotted as dashed vertical
862 lines, and intervals of rising $\delta^{18}\text{O}_{\text{sw-ivc}}$ prior to each glacial termination are indicated
863 with vertical grey bars. Note y-axes in (b), (d), and (e) are inverted.

864

865 Extended Data Fig. 3 Indian Ocean salinity and temperature stack construction

866 (a) Age model comparison using benthic $\delta^{18}\text{O}$ for all cores included in the stacks on an
867 inverted y-axis. The colours of the labels correspond to the coloured lines in all panels.
868 References for all cores are listed in Figure 1 and Methods. (b) All SST records which
869 are included in the SST stack. (c) All salinity proxy records which are included in the
870 salinity stack. (d) z-scores of all SST records included in the SST stack, the SST stack
871 (thick black line) with 95th percentile error envelope (grey shaded band), and an SST
872 stack excluding U1476 data with 95th percentile envelope (orange shaded band). (e) z-
873 scores of all salinity proxy records included in the salinity stack, the salinity stack (thick
874 black line) with 95th percentile error envelope (grey shaded band), and a salinity stack
875 excluding U1476 data with 95th percentile envelope (orange shaded band). Note that
876 there is no difference in the onset of the salinification and warming between the black

877 and orange stacks suggesting that U1476 does not force the stack calculations.
 878 Intervals of rising $\delta^{18}\text{O}_{\text{sw-ivc}}$ prior to each glacial termination are indicated with vertical
 879 grey bars.

880

881 Extended Data Fig. 4 Salinity reconstruction using different global mean sea level
 882 corrections

883 (a) $\delta^{18}\text{O}_{\text{sw-ivc}}$ records derived using 4 different GMSL reconstructions for the ice volume
 884 correction. U1476 $\delta^{18}\text{O}_{\text{benthic}}^{51}$ is plotted in b) for lead-lag comparison. Grey bars
 885 highlight the early increase in $\delta^{18}\text{O}_{\text{sw-ivc}}$ prior to terminations. The ref.⁴⁹ ice volume
 886 correction allowed modelled ice volume $\delta^{18}\text{O}$ to be used (dark green). For other GMSL
 887 reconstructions^{64,65}, a change of 1 % in $\delta^{18}\text{O}_{\text{benthic}}$ per 120 m GMSL, or maximum
 888 reconstructed GMSL was assumed. The colour of each $\delta^{18}\text{O}_{\text{sw-ivc}}$ record corresponds
 889 with the referenced scenario in the other panels. (c) Absolute $\delta^{18}\text{O}_{\text{sw-ivc}}$ amplitude of
 890 the glacial $\delta^{18}\text{O}_{\text{sw-ivc}}$ maxima compared to the preceding minima for all 4 $\delta^{18}\text{O}_{\text{sw-ivc}}$
 891 scenarios. The colours of the bars correspond to the referenced scenarios in (a). Note
 892 that differences between different scenarios are relatively small. (d) Corresponding
 893 ice volume $\delta^{18}\text{O}$ curves for the 4 GMSL reconstructions. The colours of each line
 894 correspond with the referenced scenario in (a). Intervals of rising $\delta^{18}\text{O}_{\text{sw-ivc}}$ prior to
 895 each glacial termination are indicated with vertical grey bars in (a). Note y-axes in (b)
 896 and (d) are inverted.

897

898 Extended Data Fig. 5 Surface hydrography in the source regions of the ITF and Indian
 899 Ocean

900 (a) U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ (dark green), (b) U1476 Mg/Ca-derived sea surface temperatures
 901 (orange) (this study), and (c) U1476 $\delta^{18}\text{O}_{\text{benthic}}^{51}$ (thin blue line) from the western
 902 Indian Ocean. (d) Alkenone-derived sea surface temperatures (light pink) and (e)
 903 $\delta^{18}\text{O}_{\text{benthic}}$ (thin blue line) from the South China Sea⁴⁶. (f) Mg/Ca-derived sea surface
 904 temperatures (brown) and (g) $\delta^{18}\text{O}_{\text{benthic}}$ (thin blue line) from the western Pacific warm
 905 pool⁴⁷. Onset of U1476 glacial salinification highlighted in grey bars. Note that both

906 South China Sea, and western Pacific warm pool records do not show a similarly
907 consistent lead-lag pattern between their respective SST and $\delta^{18}\text{O}_{\text{benthic}}$ data. Note
908 $\delta^{18}\text{O}_{\text{benthic}}$ data is presented on inverted y-axes.

909

910 Extended Data Fig. 6 Spectral analysis results for U1476 climate proxies

911 Spectral analysis of U1476 SST (a), $\delta^{18}\text{O}_{\text{sw-ivc}}$ (b), and $\delta^{18}\text{O}_{\text{benthic}}^{51}$ (c); as well as SST z-
912 score stack (e), $\delta^{18}\text{O}_{\text{sw-ivc}}$ z-score stack (f), and LR04 $\delta^{18}\text{O}_{\text{benthic}}$ stack for comparison (g).
913 Peaks above the red line are significant at the 95% interval. Black dashed vertical lines
914 indicate precession (23 kyr), obliquity (41 kyr), and eccentricity (100 kyr) periodicities.

