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1 **Concurrent Asian monsoon strengthening and early modern human dispersal**
2 **to East Asia during the last interglacial**

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30 Main Text

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32 **Abstract**

33 **The relationship between initial *Homo sapiens* dispersal from Africa to East Asia and the orbitally**
34 **paced evolution of the Asian summer monsoon (ASM)—currently the largest monsoon**
35 **system—remains underexplored due to lack of coordinated synthesis of both Asian**
36 **paleoanthropological and paleoclimatic data. Here we investigate orbital-scale ASM dynamics**
37 **during the last 280 thousand years (kyr) and their likely influences on early *H. sapiens* dispersal to**
38 **East Asia, through a unique integration of (i) new centennial-resolution ASM records from the**
39 **Chinese Loess Plateau, (ii) model-based East Asian hydroclimatic reconstructions, (iii)**
40 **paleoanthropological data compilations, and (iv) global *H. sapiens* habitat suitability simulations.**
41 **Our combined proxy- and model-based reconstructions suggest that ASM precipitation responded**
42 **to a combination of Northern Hemisphere ice volume, greenhouse gas, and regional summer**
43 **insolation forcing, with co-occurring primary orbital cycles of ~100-kyr, 41-kyr, and ~20-kyr.**
44 **Between ~125 and 70 kyr ago, summer monsoon rains and temperatures increased in vast areas**
45 **across Asia. This episode coincides with the earliest *H. sapiens* fossil occurrence at multiple**
46 **localities in East Asia. Following the transcontinental increase in simulated habitat suitability, we**
47 **suggest that ASM strengthening together with Southeast African climate deterioration may have**
48 **promoted the initial *H. sapiens* dispersal from their African homeland to remote East Asia during**
49 **the last interglacial.**

50 **Significance Statement**

51 The precise role of climate shifts in early human dispersal to East Asia is important in paleoclimatology
52 and paleoanthropology. Our proxy- and model-integrated paleoclimate reconstructions for the last 280
53 thousand years reveal a dynamic response of Asian summer monsoon variability to the combined effects
54 of orbital-scale insolation, Northern Hemisphere ice volume, and greenhouse gas changes. By comparing
55 paleoclimate data with a new compilation of *H. sapiens* fossil and archaeological finds from Asia and
56 simulated global *H. sapiens* habitat suitability, we show that orbitally-modulated summer monsoon
57 rainfall and temperature increases in East Asia and Southeast African climate deterioration may have
58 promoted the early *H. sapiens* dispersal out of Africa, to the more remote region(s) of East Asia, during
59 the last interglacial.

60 **Main Text**

61 Anatomically modern human (AMH), or *Homo sapiens*, emerged in Africa at least 200–300
62 thousand years ago (ka) (1, 2). Integrated paleoclimatic and paleoanthropological data have shown that
63 orbital-scale regional climate variability played a key role in driving AMH dispersal within Africa and to
64 adjacent Middle East (3-7). However, such integrated investigations remain sparse for South and East
65 Asia, despite spanning a much larger areal extent and wider range of climatic and biographical zones
66 than Africa, and hosting multiple important *H. sapiens* fossils dated back to ~100 ka (8-10) (Fig. 1).
67 Moreover, South and East Asia serve as a land conduit through which AMH dispersed from Africa to
68 Australia, Polynesia, and ultimately the Americas (8, 9) (Fig. 1). Thus, understanding *H. sapiens* fossils
69 and archaeological finds in appropriate paleoclimatic context is essential to developing a global
70 perspective on AMH evolution and dispersal beyond Africa.

71 The Asian summer monsoon (ASM), comprising of the South (Indian) and East Asian sub-monsoon
72 systems, governs moisture supply across low-latitude regions like the African monsoon, as well as to
73 Asian latitudes as high as ~50°N, as is observed in northeastern China (Fig. 1). This far-reaching areal
74 extent, and hence, climatic impact of the ASM, is globally unique. After decades of proxy and modeling
75 research, however, ASM dynamics and its orbital-scale variations remain a subject of scientific debate
76 (11-22). Furthermore, the precise role of orbital ASM dynamics on early *H. sapiens* dispersal to East
77 Asia is an important topic in both paleoclimatological and paleoanthropological research, yet our
78 understanding of it remains limited due to the scarcity of integrated ASM and paleoanthropological
79 studies.

80 Here we develop new insight into the climatic influence on the dispersal of AMH to East Asia and
81 orbital-scale ASM dynamics during the last 280 thousand years (kyr). Firstly, we study orbital-scale
82 ASM dynamics by combining new centennial-resolution environmental magnetic records from the
83 central Chinese Loess Plateau (CLP) with model-based continuous East Asian hydroclimate
84 reconstructions (23) for the last 280 kyr. Secondly, we integrate proxy- and model-based spatiotemporal
85 paleoclimatic reconstructions with Asian paleoanthropological and hydroclimatic data compilations and
86 global *H. sapiens* habitat suitability simulations. We find that settling and dispersal conditions were
87 optimal for the initial wave of AMH dispersal to East Asia during the last interglacial, when the stronger
88 summer monsoon caused warmer and more humid conditions, while the coeval Southeast African
89 conditions became less favorable.

