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How to cite:

Nilsson-Kerr, K.; Anand, P.; Sexton, P. F.; Leng, M. J.; Misra, S.; Clemens, S. C. and Hammond, S. J. (2019). Role of Asian summer monsoon subsystems in the inter-hemispheric progression of deglaciation. *Nature Geoscience*, 12 pp. 290–295.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1038/s41561-019-0319-5>

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1 **Role of Asian summer monsoon subsystems in the inter-hemispheric progression of**
2 **deglaciation**

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13 **The response of Asian Monsoon subsystems to both hemispheric climate forcing and**
14 **external orbital forcing are currently issues of vigorous debate. The Indian Summer**
15 **Monsoon is the dominant monsoon subsystem in terms of energy flux, constituting one of**
16 **Earth's most dynamic expressions of ocean-atmosphere interactions. Yet the Indian**
17 **Summer Monsoon is grossly under-represented in Asian Monsoon palaeoclimate records.**
18 **Here we present high-resolution records of Indian Summer Monsoon induced rainfall**
19 **and fluvial runoff recovered in a sediment core from the Bay of Bengal across**
20 **Termination II, 139 to 127 thousand years ago, including coupled measurements of the**
21 **oxygen isotopic composition and Mg/Ca, Mn/Ca, Nd/Ca and U/Ca ratios in surface-ocean**
22 **dwelling foraminifera. Our data reveal a millennial-scale transient strengthening of the**
23 **Asian Monsoon that punctuates Termination II associated with an oscillation of the**

24 **bipolar seesaw. The progression of deglacial warming across Termination II emerges first**
25 **in the southern hemisphere then the tropics in tandem with Indian Summer Monsoon**
26 **strengthening and finally the northern hemisphere. We therefore suggest that the Indian**
27 **Summer Monsoon was a conduit for conveying southern hemisphere latent heat**
28 **northwards, thereby promoting subsequent northern hemisphere deglaciation.**

29 Early modelling studies that attempted to evaluate the response of the boreal summer monsoon
30 to orbital forcing identified Northern Hemisphere (NH) solar insolation (during precession_{min})
31 as a primary driver, via its influence on land-ocean thermal contrasts¹. Palaeoclimate records
32 of the ISM support this view but also commonly invoke NH climate controls² owing to the
33 coincidence of weak Indian Summer Monsoon (ISM) intervals with North Atlantic Heinrich
34 Events^{2, 3}. These millennial scale cooling events originating in the high latitudes of the NH
35 have been linked to the ISM via atmospheric³ and oceanic⁴ teleconnections. Similarly, East
36 Asian Summer Monsoon (EASM) speleothem oxygen isotope ($\delta^{18}\text{O}$) records, inferred to reflect
37 both upstream depletion of $\delta^{18}\text{O}$ from tropical moisture sources and regional precipitation
38 amount⁵, have been linked to both NH solar insolation and North Atlantic forcing⁶, although
39 this interpretation has been recently questioned in light of new EASM rainfall records^{7, 8}.
40 Despite this prevailing view of NH forcing of the Asian Monsoon on millennial to orbital
41 timescales, some observations from ISM records have pointed to additional mechanisms
42 influencing ISM behaviour⁹⁻¹¹. The nature of variance in the obliquity band and lag of ISM
43 maxima with precession_{min} suggests a component of Southern Hemisphere (SH) forcing
44 through latent heat export^{9, 10}. Understanding of the ISM at timescales beyond the last glacial
45 period mainly derives from orbital-scale records from the Arabian Sea and southern Bay of
46 Bengal (BoB) (Fig. 1a). Records from these locations have applied proxies that have been
47 assumed to be representative of upwelling and changes in water column stratification driven
48 by ISM winds. However, the extent to which the ISM exclusively controls these proxies

49 remains unclear. Thus, what is urgently required to enhance our understanding of the ISM are
50 records of rainfall and runoff from the ISM's core convective region, the northern BoB in order
51 to isolate a primary and direct signal of ISM strength.

52 Here we report new geochemical records from well preserved planktic foraminifera at a sub-
53 millennial scale resolution (~250-500 years) spanning Termination II (TII, 139 to 127 thousand
54 years ago (ka)) from IODP 353, Site U1446 in the northern BoB. Site U1446 is situated in the
55 core convective region of the ISM, under the direct influence of ISM-induced rainfall and
56 fluvial runoff received from one of the world's largest river systems (Ganges-Brahmaputra).
57 Figure 1(b-e) shows the southward propagation of the ISM induced freshwater plume derived
58 from the Ganges-Brahmaputra systems, engulfing Site U1446 during the peak summer
59 monsoon season. This site is thus ideally situated to capture the signal of ISM derived rainfall,
60 fluvial runoff and sediment delivery from the Indian subcontinent. We have produced a detailed
61 stratigraphy for Site U1446 that is tied to the Antarctic Ice Core (AICC2012) chronology¹²
62 (Methods, Supplementary Fig. 1). To evaluate changes in the surface ocean salinity response
63 to rainfall and runoff, we combine oxygen isotope ($\delta^{18}\text{O}_c$) and Mg/Ca-derived SSTs from the
64 planktic foraminifera *Globigerinoides ruber (sensu-stricto)* to reconstruct $\delta^{18}\text{O}$ of seawater
65 ($\delta^{18}\text{O}_{\text{sw}}$) (Methods) (Fig. 2B n).