915

916 Extended Data Fig. 7 Cross spectral analysis results for U1476 climate proxies showing
917 lead-lag characteristics

918 Cross spectral analyses showing coherence (red) and phase (black) between U1476
919 SST, $\delta^{18}\text{O}_{\text{sw-ivc}}$, and $\delta^{18}\text{O}_{\text{benthic}}^{51}$ (top, a-c); and SST stack, $\delta^{18}\text{O}_{\text{sw-ivc}}$ stack, and LR04
920 $\delta^{18}\text{O}_{\text{benthic}}$ stack⁴⁸ (bottom, d-f). Coherence data above the red, and purple, line
921 indicates significant coherence between datasets at the 95 %, and 80 %, significance
922 level. Phase data at times of significant coherence above the black line (Phase = 0)
923 indicate significant lead of the first variable. Precession (23 kyr), obliquity (41 kyr), and
924 eccentricity (100 kyr) periodicities are indicated by vertical black dashed lines.

925

926 Extended Data Fig. 8 Spectral and cross-spectral analysis results for previously
927 published hydrography data from U1446 in the Bay of Bengal

928 (a) Spectral analysis of $\delta^{18}\text{O}_{\text{benthic}}$, and (b) $\delta^{18}\text{O}_{\text{sw-ivc}}$. (c) Phase and coherence between
929 $\delta^{18}\text{O}_{\text{benthic}}$ and $\delta^{18}\text{O}_{\text{sw-ivc}}$. Black horizontal line shows Phase = 0; positive/negative phase
930 values indicate 1st variable/2nd variable in the header leading the other variable.
931 Vertical brown line indicates coherence 95% confidence interval. Precession (23kyr),
932 obliquity (41kyr), and eccentricity (100kyr) periodicities are indicated by vertical black
933 dashed lines. All data that went into this analysis was previously published in (ref)¹⁴.

934

935 Extended Data Fig. 9 Indian Ocean hydroclimate proxies compared to U1476 salinity

936 (a) 15° S July summer insolation⁵⁷. (b) – (d), (f), (h), (j), (l), (n), (p) U1476 $\delta^{18}\text{O}_{\text{sw-ivc}}$ (this
937 study). (c) U1476 $\delta^{18}\text{O}_{\text{benthic}}$ ⁵¹ on inverted y-axis. (e) Malawi Lake SST, proxy for African
938 Monsoon variability⁵⁸. (g) Speleothem $\delta^{18}\text{O}_{\text{CaCO}_3}$ from Dongge Cave, China, proxy for
939 Southeast Asian Summer Monsoon variability⁶⁰. (i) Speleothem $\delta^{18}\text{O}_{\text{CaCO}_3}$ from Bittoo
940 Cave, India, proxy for Indian Summer Monsoon variability⁵⁹. (k) TY93-929/P $\delta^{18}\text{O}_{\text{sw-ivc}}$,
941 Arabian Sea surface ocean salinity proxy⁴⁰. (m) U1446 $\delta^{18}\text{O}_{\text{sw-ivc}}$, Bay of Bengal sea
942 surface salinity proxy¹⁴. (o) GeoB10038-4 $\delta^{18}\text{O}_{\text{sw-ivc}}$ ⁴³, eastern Indian Ocean. Grey
943 vertical bars highlight the period of salinification in U1476 which is also visible in the
944 Arabian Sea, Bay of Bengal, and eastern Indian Ocean sea surface salinity proxies.

945

946 Extended Data Fig. 10 Changes in land surface as a function of changes in global mean
947 sea level

948 (a) Pixels occurring within the orange polygon were used to calculate the land/sea
949 ratio in each time-slice map created by the ANICE-SELEN model. (b) Change in land to
950 sea surface ratio in the Indonesian archipelago as modelled by the coupled ice sheet-
951 topography model ANICE-SELEN for a subset of 9 glacial-interglacial cycles in respect
952 to GMSL. Changes occurring from falling and rising sea level are plotted in blue and
953 orange respectively – the hysteresis between falling and rising sea levels results from
954 the delayed response of the solid Earth to changes in ocean water surface loading. (c)
955 Slope of the land/sea surface ratio as a function of GMSL to highlight specific sea levels
956 at which the rate of land exposure during sea level fall, or land flooding during sea
957 level rise, is particularly fast with respect to the change in GMSL. Vertical blue shaded
958 bars highlight the GMSL interval within which the change in ratios at GMSL fall is
959 particularly fast. The map in (a) was plotted using the library Cartopy⁶⁶ in Python.
960 Outlines for countries are taken from ref⁶⁷.

Indian Ocean surface circulation