90 **New ASM records from the CLP.** The CLP (~640,000 km²) extends longitudinally from ~100 to 115°E
91 and latitudinally from ~34 to 41°N (Fig. S1). The present-day climate on the CLP is dominated by
92 seasonally-alternating southeasterly summer and northwesterly winter monsoon changes (22, 24, 25)
93 (Fig. S1). The southeasterly wind penetration inland from tropical oceans (Fig. 1) produces summer time
94 (May–September) rain that accounts for ~60–75% of the annual total (22, 24). Materials forming CLP
95 loess-paleosol deposits are transported predominantly by near-surface winter monsoon winds from
96 upstream arid northwestern China (25-27). Within the loess package, the extent of soil formation
97 depends on moisture availability that is governed by the ASM. Thus, the CLP loess-paleosol deposits
98 were widely used for paleo-monsoon reconstructions (12, 22, 24-26, 28).

99 Our study site, the Huanxian loess-paleosol section (107°15'E, 36°37'N), is located on the central
100 CLP and sensitive to ASM penetration (Fig. S1). In this section, the loess-paleosol sequence

101 accumulated rapidly, with a sedimentation rate twice that of the classical sections located to the south
102 and east. This enables investigation of the orbital-scale ASM variability at the Huanxian section in
103 greater detail than typical. To measure ASM proxies in the laboratory, including magnetic susceptibility
104 (χ) and anhysteretic remanent magnetization (ARM), we collected in the field 2,066 samples from the 44
105 m thick strata, which covers from Holocene paleosol S_0 to mid-Pleistocene loess L_3 , ranging between
106 marine isotope stage (MIS) 1 and MIS 8, at 2–2.5 cm intervals (equivalent to a temporal resolution of
107 ~0.1–0.8 kyr). Our age model reconstruction for the Huanxian loess-paleosol section consists of two
108 steps (cf. Methods and Fig. S2). First, an initial age model was constructed through a detailed
109 cycle-based correlation of χ with a globally averaged marine benthic foraminiferal $\delta^{18}\text{O}$ stack. Second,
110 our final age model was based on a further, even more precise alignment, of our initial Huanxian
111 loess-paleosol chronology to precisely U/Th-dated speleothem $\delta^{18}\text{O}$ records from East China (15).
112 Support for our chronology construction comes independently from recent optically stimulated
113 luminescence dating (29) (Fig. S2D).

114 Rock magnetic analyses suggest that the Huanxian loess-paleosol magnetic properties are
115 dominated by fine-grained magnetite/maghemite particles (Figs. S3–S7; Supplementary Text 1).
116 Enhanced pedogenesis within the sediment column under wetter climate accelerates formation of fine
117 magnetite/maghemite particles, leading to higher χ and ARM values, and vice versa (24, 25). Therefore,
118 the CLP loess-paleosol χ and ARM records are closely linked to the ASM precipitation. The lithological,
119 χ , and ARM records from the Huanxian loess-paleosol section vary consistently over the last 280 kyr
120 (Fig. 2A–C). Paleosol layers (i.e., S_0 , S_1 , and S_2) have higher χ and ARM values than loess layers (i.e.,
121 L_1 , L_2 , and L_3), which is consistent with higher ASM precipitation during interglacials relative to
122 glacials. The Huanxian χ and ARM records are marked by more square-wave ~100-kyr cycles, which

123 differ slightly from the asymmetric glacial-interglacial structure in the global reference sea level/ice
124 volume record (30) (Fig. 2B–D). In addition to the ~100-kyr periodicity, Huanxian χ and ARM records
125 are superimposed with lower-amplitude precessional (~20-kyr) variability, indicative of a possible
126 low-latitude forcing linked to Northern Hemisphere summer insolation (NHSI). During MIS 5 and MIS
127 7, the superimposed precession-paced stadial substages occur close to NHSI minima and are not as dry
128 as full glacial periods. During MIS 3–4 and early MIS 6, when glacial conditions were modest,
129 somewhat moister interstadials occurred around NHSI maxima, albeit not as moist as interglacial periods
130 (MIS 5 and MIS 7). However, during MIS 2–3, late MIS 6, and MIS 8, when glacial conditions were
131 more extreme, aridity prevailed despite NHSI maxima. Spectral analyses of χ and ARM records confirm
132 pervasive orbital cycles of eccentricity (~100-kyr), obliquity (41-kyr), and precession (~20-kyr), which
133 are broadly comparable to the combined spectral results from NHSI, global average sea level, and
134 atmospheric CO₂ records (30–32) (Fig. 2B–E). The NHSI is characterized by a precessional cyclicality,
135 whereas globally averaged sea level and atmospheric CO₂ records are dominated by a strong ~100-kyr
136 eccentricity-paced cyclicality, with subdued expressions of obliquity- and precession-paced cycles.