66 We also present Mn/Ca, Nd/Ca and U/Ca ratios (Supplementary Fig. 8) of *G. ruber ss* calcite
67 in a novel application to reconstruct fluvial runoff, where high concentrations of Mn, Nd and
68 U are delivered from the continental hinterland by the ISM's vigorous hydrological and
69 weathering regime¹³⁻¹⁵. This regime exerts a strong seasonal bias on the vertical and lateral
70 distribution of dissolved 'lithogenic' elements within the BoB¹⁴, with a strong lithogenic signal
71 existing in the upper 100m of the northern BoB as a result of high terrigenous fluxes¹⁵. The
72 origin of Nd in planktic foraminiferal calcite remains controversial with the Nd being attributed
73 to either reflect in-situ seawater Nd signal¹⁶, a mixed signal from sediments and bottom

74 waters¹⁷ or to arise from intra-test organic matter¹⁸. We interpret our foraminiferal Mn/Ca,
75 Nd/Ca and U/Ca data to reflect a primary signal of upper ocean chemistry modulated by high
76 fluxes of lithogenic elements from high fluvial runoff for several reasons. First, the
77 foraminifera cleaning method we applied included a reductive cleaning step that ensures
78 removal of Fe-Mn coatings added on the foraminifera test at the sediment-water interface¹⁹.
79 Second, Mn/Ca correlates with Nd/Ca and U/Ca (Supplementary Fig. 7), suggesting that the
80 concentrations of these elements are all derived from the same dominant process (i.e. in this
81 hydrographic setting, fluvial runoff). Third, the concentrations of lithogenic elements in
82 modern seawater in the northern BoB are much higher than for global average seawater¹⁵
83 (owing to high dissolved elemental fluxes from the continent, driven by the ISM). Fourth, the
84 observed concentrations of these elements are beyond what is typically found in planktic
85 foraminifera²⁰. We normalised Mn/Ca, Nd/Ca and U/Ca to unit variance²¹ to produce a stack
86 of *G. ruber ss* geochemical tracers of fluvial runoff (Fig. 2B m) (Methods). The range of values
87 exhibited by this runoff tracers record overlaps with the range of these same elements in
88 modern *G. ruber ss* as measured from a 2005 sediment trap in the northern BoB (red vertical
89 bar in Fig. 2B m). This underscores that our *G. ruber ss*-based stacked record of Mn, Nd and
90 U concentrations is recording high concentrations of these elements in local seawater (derived
91 from high runoff fluxes), rather than being a post-depositional phenomenon via diagenetic
92 alteration of the foraminiferal calcite. Therefore, comparing *G. ruber ss* $\delta^{18}\text{O}_{\text{sw}}$ and *G. ruber ss*
93 runoff tracers together provides a novel opportunity to reconstruct changes in both salinity and
94 fluvial runoff sourced directly from the ISM. Application of these runoff tracers in *G. ruber ss*
95 as representing ISM river fluxes is supported by elemental signatures of continental origin from
96 discrete portable X-Ray Fluorescence (pXRF) measurements on bulk sediment samples that
97 are purely diagnostic of continental detrital input from runoff (Al, Ti, K, Rb) (Fig. 2B l)
98 (Methods, Supplementary Fig. 9).

99 Our high-resolution time series of $\delta^{18}\text{O}_{\text{sw}}$, *G. ruber ss* runoff tracers and pXRF element stack
100 show a similar pattern of ISM behaviour across TII, accounting for the differing intensity in
101 the response and thresholds between surface freshening and riverine sediment fluxes²². The
102 data reveal a brief intensification of the ISM from ~134 to 133 ka, reflected as a decrease in
103 $\delta^{18}\text{O}_{\text{sw}}$ (Fig. 2B n), an increase in *G. ruber ss* runoff tracers (Fig. 2B m), and pXRF element
104 stack (Fig. 2B l) late in Marine Isotope Stage (MIS) 6, prior to TII onset. This was immediately
105 preceded by a ~1 kyr duration SST warming in the BoB (Fig. 2B o), suggesting advection of
106 SH heat across the equator provided a crucial precondition²³ for the subsequent transient
107 strengthening of monsoonal circulation at 134 ka. Our data show that the ISM then undergoes
108 two phases of deglacial strengthening; first at ~131 to 130 ka, followed by a further
109 strengthening at ~129 ka, with the final attainment of a vigorous interglacial ISM coeval with
110 the development of full deglaciation into the Last Interglacial (MIS 5e) (Fig. 2B).

111 **Interstadial within Termination II**

112 The structure of the last two terminations, TI and TII, is fundamentally different (Fig. 2,
113 Methods). TI is punctuated by several millennial scale events, manifested in the Bølling-
114 Allerød and Younger Dryas, associated with fluctuations in Atlantic Meridional Overturning
115 Circulation (AMOC)²⁴ (Fig. 2A). Such millennial scale events have remained largely
116 unidentified in reconstructions of TII. However, we identify a climatic event punctuating TII,
117 evident in ISM rainfall and runoff (Fig. 2B l, m and n) at ~134 to 133 ka, prior to the timing of
118 TII deglaciation in the NH²⁵. We refer to this event as the Termination II Interstadial (TII IS).
119 ISM strengthening during the TII IS was preceded by a 1°C warming in *G. ruber ss* derived
120 SSTs at ~135 ka (Fig. 2B o). This warming coincides with early deglaciation in the SH (Fig.
121 2B i, k) but with the establishment of cool condition in the North Atlantic associated with
122 Heinrich Stadial 11 (HS11) onset²⁶. We infer that this SST warming in the BoB reflects cross-
123 equatorial heat transport in response to contemporaneous warming in the SH. These SH-

124 derived energy fluxes, advecting northwards, leads to the transient strengthening of the ISM
125 that marks the TII IS (Fig. 2B l, m and n). We thus attribute the TII IS to a transient oscillation
126 of the bipolar seesaw, akin to mechanisms proposed for TI^{24, 27}. The TII IS is also depicted in
127 other NH records, a western Mediterranean Sea SST record^{26, 28} (Fig. 2B f) and the EASM
128 speleothem $\delta^{18}\text{O}$ record^{6, 29} (Fig. 2B e). Further support for a cross-equatorial northward flux
129 of SH-derived heat through a bipolar seesaw mechanism is provided by a cooling in the South-
130 East Atlantic coeval with the TII IS, which has been attributed to a reduction in Agulhas
131 Leakage associated with a northward shift of the atmospheric belts towards the warmer
132 (northern) hemisphere³⁰. The timing of TII IS is within error of Meltwater Pulse 2B (MWP 2B,
133 133 ± 1 ka)²⁶. Thus, it appears that TII IS may have contributed to rapid retreat of NH ice sheets
134 and the resulting MWP 2B owing to heat import into the NH. The resulting enhanced
135 freshwater fluxes into the North Atlantic³¹ causes an intensification of HS11 (Fig. 2B c, d),
136 cooling of the NH and the ending of TII IS associated with a southward shift of the Inter-
137 Tropical Convergence Zone (ITCZ)³². Recent work has argued for a robust North Atlantic
138 control on the EASM^{6, 29}. Yet our findings for a SH origin for the transient EASM strengthening
139 during TII IS, perhaps via the ISM, reveal that the nature of these inter-hemispheric controls
140 on a given monsoonal subsystem is not fixed, but dynamic across different timescales.

141 **Inter-hemispheric progression of deglaciation**

142 The nature of deglaciation during TII is thought to be a result of orbital preconditioning; an
143 earlier maximum in SH solar insolation 10 kyr prior to NH solar insolation maxima promoting
144 earlier Antarctic warming²⁵ (Fig 2B b). Furthermore, obliquity_{max} (Fig. 2B a) was reached prior
145 to precession_{min}³³ (Fig. 2B b), triggering an increased inter-hemispheric temperature contrast
146 and strengthening of the Hadley Cell in the warmer (southern) hemisphere. The colder
147 (northern) hemisphere is compensated by increased cross-equatorial heat transport³⁴. Figure 3
148 shows the statistically determined timings³⁵ of regional deglaciation throughout TII. The

149 combination of obliquity_{max} and early deglacial SH warming (Fig. 3h) dictates that heat and
150 moisture transported to the ISM would have been across the equator from the southern Indian
151 Ocean. We thus conclude that SH sourced energy fluxes (Fig. 3h) were responsible for early
152 deglacial strengthening of the ISM at ~131 to 130 ka (Fig. 3e-g). A contemporaneous early
153 deglacial warming occurs in the western Mediterranean^{26, 28} (Fig. 3d) that we infer reflects
154 adiabatic descent from the descending limb of the Hadley Cell³⁶, propagating SH sourced
155 energy fluxes northward. This northward propagation of SH heat and moisture into higher NH
156 latitudes was slowed by the persistence of a cold North Atlantic with HS11 (Fig. 3a, b).
157 Subsequently, the inter-hemispheric progression of deglacial warming is propagated into the
158 higher latitudes of the North Atlantic (Fig. 3a, b) with associated EASM strengthening (Fig.
159 3c). Our ISM records (Fig. 2B m, n) show strong covariance with the Antarctic CH₄ record
160 (Fig. 2B j) during both the TII IS and broader deglaciation. This finding supports hypotheses
161 that call for tropical wetlands as being an important global methane source during glacial-
162 interglacial transitions and that the tropical monsoonal system plays a fundamental role in
163 regulating concentrations of this greenhouse gas³⁷.

164 **Millennial-scale phasing of Asian Monsoon subsystems**

165 Our ISM records across TII provide insights into the relationship between the two main Asian
166 Monsoon subsystems at the millennial scale. Deglacial ISM strengthening is temporally
167 decoupled from EASM strengthening by ~1 to 2 kyr (Fig. 3). We infer that this lag is not
168 associated with respective age-models and instead ultimately reflects the time transgressive
169 nature of deglacial strengthening in the Asian Monsoon subsystems and influence of differing
170 forcing mechanisms triggering this strengthening. The makeup of these two monsoonal
171 subsystems is quite different; differing land-ocean configurations, atmospheric and ocean
172 dynamics³⁸ thus, it is likely that during major changes in background climate state the ISM and
173 EASM exhibit such time-transgressive responses.

174 Our findings thus allow us to reject the hypothesis of a singular common (NH) forcing
175 mechanism of the Asian Monsoon⁶. Therefore, despite the iconic nature of the EASM
176 speleothem records⁶, our high-resolution ISM rainfall and runoff data suggest that the
177 assumption that they are representative of the Asian Monsoon as a whole needs to be
178 reconsidered, at least on millennial timescales. This decoupling of the ISM and EASM across
179 TII may owe its origins to the complexities and large-scale variation in the moisture supply
180 amalgamated in the speleothem $\delta^{18}\text{O}$ signal^{8, 39}. Our new records point to a greater dynamism
181 in the mechanisms regulating Asian Monsoon rainfall beyond just teleconnections to the North
182 Atlantic⁶. This emphasises the need for more high-resolution palaeoclimate time series that are
183 directly influenced by monsoonal rainfall, for both the EASM and ISM, in order to shed further
184 light on the mechanism and feedbacks regulating monsoonal subsystems.