137 **Dynamics of orbital-scale ASM variability.** The co-occurring primary orbital cycles of ~100-kyr,
138 41-kyr, and ~20-kyr in the Huanxian loess-paleosol sequence cannot solely be explained by either an
139 external (insolation) or internal (ice volume and greenhouse gas concentration) driver, but more likely
140 through their combined action. Such an interpretation is further supported by a high-fidelity paleoclimate
141 simulation, in which we utilized the climate output from a general circulation model forced by a
142 combination of orbital-scale insolation, global ice volume, and atmospheric CO₂ forcing factors (model
143 details are provided in reference (23)). Model-based reconstructions of (i) annual and summer (May to
144 September) precipitation over North (100–120°E; 30–45°N) and South China (100–120°E; 20–30°N), (ii)

145 low-latitude East Asian (100–120°E, 20°N) summer temperature, (iii) summer precipitable moisture on
146 the West Pacific and North Indian oceans (80–150°E; 0–35°N), and (iv) summer wind speed show
147 broadly similar orbital variability as our proxy records during the last 280 kyr, with combined
148 eccentricity, obliquity, and precession cycles (Fig. 2). Therefore, both proxy- and model-based
149 reconstructions support that the NHSI, ice volume, and greenhouse gas concentration jointly governs
150 East Asian summer precipitation (12, 21, 22, 33).

151 In contrast to Huanxian records, precession signal is largely subdued or absent in many χ records
152 located to the south and east (Figs. S1 and S8). However, like Huanxian records, precessional variability
153 is prominent in the Jingyuan carbonate $\delta^{13}\text{C}$ record (22) and the Xijing spliced grain size- χ stack from
154 the western CLP (20) and the Baoji ^{10}Be -based precipitation reconstruction from the southern CLP
155 margin (12) (Fig. S9). Thus, faint or absent precessional variability in those southern/eastern CLP
156 loess-paleosol sections, which are usually associated with lower sedimentation rates, does not necessarily
157 mean that CLP precipitation responded negligibly to precession-paced NHSI changes. Our Huanxian
158 hydroclimatic records, together with the Jingyuan, Xijing, and Baoji hydroclimatic records (12, 20, 22),
159 reveal a widespread presence of precessional ASM variability across the entire CLP, beyond the western
160 sections or the southern CLP margin as recently recognized (12, 20, 22) (Fig. S9). The distinct
161 precession signal identified here, a typical monsoon pacing feature related to low-to-middle latitude
162 insolation forcing (15, 16), together with our detailed rock magnetic results (Figs. S3–S7; Supplementary
163 Text 1), supports the notion that the classical use of loess-paleosol χ as an ASM indicator (24, 25) is also
164 (largely) valid for high sedimentation rate sections from the central CLP marked by higher ASM
165 precipitation than the western CLP. However, secondary influences of pedogenic duration and
166 temperature on χ cannot be fully excluded (20).

167 The precession signal in the Baoji ^{10}Be record is not as obvious as that seen in Huanxian, Jingyuan,
168 and Xijing ASM records (Fig. S9), which is possibly due to a lower sedimentation rate and data
169 resolution as well as prominent gaps within MIS 5 and MIS 7. The Huanxian, Jingyuan, and Baoji
170 records have a stronger ~100-kyr cyclicity than the Xijing record. These nuanced differences likely
171 reflect variable responses of proxies to the extent of ASM precipitation. The Huanxian environmental
172 magnetic records may be more directly related to regional ASM precipitation than the Jingyuan
173 carbonate $\delta^{13}\text{C}$ record and Xijing spliced grain size- χ stack. Jingyuan carbonate $\delta^{13}\text{C}$ reflects local
174 vegetation conditions likely linked to the complex interactions of precipitation, temperature, and CO_2
175 (20, 22). The Xijing spliced grain size- χ stack contains not only ASM precipitation-induced χ variations,
176 but also winter monsoon-related grain size changes (25-27).

177 To better document the ASM history across the entire CLP and minimize the limitations of specific
178 proxy records, we compile a new ASM stack by summing the Huanxian χ and ARM records, the
179 Jingyuan carbonate $\delta^{13}\text{C}$ record (22), the Xijing spliced grain size- χ stack (20), and the Baoji ^{10}Be record
180 (12) (Fig. S9). This new ASM stack shows consistency with East China composite speleothem $\delta^{18}\text{O}$
181 records (15) in portraying the precessional variability, although our ASM stack contains additionally
182 ~100-kyr and 41-kyr cycles that are not distinct in the speleothem $\delta^{18}\text{O}$ records (Fig. 3A–B).
183 Nevertheless, co-occurring ~100-kyr, 41-kyr, and ~20-kyr periodicities have been captured by the
184 Xiaobailong Cave $\delta^{18}\text{O}$ record from Southwest China (13), the $\delta^{18}\text{O}$ and $\delta\text{D}_{\text{wax}}$ records from the Indian
185 margin U1446 sediment core (17, 18), and the Arabian Sea summer monsoon stack (14) (Fig. 3). These
186 records together provide an important Asian climatic context for AMH dispersal from Africa to East
187 Asia.