185 Our findings from TII indicate that the ISM is a key inter-hemispheric link in the transfer of
186 heat and moisture between the warm SH into the colder NH (Fig. 3). Our sub-millennial scale
187 records provide support for hypotheses that argue for an important role of the tropics⁴⁰ in
188 conveying SH latent heat northwards into the NH, thereby promoting NH deglaciation.
189 However, the evolution of the ISM captured in our data suggests that a fully strengthened
190 ‘interglacial’ mode of the ISM cannot be attained until the NH experiences full deglacial
191 climatic amelioration (Fig. 3). Our results highlight the need for explicit differentiation
192 between the ISM and EASM owing to their respective sensitivities to fundamentally different
193 components of the Earth system during global climate change. Our data also reveal that inter-
194 hemispheric climatic controls on the two primary monsoonal subsystems are dynamic across
195 different timescales and that, during a glacial transition, these two monsoonal subsystems can
196 be governed by different inter-hemispheric controls.

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325 **Acknowledgements**

326 We thank Peter Webb for his help with setting up pXRF analysis, Hilary Sloane for her help
327 with stable isotope analysis, P. Divakar Naidu for providing 2005 NBBT sediment traps. We
328 thank three anonymous reviewers for their insightful comments and suggestions that improved
329 this manuscript. P. A. and K.N-K. acknowledge funding through a NERC PhD grant
330 (NE/L002493/1) associated with the CENTA Doctoral Training Partnership. Samples were
331 provided by the International Ocean Discovery Program (IODP). Stable isotope analysis of
332 planktic foraminifera was funded by NIGFSC grant IP-1649-1116 to P.A.

333 **Author contributions**

334 P.A. conceived the research idea and further developed it with K.N-K. K.N-K processed
335 samples, picked foraminifera, and conducted foraminifera cleaning and trace element analysis
336 under guidance from P.A. and S.M. M.J.L. over saw the stable isotope analysis and S.J.H.
337 helped with trace element analysis. S.C.C. produced benthic oxygen isotope data for age model
338 development. K.N-K., P.A. and P.F.S. discussed the data interpretation and wrote the
339 manuscript, and all authors contributed to the final text.

340 **Competing interests**

341 The authors declare no competing interests.

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344

345 **Figure 1. ISM induced freshening in the Bay of Bengal** a) Map depicting ISM inferred wind-
346 driven upwelling and stratification records (as circles: pink⁴¹, purple⁴², blue⁹, orange⁴⁴, black⁴⁵
347 and green¹⁰) that extend across TII. Yellow circle indicates Bittoo cave². b-e) Average monthly
348 sea surface salinity during 2017 ISM months⁴⁵ exhibiting proliferation of fluvial input. Site
349 U1446 is indicated by red star. f) Winter (black) and summer (red) monsoon season
350 temperature (solid) and salinity (dashed) depth profiles⁴⁶ above Site U1446. Shaded bar
351 indicates inferred depth range of *G. ruber ss*. Figure created using Ocean Data View software
352 (<http://odv.awi.de/>).

353

354 **Figure 2. Sequence of global events across TI (A) and TII (B)** a) Obliquity³³ b) June 21st
355 and December 21st insolation³³ c) ODP 983, North Atlantic, IRD⁴⁷ d) ODP 983 % NPS⁴⁷ e)
356 EASM speleothem $\delta^{18}\text{O}^6$ f) ODP 976, western Mediterranean, SST^{26, 28} g) Bittoo Cave
357 speleothem $\delta^{18}\text{O}^2$ h) ISM $\delta^{18}\text{O}_{\text{sw-IVC}}$ stack⁴⁸⁻⁵⁰ i) MD97-2120, southwest Pacific, SST⁵¹ j) EDC
358 CH_4 ^{37, 12} k) EDC $\delta\text{D}^{52, 12}$ l) U1446 pXRF stack m) U1446 *G. ruber ss* (red) and *N. dutertrei*
359 (brown) runoff tracers. Red bar shows modern sediment trap data range n) U1446 *G. ruber ss*
360 (green) and *N. dutertrei* (grey) $\delta^{18}\text{O}_{\text{sw-IVC}}$ and o) U1446 SST. Star represents modern day mean
361 annual SST at study site⁴⁶. Shaded envelopes represent 1σ (Methods). Red triangles represent
362 age control points contained within interval shown and associated AICC2012 chronology
363 errors¹² (Methods).

364

365 **Figure 3. TII onset and duration** a) ODP 983, North Atlantic, % NPS⁴⁷ on AICC2012
366 chronology¹² b) ODP 1063, Atlantic Ocean, % Warm species⁵³ on AICC2012 chronology¹² c)
367 EASM speleothem $\delta^{18}\text{O}$ ⁶ d) ODP 976, western Mediterranean Sea, SST²⁸ on Corchia Cave
368 radiometrically constrained chronology²⁶ e) U1446 *G. ruber ss* runoff tracers (this study) f)
369 U1446 *G. ruber ss* $\delta^{18}\text{O}_{\text{sw-IVC}}$ (this study) g) U1446 pXRF stack h) EDC δD ⁵² on AICC2012
370 chronology¹². Pink shaded area denotes t_2 (deglaciation onset) and t_1 (attainment of
371 interglacial) as modelled using RAMPFIT³⁵ (Methods).

372 **Methods**

373 Site U1446 (19°5.02'N, 85°44'E) was drilled during IODP Expedition 353 and located at a
374 depth of 1430 meters below sea level in the Mahanadi Basin⁵⁴. The BoB represents the core
375 convective region of the ISM due to the thermodynamic structure of the water column resulting
376 in positive ocean-atmosphere feedbacks favouring high SSTs (>28°C) allowing convection to
377 be sustained during the summer monsoon months of June through to September⁵⁵. The ISM
378 exerts a strong seasonal signature of surface water freshening and stratification within the BoB
379 due to a net surface water exchange of $184 \times 10^{10} \text{ m}^3$ during the ISM months⁵⁶. ISM induced
380 river runoff generates a north-south salinity gradient; the northern BoB undergoes a reduction
381 in salinity of 9‰ during this period⁵⁷.

382 **Age Model**

383 The much expanded nature of the sediment sequence at Site U1446 (~25 cm/ka), and
384 consequent high fidelity of our palaeoclimatic records, significantly reduces the error of the
385 duration of events and the rates of change inferred from our records⁵⁸. Using Analyseries⁵⁹ we
386 graphically correlated benthic foraminifera (*Uvigerina spp.* and *Cibicidoides wuellerstorfi*)
387 $\delta^{18}\text{O}$ (Clemens, S. C., unpublished data) to benthic $\delta^{18}\text{O}$ from south Pacific core PS75/059-2⁶⁰
388 (Supplementary Fig. 1a). This itself is tied to the AICC2012 chronology¹² by exploiting the

389 age-depth relationship from PS75/059-2 Fe dust flux record⁶¹ which has been tuned to the EDC
390 Antarctic ice core^{61, 62} (Supplementary Fig. 2). Tuning to AICC2012 was chosen rather than
391 the absolute dated EASM speleothem record to allow for independent assessment of the
392 lead/lag relationship between the ISM and the EASM. We infer that our records are not biased
393 to the high latitudes of the southern hemisphere by our tuning strategy due to synchronicity
394 existing between the Chinese Loess magnetic susceptibility record with EDC Antarctic ice core
395 dust fluxes⁶². To ascertain our confidence in our age model, we further tied U1446 benthic $\delta^{18}\text{O}$
396 to ODP Leg. 117, Site 1146 benthic $\delta^{18}\text{O}$ which has been transferred to the speleothem
397 chronology⁶³. We present site U1446 benthic $\delta^{18}\text{O}$ on three different age models (AICC2012¹²,
398 RC2011⁶³ and LR04⁶⁴) (Supplementary Fig. 1c) in order to confirm the lead of U1446 ISM
399 records over the EASM across TII regardless of chronology (Supplementary Fig. 3).

400 We used Bchron⁶⁵, a Bayesian probability model, to model the 95% uncertainty envelope
401 between tie points with the AICC2012 chronology error (modelled as Gaussian distribution)
402 of EPICA Dome C at those points¹² (Supplementary Fig. 1b).

403 All datasets used to assess relative lead and lag relationships are on a consistent age-model;
404 that of AICC2012¹² or absolute radiometrically constrained chronology^{2, 6, 26} (see original
405 references for detail).

406 **Foraminiferal stable isotope and trace metal analysis**

407 The planktic foraminifera *Globigerinoides ruber sensu-stricto* (*ss*), was identified using the
408 taxonomic description in ref. 66. Between 6 to 30 individuals were picked from the 250-355 μm
409 size-fraction and gently crushed prior to analysis. Oxygen isotope analyses were performed at
410 the British Geological Survey, NERC Isotope Geoscience Facilities, Keyworth using an
411 Isoprime dual inlet mass spectrometer with Multiprep device. The reproducibility of oxygen
412 isotope measurements is $\pm 0.05\text{‰}$ (1σ) based on replicate measurements of carbonate standards.
413 All data are reported in the usual delta notation ($\delta^{18}\text{O}$) in ‰ on the VPDB scale.

414 For trace metal analysis, samples were cleaned using a modification of the method described
415 in ref. 19 and reversal of the oxidative and reductive steps⁶⁷. Due to the proximal setting of Site
416 U1446 an extended clay removal step was essential in order to ensure removal of any fine clays
417 that may bias Mg content in carbonate samples. Samples were initially rinsed with repeated
418 MQ and methanol rinses with ultrasonification of 40 seconds between each rinse. Samples were
419 then inspected under a microscope and any discoloured fragments, fragments with pyrite or
420 silicate particles were removed. Subsequently samples were subjected to a reductive and 10%
421 oxidative step to ensure removal of any coatings and organics. Samples were then polished
422 using a weak (0.001M) HNO₃ leaching step and dissolved (0.075M HNO₃) on the day of
423 analysis. Samples were analysed at the Open University using an Agilent Technologies Triple-
424 Quad ICP-MS. Contaminant ratios (Al/Ca and Fe/Ca) were monitored in order to assess any
425 clay and organic contaminations (Supplementary Fig. 4).