188 **Climatic influence on initial AMH dispersal to East Asia.** Multiple lines of fossil, archeological, and
189 genetic evidence suggest that initial AMH arrivals in East Asia can be traced back to the last interglacial
190 (more broadly MIS 5). Early Late Pleistocene sites with robust chrono-stratigraphic contexts and fossils
191 that can be reasonably attributed to *H. sapiens* include localities such as Luna Cave (120–70 ka) (34),
192 Zhiren Cave (113–100 ka) (35), and Fuyan Cave (120–80 ka) (36), that all range from ~130 ka to ~70 ka
193 (Fig. 4A). Although a recent dating study on the Luna and Fuyan sites argued for younger ages (37), the
194 two follow-up studies criticized these younger ages by raising important flaws in its sampling procedures
195 and species attributions, thereby suggesting that MIS 5 fossil ages remained feasible (38, 39); an
196 interpretation we support. Similarly old hominin fossils tentatively attributed to *H. sapiens* were also
197 reported from Tongtianyan Cave (Liujiang, 130–70 ka) (40) and Ganqian Cave (140–100 ka) (41).
198 Hominin fossils from Jimuyan (42), Dingcun (43), and Salawusu (43-45) have *H. sapiens* features, even
199 though some primitive features in combination with larger age uncertainties make the interpretation of
200 these fossils, in terms of AMH dispersal timing, relatively less unequivocal (43, 46). Likewise, two
201 complete crania with closer affinities to *H. sapiens* but also some archaic features were reported from
202 Ryonggok, North Korea (47, 48). Despite the fact that older ages were initially proposed for this finding,
203 a younger age of 46–49 ka is currently more accepted (47, 48). The teeth from Lida Ajer Cave, Sumatra
204 (73–63 ka) (49), suggests that AMH reached the island by ~70 ka. However, before settling in Sumatra,
205 AMH must already have crossed mainland Southeast Asia (Fig. 1). Recently this was confirmed by the *H.*
206 *sapiens* presence at Tam Pà Ling (Northern Laos) between 86 ka and 68 ka (50) (Fig. 1). Moreover, the
207 65-ka-old sophisticated toolkit found in North Australia indicate that AMH possibly crossed Southeast
208 Asian islands during late MIS 5 when regional climate remained favorable and sea level started to
209 decline (8, 51). The AMH presence in Asia during MIS 5 is supported not only by a large number of

210 geo-chronologically dated fossils and artifacts (Figs. 1 and 4A; Table S1) but also by independent
211 genetic studies (52, 53) that suggest the Asian presence of modern human lineages earlier than 75 ka.
212 Lastly, it is additionally supported by a recent finding that a deeply divergent modern humans
213 contributed genetically to the ancestry of Altai Neanderthals by roughly 100 ka (53). We are cognizant
214 of the inherent dating uncertainties associated with a few hominin sites and the debate regarding their
215 species attribution (54, 55), so we do not attempt to distinguish AMH dispersal time to either the earlier
216 or later part of MIS 5. Nevertheless, the available data confirm initial AMH arrivals in East Asia by the
217 last interglacial (8).

218 The AMH occupation in MIS 5 East Asia (Fig. 4A) coincided with regional rain and temperature
219 increases as seen in our proxy- and model-based reconstructions and existing paleoclimatic records from
220 Asia (Figs. 2 and 3). To further examine ASM climate influence on AMH dispersal, we analyze *H.*
221 *sapiens* habitats from a recently established transient Pleistocene simulation of this kind (7). This
222 multi-dimensional statistical model simulates the habitat suitability for *H. sapiens* occupation at a given
223 location and time, by quantifying the relationships among geo-chronologically dated fossil/archaeological
224 data and different climatic variables of biological importance, i.e., yearly precipitation minimum, annual
225 mean precipitation, temperature, and net primary productivity (7). The simulated *H. sapiens* habitat
226 suitability over East Asia (80–130°E; 20–55°N) shows large temporal variation during the last 280 kyr
227 (Fig. 4B), with both ~100-kyr and ~20-kyr cyclicities comparable to the aforementioned Asian
228 hydroclimatic oscillations (Figs. 2 and 3). Interestingly, the temporal increases in simulated East Asian *H.*
229 *sapiens* habitat peaked at ~120 ka, ~95 ka, and ~70 ka, in comparison to the preceding glacial MIS 6 (Fig.
230 4B). This is coeval with the orbitally-modulated ASM strengthening (Figs. 2 and 3) and the earliest AMH
231 fossil occurrences in East Asia (Fig. 4A; Table S1). We argue that the ASM strengthening in MIS 5

232 induced (i) regional precipitation increases (Figs. 2 and 3), (ii) a greener, more lushly vegetated East Asia,
233 and (iii) more abundant food resources, which would have benefited the expansion in ranges of various
234 faunas, including *H. sapiens* (56). Such optimum environmental conditions, together with the greater
235 climatic tolerance of *H. sapiens* that developed during ~300–100 ka (4, 7), plausibly provided an
236 unprecedented opportunity for AMH dispersal to East Asia during the last interglacial. According to the
237 habitat map averaged over 125–70 ka (Fig. 4C), transcontinental optimal habitats might have stimulated
238 AMH populations to disperse from their African homeland to East Asia via southern (South Asia) and
239 northern routes (continental Central Asia). An earlier (pre-70-ka) AMH dispersal utilizing the southern
240 route to East Asia is most consistent with ASM strengthening (Fig. 3). Moreover, the southern dispersal
241 route lies under strong, continual ASM influence and is supported by the MIS 5 AMH archeological
242 evidence from India, including the sites of Sandhav (~110 ka) (57), Katoati (96 ka) (58), Jwalapuram
243 (85–75 ka) (59), and Sri Lanka (74–64 ka) (58) (Figs. 1 and 4C). Although recent findings suggest that
244 early *H. sapiens* may have dispersed to Greece (Europe) and Israel (West Asia) as early as ~200 ka (60,
245 61), *H. sapiens* fossil/archeological evidence remains currently absent from MIS 6–5 Central Asia (8).
246 This absence probably indicates that the relatively colder/drier northern dispersal route beyond the ASM
247 reach may have occurred later than the southern route (8, 62), with an initial failure in competition with
248 pre-existing populations of Denisovans or Neanderthals (36, 63) (Fig. 4C).

249 Before the *H. sapiens* appearance, East Asia was occupied by a number of hominins characterized by
250 a mosaic of plesiomorphic features with derived traits (such as enlarged cranial capacity, facial
251 gracilization, simplified enamel-dentine junction surfaces or symmetrical premolar crowns). These
252 samples include fossils recovered from either Huanglong Cave, Harbin, Panxian Dadong, Xuchang, Dali
253 or Tongzi (43, 64-70). They have been tentatively classified as “non-erectus” Asian Mid-Pleistocene

254 hominins (65, 70). However, we find that the large majority of East Asian *H. sapiens* and other hominin
255 sites older than 70 ka are consistently under ASM influence. Lower latitudes with higher ASM
256 precipitation contain more hominin sites of the late Mid-Pleistocene and early Late Pleistocene than
257 higher latitudes with lower ASM precipitation. Particularly, almost all robustly dated pre-70-ka *H.*
258 *sapiens* evidence is found from Southeast Asia with wetter and greener landscapes under continual ASM
259 influence. These observations are consistent with a close link between hominin occupation and the ASM.
260 The ASM-induced changes in the habitats of East Asian hominins affected their mobility and possibly
261 their degrees of isolation, which in turn may have affected the probability of their mixing and
262 interbreeding (71). Although we are far from understanding the phenotypic signal of interbreeding (72),
263 we cannot rule out that part of the anatomical variability of the late-Middle to Late Pleistocene groups in
264 Asia is related to the admixture of *H. sapiens* with the pre-existing indigenous populations at the time of
265 AMH's arrival (73).

266 In contrast to a shift to wetter conditions in East Asia induced by ASM strengthening as suggested
267 by our both proxy- and model-based hydroclimatic reconstructions (Fig. 2), large areas of Southeast
268 Africa—the major homeland of *H. sapiens*—had a deteriorating climate during MIS 6–5 transition (3,
269 74-78). For example, paleoclimatic records from the Limpopo catchment, KwaZulu-Natal, and Lake
270 Magadi suggests a series of “megadroughts” in subtropical Southeast Africa during MIS 5 (74-76). A
271 principal component analysis of hydrologically sensitive fossil and mineralogical records from the Lake
272 Malawi suggests that tropical Southeast Africa was largely drier during MIS 5 relative to MIS 6 (78).
273 The deterioration of climatic conditions could have decreased vegetation and reduced mammal
274 populations and the availability of resources and habitats. This is confirmed by our *H. sapiens* habitat
275 simulation, which suggests that habitat peaks and troughs in East Africa and habitat peaks in South

276 Africa lowered during MIS 5, in comparison to the preceding MIS 6 (Fig. S10). This in turn enhanced
277 selective pressures, so *H. sapiens* may have been forced to expand beyond Africa and into the nearby
278 West Asia. Upon arrival of *H. sapiens* populations in the West Asian regions around the Mediterranean
279 Sea, as indicated by evidence from Israel (79-81), some may have dispersed further to remote East Asia
280 during MIS 5, when increased ASM precipitation produced suitable conditions with abundant resources
281 (e.g., food, water, and shelter), attracting *H. sapiens* colonization. The combination of climate
282 deterioration in large areas of Southeast African and favorable climate in East Asia may have promoted
283 continental-scale early *H. sapiens* dispersal to East Asia during MIS 5.

284 To summarize, through synthesis of new proxy- and model-based East Asian climate
285 reconstructions, compilations of Asian paleoanthropological and paleoclimatic data, and *H. sapiens*
286 habitat simulations through time and space, we improve current understanding of orbital-scale ASM
287 dynamics, and more importantly, reveal the close links between ASM climate and initial AMH dispersal
288 to East Asia. New centennial-resolution environmental magnetic records derived from a unique high
289 sedimentation rate loess-paleosol section on the central CLP, together with the latest proxy records from
290 other parts of the plateau (12, 20, 22), document a pervasive precession signal in the hydroclimatic
291 evolution across the CLP, in addition to the well-recognized ~100-kyr cyclicity. Our results provide new
292 Asian evidence for previously suggested complex models explaining the origin and dispersal(s) of *H.*
293 *sapiens*, which points to less linear evolutionary scenarios where climatic changes likely played a major
294 role in the dispersals, fragmentation, assimilation and recombination of new immigrant populations with
295 pre-existing local groups (71, 82, 83). Integration of paleoclimate data with compiled hominin fossil and
296 archeological finds from Asia and simulated *H. sapiens* habitats shows that increased monsoonal rain
297 and higher temperature across the Asian continent, together with climate deterioration in Southeast

298 Africa, provided an optimum window of opportunity for early AMH dispersals to remote East Asia
299 during the last interglacial.