426 **Estimating temperature and $\delta^{18}\text{O}_{\text{sw}}$**

427 The addition of a reductive step during foraminiferal trace element cleaning has been shown to
428 reduce Mg/Ca values⁶⁸. Following ref. 69, we apply a correction for a 10% reduction in Mg/Ca
429 associated with the reductive method due to the chosen temperature calibration being based on
430 analysis using only the oxidative step⁷⁰. The Mg/Ca temperature calibration used was
431 accordingly adjusted:

$$432 \quad \text{Mg/Ca} = 0.38(\pm 0.02) \exp((0.09 \pm 0.003) * T)^{70}$$

$$433 \quad \text{Adjusted Mg/Ca} = 0.342 \exp(0.09T)$$

434 An ice volume correction was applied to the calcite $\delta^{18}\text{O}_c$ following the Red Sea Level Curve
435 (95% probability maximum)⁷¹ with a conversion factor $\delta^{18}\text{O}$ enrichment of 0.008‰ per meter
436 sea level lowering applied⁷²:

$$437 \quad \delta^{18}\text{O}_{\text{IVC}}(t) = \delta^{18}\text{O}(t) + (\text{RSL}(t) * 0.008)$$

438 The temperature estimates derived from Mg/Ca and the measured calcite $\delta^{18}\text{O}_c$ of planktic
439 foraminifera allows for the derivation of seawater $\delta^{18}\text{O}_{\text{sw}}$:

$$440 \quad T^{\circ}\text{C} = 14.9(\pm 0.1) - 4.8(\pm 0.08) * (\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}}) - 0.27\text{‰}^{73}$$

441 The $\delta^{18}\text{O}_{\text{sw}}$ has been shown to correlate strongly with salinity in the northern BoB. Factors
442 controlling this relationship include precipitation, river runoff and evaporation thus during the
443 summer monsoon months precipitation and runoff exceeds evaporation promoting a low
444 $\delta^{18}\text{O}_{\text{sw}}$ -Salinity Slope^{74, 75}. However, we do not convert U1446 $\delta^{18}\text{O}_{\text{sw}}$ to salinity using modern
445 day calculated regressions due to observation of significant spatiotemporal variations and
446 uncertainties in assumptions associated with extending these relationships into the past⁷⁴.
447 Furthermore, recent work has indicated the potential control salinity exerts on Mg-
448 incorporation in foraminiferal calcite⁷⁶. Low salinity during the warmer ISM season may
449 potentially dampen our reconstructed SSTs based on Mg/Ca relative to actual SST however,
450 there would be a limited overall effect on the reconstructed $\delta^{18}\text{O}_{\text{sw}}$.

451 *N. dutertrei* is typically inferred to represent thermocline conditions (~70-120m)
452 accompanying the deep chlorophyll maximum^{77, 78}. However, across the TII IS *N. dutertrei*
453 shows more depleted $\delta^{18}\text{O}_{\text{sw-IVC}}$ values than surface dwelling *G. ruber ss* (Fig. 2B n). We infer
454 that this is associated with the unique hydrographic conditions that Site U1446 experiences and
455 that *N. dutertrei* occupies a shallower depth, in the freshwater lens of the upper water column,
456 than what is typically inferred. Additionally, available Mg/Ca calibrations based on upper
457 thermocline habitat, and therefore a narrower temperature range, underestimates the
458 temperature values for *N. dutertrei* thus resulting in more depleted $\delta^{18}\text{O}_{\text{sw-IVC}}$ values as the
459 calcite $\delta^{18}\text{O}$ values are more enriched than *G. ruber ss* (Supplementary Fig. 5). During the TII
460 IS, *G. ruber ss* and *N. dutertrei* $\delta^{18}\text{O}_{\text{sw-IVC}}$ is decoupled by ~100 years (Fig. 2B n) highlighting
461 the vertical flux of ISM induced freshening.

462 Error propagation of the temperature and $\delta^{18}\text{O}_{\text{sw}}$ estimates was calculated using the following
 463 equations⁷⁹ where Mg/Ca standard deviation is $0.029\text{mmol/mol}^{-1}$ and $\delta^{18}\text{O}_c$ is 0.05‰ based on
 464 repeated analysis of internal standards. The error propagation is based on assumptions of no
 465 covariance among a, b, T and $\delta^{18}\text{O}_c$ ⁷⁹:

$$466 \quad \sigma_T^2 = \left(\frac{\partial T}{\partial a} \sigma_a\right)^2 + \left(\frac{\partial T}{\partial b} \sigma_b\right)^2 + \left(\frac{\partial T}{\partial \text{Mg/Ca}} \sigma_{\text{Mg/Ca}}\right)^2$$

467 where:

$$468 \quad a = 0.342(\pm 0.02)^{70}$$

$$469 \quad b = (0.09 \pm 0.003)^{70}$$

$$470 \quad \frac{\partial T}{\partial a} = -\frac{1}{a^2} \ln\left(\frac{\text{Mg/Ca}}{b}\right)$$

$$471 \quad \frac{\partial T}{\partial b} = -\frac{1}{ab}$$

$$472 \quad \frac{\partial T}{\partial \text{Mg/Ca}} = \frac{1}{a} \times \frac{1}{\text{Mg/Ca}}$$

$$473 \quad \sigma_{\delta^{18}\text{O}_{\text{sw}}}^2 = \left(\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial T} \sigma_T\right)^2 + \left(\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial a} \sigma_a\right)^2 + \left(\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial b} \sigma_b\right)^2 + \left(\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial \delta^{18}\text{O}_c} \sigma_{\delta^{18}\text{O}_c}\right)^2$$

474 where:

$$475 \quad a = 14.9(\pm 0.1)^{73}$$

$$476 \quad b = -4.8(\pm 0.08)^{73}$$

$$477 \quad \frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial T} = -\frac{1}{b}$$

$$478 \quad \frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial a} = \frac{1}{b}$$

479
$$\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial b} = \frac{T}{b^2} - \frac{a}{b^2}$$

480
$$\frac{\partial \delta^{18}\text{O}_{\text{sw}}}{\partial \delta^{18}\text{O}_{\text{c}}} = 1$$