300

301 **Methods**

302 Following removal of weathered surface outcrop, 2,066 fresh samples were collected from paleosol S₀
303 (MIS 1) to loess L₃ (MIS 8) at 2–2.5 cm intervals (equivalent to ~0.1–0.8 kyr time spacing) from the
304 Huanxian loess-paleosol section. About 10 g of each sample was powdered and then packed into a
305 nonmagnetic cubic box (2 cm × 2 cm × 2 cm) for χ and ARM measurements in the laboratory. We
306 measured room temperature χ using a SM-150L magnetic susceptibility meter (ZH instruments, Czech
307 Republic) at a frequency of 500 Hz and an applied field of 80 A/m at the Institute of Earth Environment,
308 Chinese Academy of Sciences, Xi'an, China. ARM was imparted using a peak alternating field (AF) of
309 100 mT and a 0.05 mT direct current (DC) bias field and was measured using a 2-G Enterprises Model
310 755 cryogenic magnetometer housed in a magnetically shielded space at the China University of
311 Geosciences (Wuhan), China.

312 We established a first-order chronology for the Huxian loess-paleosol section based on the well
313 identified cycle-based correlation between CLP loess-paleosol χ and marine benthic foraminiferal $\delta^{18}\text{O}$
314 records (24, 25) (Fig. S2A–B). In addition to the top and bottom points, six extra points around the
315 transitions between high and low χ units were used as tie points to construct this first-order chronology
316 (Fig. S2B). Both CLP χ and East China speleothem $\delta^{18}\text{O}$ records are grossly linked to the same
317 large-scale shifts in ASM circulation (15, 24, 25, 84). We further refined the first-order chronology by
318 repeatedly matching χ with the precisely-dated composite East China speleothem $\delta^{18}\text{O}$ record (15) in an

319 objective way until their cycles are synchronized to in-phase variations (Fig. S2C). This recently
320 developed approach enables a more precise speleothem-based CLP loess-paleosol chronology relative to
321 previous age models based on land-sea correlation or orbital tuning (12, 28, 85). In addition to the eight
322 points selected for the first-order chronology construction, we selected seven additional tie points either
323 located on high-amplitude χ peaks of the well-developed strong pedogenic interglacial paleosol S₂ or at
324 the onset/termination of relatively weaker pedogenic sub-paleosols (corresponding to somewhat moister
325 interstadials and lower-amplitude χ peaks) within glacial loess layers, to construct the refined age model
326 for the Huanxian loess-paleosol section based on cyclic correlation between the χ and East China
327 speleothem $\delta^{18}\text{O}$ records (Fig. S2C). This refined chronology is supported independently by recent
328 optically stimulated luminescence dating of the Jingbian loess-paleosol section on the northern CLP
329 margin (29) (Fig. S2D). The Huanxian χ data on the refined chronology closely follow the speleothem
330 $\delta^{18}\text{O}$ record over precessional cycles (Fig. S2C). Land-sea correlation and loess-speleothem match, with
331 distinct tie point selection, do not result in significant differences in the CLP loess-paleosol age models,
332 generally with only millennial differences (22, 24-26, 28).

333 We established a new ASM stack by compiling proxy records from East Asia, including the
334 Huanxian χ and ARM records, the Jingyuan carbonate $\delta^{13}\text{C}$ record (22), the Xijing spliced grain size- χ
335 stack (20), and the Baoji ^{10}Be -based precipitation reconstruction (12). Like our established Huanxian χ
336 and ARM time series above, we first refined age models for the Jingyuan carbonate $\delta^{13}\text{C}$ record (22),
337 Xijing spliced grain size- χ stack (20), and Baoji ^{10}Be -based precipitation record (12) by synchronizing
338 them to the precisely U/Th-dated East China speleothem $\delta^{18}\text{O}$ record (15). After synchronization, we
339 used the interpolating function in the *Acycle* software (86) to conservatively resample all used records at
340 0.5-kyr intervals to obtain evenly spaced data series. We constructed the ASM stack from the CLP by

341 averaging the evenly-spaced Huanxian χ and ARM, Jingyuan carbonate $\delta^{13}\text{C}$, Xijing spliced grain size- χ
342 stack, and Baoji ^{10}Be -based precipitation time series with equal weight. To evaluate the robustness of the
343 orbital signature, we used the smoothed periodogram to analyze the power spectra of proxy- and
344 model-based paleoclimatic reconstructions with the function Spectral Analysis in the *Acycle* software
345 (86), with a bandwidth of 2 and a sampling interval of 1 kyr.

346 To identify the magnetic minerals in the sediments, we measured temperature-dependent magnetic
347 susceptibility curves (χ -T), isothermal remanent magnetization (IRM) acquisition curves, magnetic
348 hysteresis loops, first-order reversal curve (FORC) diagrams, and low temperature cycles of the
349 saturation isothermal remanent magnetization (SIRM) for nine samples from the Huanxian section at the
350 Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China. They contain four loess
351 samples from loess layers L₁, L₂, and L₃, and five paleosol samples from paleosol layers S₀, S₁, and S₂.
352 χ -T curves were measured in an argon atmosphere from room temperature to 700 °C and back to room
353 temperature with a MFK1-FA susceptometer equipped with a CS-3 high-temperature furnace (AGICO,
354 Brno, Czech Republic). IRM acquisition curves, magnetic hysteresis loops, and FORC diagrams were
355 measured with a Princeton Measurements Corporation (Model 3900) vibrating sample magnetometer
356 (VSM). Each IRM acquisition curve contains 200 data points measured at logarithmically spaced field
357 steps to 1 T. Each hysteresis loop was measured between ± 1 T at 3 mT increments, with a 300 ms
358 averaging time. For each sample, 80 FORCs were measured at 5 mT increments to ~ 600 mT, with a 100
359 ms averaging time. Low-temperature magnetic measurements were conducted with a Quantum Design
360 superconducting quantum interference device (SQUID) Magnetic Property Measurement System
361 (MPMS) (Quantum Design Inc, USA). A room temperature saturation isothermal remanent

362 magnetization (SIRM), which was imparted in a 5 T field at 300 K, was measured at 5 K intervals from
363 300 to 5 K and back to 300 K in zero magnetic field.

364

365 **Data availability.** All of our measured proxy data are included in the Dataset and will be available in the
366 East Asian Paleoenvironmental Science Database.

367

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377

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379 M.M.-T. contributed to the paleoanthropological interpretation. M.K. calculated the model-based East
380 Asian climate reconstructions. J.L.J. and Z.Y.Z. carried out the laboratory analysis. X.X.L. undertook the
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382 X.K.Q., P.Z., and Z.S.A. contributed to paleoclimatic data analysis, interpretation and discussion. H.A.
383 wrote the manuscript with contributions from all other authors.

384

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569

570 Figure captions:

571 **Figure 1. Study context.** African and Eurasian annual precipitation map averaged between 130 and 70
572 ka from the latest model-based climate reconstructions (23), with referenced paleoclimatic and
573 archaeological sites in Asia, Tibetan Plateau (>2000 m topography), and schematized African and Asian
574 monsoon circulations. Background data for the listed Asian *H. sapiens* sites are included in Table S1.

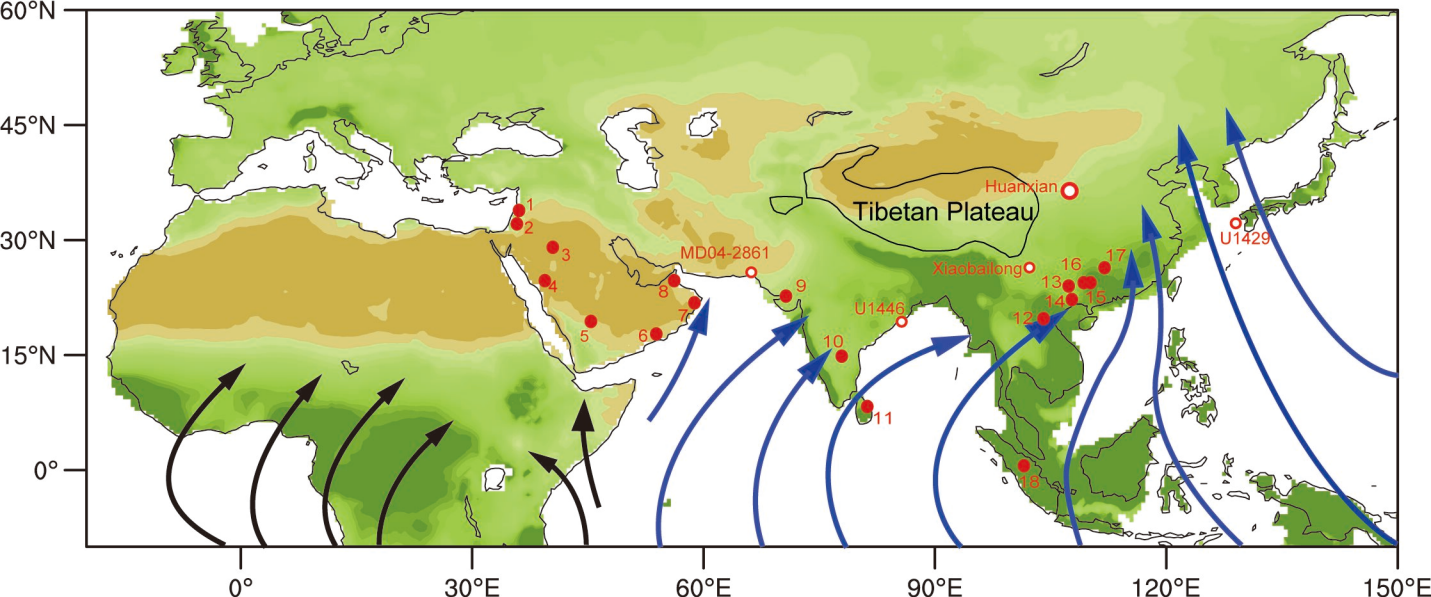
575 **Figure 2. Proxy- and model-based reconstructions of orbital-scale East Asian climate variability.**