481 To further constrain errors associated with calculating SST and $\delta^{18}\text{O}_{\text{sw}}$ we used Paleo-Seawater
482 Uncertainty Solver (PSUSolver)⁸⁰. PSUSolver models uncertainties associated with age model,
483 calibrations, analytical and sea level estimate errors by performing bootstrap Monte Carlo
484 simulations⁸⁰. Accounting for AICC2012 age model errors¹² we input an average age model
485 error of 2 ka and analytical errors; Mg/Ca of 0.029mmol/mol⁻¹ and $\delta^{18}\text{O}_{\text{c}}$ is 0.05‰, in order for
486 PSUSolver to probabilistically constrain the median estimate and confidence intervals for SST
487 and $\delta^{18}\text{O}_{\text{sw}}$ (Supplementary Fig. 6a). To assess the influence age model error exerts on U1446
488 SST and $\delta^{18}\text{O}_{\text{sw}}$ we also input an age model error of 1 ka (Supplementary Fig. 6b) and 0 ka
489 (Supplementary Fig. 6c). This indicates that age model errors exert the strongest influence on
490 PSUSolver SST and $\delta^{18}\text{O}_{\text{sw}}$. An average age model error of 2 ka renders the TII IS
491 inconspicuous. However, we have confidence in our original U1446 SST and $\delta^{18}\text{O}_{\text{sw}}$
492 interpretations despite the associated errors with the AICC2012 chronology owing to TII IS
493 having been resolved in other independently dated records (Fig. 2B) and the coherence of
494 U1446 $\delta^{18}\text{O}_{\text{sw}}$ with deglacial warming in western Mediterranean Sea SST records from ODP
495 Site 976²⁸ (Fig. 3) that has a radiometrically constrained age model²⁶.

496 **Interpreting Mn/Ca, Nd/Ca & U/Ca as river runoff proxies**

497 Mn/Ca ratios measured in foraminifera are typically used as an indicator of contamination of
498 foraminifer calcite from authigenic Mn-rich oxide coatings on the foraminifer shell. Our Mn/Ca
499 data display no correlation with Mg/Ca ($r^2=0.0894$), strongly arguing against the presence of
500 Mn-rich oxide coatings on our foraminifera that would bias our Mg/Ca-derived SSTs. The
501 foraminifera cleaning method applied in this study had the reductive cleaning step included,

502 which ensures removal of Fe-Mn coatings, added on the carbonate tests at the sediment-water
503 interface^{19, 68}. Mn/Ca correlates with Nd/Ca and U/Ca (Supplementary Fig. 7), reinforcing
504 evidence that these elements are delivered to our study site via fluvial runoff and can thus be
505 used as runoff proxies in this proximal setting. High fluvial fluxes in the BoB reflect the
506 monsoon region's vigorous hydrological and concomitant weathering regime. This is
507 expressed by the vast quantities of material discharged via the rivers; the Ganges-Brahmaputra
508 systems contribute alone 1.06 x 10⁹ tonnes of sediment annually⁸¹. Such a unique hydrographic
509 setting allows high concentrations of dissolved lithogenic elements (Mn, Nd, U) to be
510 precipitated (either as authigenic or biogenic carbonate phases) upon mixing with seawater.
511 The observed concentrations of these elements at Site U1446 are well beyond the
512 concentrations that are typically found in planktic foraminifera²⁰. Similarly, elevated levels of
513 Mn/Ca, Nd/Ca and U/Ca ratios have been found in planktic foraminifera from Ceara Rise, ODP
514 Site 926, receiving amazon fluvial fluxes^{82, 83}. Furthermore, we generated trace element data
515 for *G. ruber ss* from NBBT-05-S sediment trap from the northern BoB. The range of values
516 exhibited by this runoff tracers record (Mn, Nd and U) overlaps with the range found in the
517 NBBT-05-S sediment trap data (Fig. 2B m). Thus, we interpret Mn/Ca, Nd/Ca and U/Ca ratios
518 in *G. ruber ss* (Supplementary Fig. 8) as a proxy for fluvial runoff at marginal sites and suggest
519 that they could be further ground-truthed for application in other marginal marine settings.
520 Owing to the similarity between Mn/Ca, Nd/Ca and U/Ca we normalise using the standard
521 deviation²¹:

$$522 \quad /Ca(t)_{\text{norm}} = \frac{/Ca(t) - \overline{/Ca}}{\sigma(/Ca)}$$

523 Where:

524 $/Ca(t)$ (e.g. Mn/Ca) represents the trace element to Ca ratio at a given time.

525 \overline{X}/Ca represents the mean of all the trace element to Ca ratios (e.g. Mn/Ca) across study
526 interval.

527 $\sigma(X)/Ca$ represents the standard deviation of the trace element to Ca ratio across study interval.

528 Subsequently we average these values ($X/Ca(t)_{norm}$) for each of the tracers to produce a factor
529 representing *G. ruber ss* runoff tracers. Furthermore, there is a similar signature among these
530 tracers with the data gained from pXRF (Supplementary Fig. 9).

531 **Discrete portable X-Ray Fluorescence Analysis**

532 Analysis of major and minor elements was performed using a Niton XL3t900 portable X-Ray
533 Fluorescence (pXRF). Prior to analysis 5 grams of material was weighed, dried in an oven at
534 40°C and subsequently homogenized into a fine powder through use of a pestle and mortar.
535 The powdered material was transferred into 7ml vials, sealed tightly with non-PVC Clingfilm
536 and placed flush over the aperture of the X-ray emitter (Saker-Clark, M., per comms).
537 Calibration for each element of interest was performed through analysis of geochemical in-
538 house and reference powdered rock standards with known concentrations. A set of internal and
539 reference standards were run every 10th sample for quality control (Supplementary Table 1).
540 Bulk sediment elemental geochemistry is controlled by detrital (i.e. terrigenous input via river
541 runoff) and authigenic processes. Therefore, in order to reconstruct ISM derived river runoff a
542 selection of inferred terrigenous derived elements were selected to represent increased fluvial
543 runoff and detrital input to the site; Ti, K, Al and Rb (Supplementary Fig. 9). These elements
544 were combined through normalising to unit variance (described in the above section for *G.*
545 *ruber ss* runoff tracers) to produce a factor of pXRF runoff element variations²¹ due to showing
546 strong correlation with each other (Supplementary Fig. 10). In order to clarify the inconsistency
547 in elements chosen to represent fluvial runoff between the pXRF element stack and the *G.*
548 *ruber ss* tracers: i) Uranium concentrations in discrete U1446 samples were below detection

549 limit and Nd was not measured and ii) Mn concentrations in ocean sediments is complicated
550 by redox processes and therefore, not a suitable candidate for representing the detrital phase in
551 bulk sediment elemental profiles. We infer that due to increased terrigenous supply during a
552 strengthened ISM, reduced bottom water conditions are established, resulting in Mn reduction
553 and dissolution into pore waters due to the increased solubility of reduced Mn (Mn^{2+})⁸⁴⁻⁸⁷. In
554 contrast, during times of weaker ISM and reduced terrigenous supply, aerobic conditions
555 promote formation of solid-phase Mn oxyhydroxides and thus increase in Mn concentrations in
556 the bulk sediment (Supplementary Fig. 9)⁸⁴⁻⁸⁷. This reasoning is coherent with conditions found
557 in the Cariaco Basin, proximal to high terrigenous fluxes via river runoff⁸⁸.

558 **Detection of TII Change Points**

559 In order to empirically assess deglaciation onset during TII we employed the RAMPFIT³⁵
560 algorithm. RAMPFIT segments the data into three parts using a weighted least squares
561 regression and brute force to find two breakpoints denoted as $t1$ and $t2$ ³⁵. RAMPFIT was used
562 to estimate deglaciation onset ($t1$) and duration ($t2$) in the EASM speleothem $\delta^{18}O$ record⁶,
563 ODP 976 western Mediterranean Sea SST^{26,28}, ODP 1063 % warm species⁵³, ODP 983 %
564 NPS⁴⁷, EPICA Dome C δD ⁵² and U1446 $\delta^{18}O_{sw}$, *G. ruber ss* runoff tracers and pXRF stack
565 (Fig. 3). These records were chosen in order to identify the proliferation of deglaciation across
566 the NH having propagated from the SH. 400 iterations of wild bootstrap with seed generator
567 number of 400 was used to determine the uncertainties (Supplementary Table. 2).

568 **Comparison of TII with TI**

569 The same methods described above were employed to characterise deglaciation across TI
570 (Supplementary Fig. 10). Our results for TII demonstrate the sequence of deglaciation having
571 been driven from the SH, a lagged NH response and the ISM contributing to the inter-
572 hemispheric transfer of heat and moisture. Furthermore, we highlight the out-of-phase
573 behaviour between the EASM and ISM (Fig. 3). However, this is in contrast to the sequence

574 of events across TI in which the ISM appears to be in-phase with the EASM and other NH
575 climate records (Supplementary Fig. 11). Our results from TII thus exemplify the heterogeneity
576 between TI and TII that draws on previous work in which orbital preconditioning is regarded
577 as the driver in dictating the internal climate feedback response^{89, 90}. Furthermore, the
578 behaviour of the ISM during TII may be a result of the anomalous orbital conditions which
579 stray from classic Milankovitch theory⁹¹. The early rise in NH solar insolation during TI is
580 thought to have initiated deglaciation with rapid NH ice sheet retreat occurring from ~19-20
581 ka⁹² resulting in AMOC shutdown and subsequent warming in the SH⁹³. This is in contrast to
582 TII where the earlier rise in SH summer insolation occurs 10 ka prior to NH solar insolation
583 increase^{25, 94}. We postulate based on the opposing hemispheric controls on the ISM during TI
584 and TII that the ISM is not hemispherically biased but is governed by inter-hemispheric climate
585 controls in comparison to the predominantly NH-forced EASM⁶.

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686 **Data Availability**

687 Data generated from this study (IODP Exp. 353, Site U1446) are available via the National
688 Geoscience Data Centre (NGDC), DOI: 10.5285/061d77af-a805-4cf0-b969-0b8f042fae74.

689 Antarctic EDC ice-core records presented on AICC2012 chronology are available from:

690 <https://doi.pangaea.de/10.1594/PANGAEA.824883> and

691 <https://doi.pangaea.de/10.1594/PANGAEA.824891>

692 The EASM composite speleothem $\delta^{18}\text{O}$ record is available from:

693 <https://www.ncdc.noaa.gov/paleo-search/study/20450>

694 Bittoo Cave speleothem $\delta^{18}\text{O}$ record is available from:

695 <https://www.ncdc.noaa.gov/paleo-search/study/20449>

696 ODP 983 and 1063 data is available as a supplementary data set associated with Ref. 53.

697 ODP 976, western Mediterranean Sea SST data on Corchia radiometrically constrained
698 chronology is available as a supplementary dataset associated with Ref. 26.

699 Benthic $\delta^{18}\text{O}$ of PS75/059-2 is available at: <https://doi.org/10.1594/PANGAEA.833422>

700 PS75/059-2 on AICC2012 chronology at: <https://doi.org/10.1594/PANGAEA.826580>.

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