576 (A) Lithology, (B) magnetic susceptibility (χ , green curve), and (C) ARM (brown curve) from the
577 Huanxian loess-paleosol section with their comparison with 30°N July insolation (32) (red curve) and
578 their power spectra. S-numbers and L-numbers refer to consecutive paleosol and loess horizons counting
579 back from the present-day, respectively. Time series and power spectra of (D) sea level reconstruction
580 from a global benthic foraminiferal $\delta^{18}\text{O}$ stack (30) and (E) atmospheric CO_2 reconstruction from
581 Antarctic ice core (31). Numbers on the sea level record refer to the successive marine isotope stages.
582 Time series and power spectra of (F) annual and (G) summer precipitation over North China (100–
583 120°E; 30–45°N), (H) annual and (I) summer precipitation over South China (100–120°E; 20–30°N), (J)
584 average summer surface temperature over low-latitude East Asia (100–120°E, 20°N), (K) summer
585 precipitable moisture on the West Pacific and North Indian oceans (80–150°E; 0–35°N), (L) summer
586 wind speed, in response to combined ice volume, atmospheric CO_2 concentration, and insolation forcing,
587 which are calculated from the latest model-based climate reconstructions (23). Summer is represented by
588 May to September. (M) International Ocean Discovery Program (IODP) Site U1429 Mg/Ca sea surface
589 temperature (SST) record from the East China Sea (11) and its power spectrum. The dashed lines in the
590 power spectra (right panel) denote regions statistically significantly above the 95% confidence level

591 (Student's *t*-test). The vertical shading indicates the approximate timing of early AMH arrivals in East
592 Asia.

593 **Figure 3. Climatic context for early *H. sapiens* dispersal to East Asia.** Time series and power spectra
594 of (A) new CLP ASM stack based on the Huanxian χ and ARM records, the Jingyuan carbonate $\delta^{13}\text{C}$
595 record (22), the Xijing spliced grain size- χ stack (20), and the Baoji ^{10}Be -based precipitation record (12),
596 (B) China composite speleothem $\delta^{18}\text{O}$ record (15), (C) speleothem $\delta^{18}\text{O}$ from Xiaobailong Cave, South
597 China (13), (D, E) Indian margin Site U1446 sediment core seawater $\delta^{18}\text{O}$ and $\delta\text{D}_{\text{wax}}$ records (17, 18),
598 and (F) summer monsoon stack from sediment core MD04-2861, Arabian Sea (14). The vertical shading
599 indicates the approximate timing of early AMH arrivals in East Asia.

600 **Figure 4. *Homo sapiens* habitat suitability.** (A) Raw and aggregated age distributions of early *H.*
601 *sapiens* fossils from China, including Luna Cave (120–70 ka) (34), Zhiren Cave (113–100 ka) (35),
602 Tongtianyan Cave (Liujiang, 130–70 ka) (40), Ganqian Cave (140–100 ka) (41), and Fuyan Cave (120–
603 80 ka) (36), and from Southeast Asia represented by Tam Pà Ling (86–68 ka) in Northern Laos (50) and
604 Lida Ajer Cave (73–63 ka) in Sumatra (49). (B) Simulated timeseries of *H. sapiens* habitat suitability in
605 East Asia during the last 280 kyr and (C) simulated *H. sapiens* habitat map over 125–70 ka (7) with
606 occupied localities by *H. neanderthalensis*, Denisovans and early *H. sapiens*.



➔ African monsoon
 ➔ Asian monsoon

○ Hydroclimatic site
 ● Site occupied by *H. sapiens*

- | | | | |
|--|--|--|---|
| <p>1 Qafzeh (90 ka)</p> <p>5 Mundafan (100–80 ka)</p> <p>9 Sandhav (110 ka)</p> <p>13 Luna (120–70 ka)</p> <p>17 Fuyan (120–80 ka)</p> | <p>2 Skhul (130–100 ka)</p> <p>6 Al Wusta (~95–86 ka)</p> <p>10 Jwalapuram (85–75 ka)</p> <p>14 Zhiren (113–100 ka)</p> <p>18 Lida Ajer (73–63 ka)</p> | <p>3 Jebel Qattar (75 ka)</p> <p>7 Aybut Al Auwal (105 ka)</p> <p>11 Sri Lanka (74–64 ka)</p> <p>15 Liujiang (130–70 ka)</p> | <p>4 Alathar paleolake (121–112 ka)</p> <p>8 Jebel Faya C (125 ka)</p> <p>12 Tam Pà Ling (86–68 kyr)</p> <p>16 Ganqian (140–100 ka)</p> |
|--|--|--|---|

