doi:10.1038/nature19471

HUMAN MIGRATION

Climate and the peopling of the world

The human dispersal out of Africa that populated the world was probably paced by climate changes. This is the inference drawn from computer modelling of climate variability during the time of early human migration.

PETER B. DEMENOCAL & CHRIS STRINGER

One of the most puzzling questions about the origins of modern humans has been why the dispersal of *Homo sapiens* out of Africa occurred so long after their first known appearance in east Africa approximately 150,000 to 200,000 years ago[1]. Fossil, archaeological and genetic evidence indicates that early migrations out of Africa into the Levant (eastern Mediterranean) and the Arabian peninsula occurred around 120,000 to 90,000 years ago[1], but the further dispersal of our kind halfway around the world did not begin until about 60,000 years ago[1]. This out-of-Africa migration was pulsed, with waves of dispersal eastward to south Asia, Indonesia and Australia by 50,000 years ago, migration westward to Europe by 45,000 years ago[1], migration into north Asia by 20,000 years ago and to the Americas by 15,000 years ago[2] (Fig. 1). A paper online in *Nature* by Timmermann and Friedrich[3] provides modelling insights into the potential role of climate in the human migration out of Africa.

The role of climate change in pacing these ancient human dispersals has been the subject of intense study and debate. All hypotheses share the basic principle that climate affects resource richness, which, in turn, sets the 'carrying capacity' — the human population that can be supported in a given region. This then guides human dispersal. Climate agents that might affect resource richness include large volcanic eruptions[4], glacial 'Heinrich events' associated with ice-sheet collapse[5], orbital monsoonal-rainfall changes (Earth's orbit undergoes slight changes in its rotational axis every 21,000 years, which affects seasonal solar radiation and thus monsoonal climate)[6–8] and sea-level fluctuations[9].

Many studies have used climate models to explore the effects of these palaeoclimatic agents on human migrations[5,7,10]. These simulations provide spatio-temporal models of ancient climates that can be compared with the available fossil, archaeological and genetic evidence. The challenge has been to construct a model that has sufficiently realistic palaeoclimate representations, while simultaneously modelling changes in human carrying capacity that match observed dispersal routes and timing[7]. It's a tough problem.

Timmermann and Friedrich tackle this with the most comprehensive climate, vegetation and human-dispersal modelling study performed so far. They use a fully coupled ocean–atmosphere–vegetation climate model that is forced by specified changes in orbital insolation (solar-radiation levels that depend on Earth's tilt and changes in the Earth–Sun distance), carbon dioxide levels, glacial ice and sea-level boundary conditions to compute transient changes in climate and vegetation over the past 125,000 years. The authors validated the model climate fields against available palaeoclimate and palaeoceanographic data to ensure that the results were reasonable. There are, however, some deficiencies in the model, such as the weaker-than-observed African monsoonal-rainfall response to orbital insolation forcing that is evident in nearly all such models[11]. The authors modelled human dispersals using computer simulations of population density as a function of environmental parameters (while also accounting for parameter uncertainties) at a global geographic resolution of 1° latitude × 1° longitude.

What Timmermann and Friedrich found was both remarkable and instructive. Today, the Sahara and Arabian deserts form an effective barrier to faunal dispersals out of Africa. But in the past, changes in the orientation of Earth's axis of rotation at that time invigorated the monsoonal climate and established wetter conditions in the Arabian and Sinai peninsulas, enabling migration paths out of Africa along vegetated, resource-rich corridors. These corridors were established during three time windows: 130,000 to 118,000 years ago, 106,000 to 94,000 years ago and 89,000 to 73,000 years ago (although the first green corridor, established 130,000 to 118,000 years ago, was not associated with human migration out of Africa in the authors' model). These age ranges coincide with warm substages within the single interglacial known as Marine Isotope Stage 5 (MIS5) of the geological temperature record. This orbital pacing of migration waves out of Africa supports earlier conclusions that the resulting environmental change was a probable mechanism that drew early populations of humans out of their ancestral African home because of the establishment

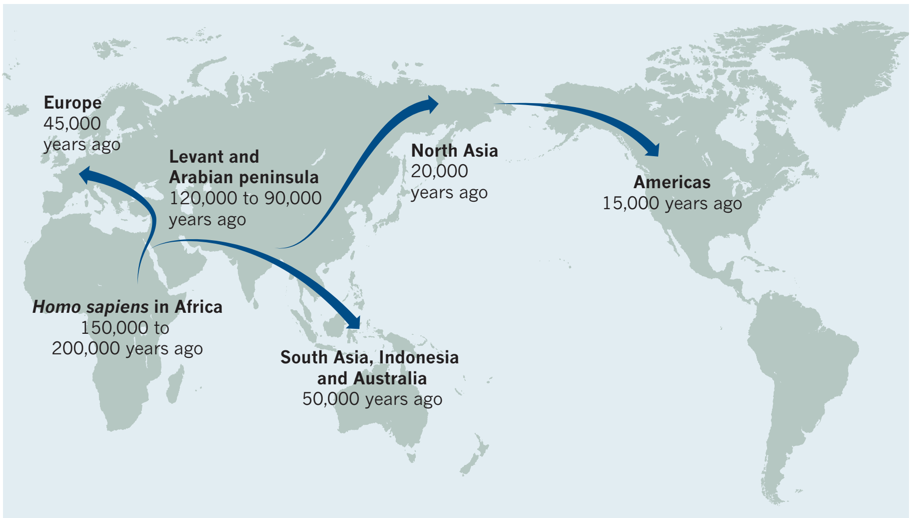

Figure 1 | Human migration out of Africa. Previous studies[1,2] of human migration out of Africa, using fossil, archaeological and genetic evidence, have provided a timeline of the human global dispersals shown. Timmermann and Friedrich[3] used linked climate, vegetation and human-dispersal models to understand how climate change may have paced the tempo of human migrations out of Africa. Their results support the view that climate may have been a key factor, but show both similarities and differences when compared with the results of previous studies. One notable difference is that Timmermann and Friedrich suggest a much earlier arrival of modern humans in Europe.

of new, resource-rich exit routes[6–8,10,12,13].

However, the onset of dry, resource-poor conditions during glacial MIS4 (71,000 to 60,000 years ago) terminated the exchange like closing a valve. The next key migration wave out of Africa occurs during the subsequent, orbitally driven increase in monsoonal rainfall during early MIS3 (59,000 to 47,000 years ago). This wave of migration boosted remnant Eurasian populations, leading to rapid population increases in Europe and elsewhere between 60,000 and 40,000 years ago. At the same time, the authors simulate a rapid eastward expansion into India and south Asia, with humans arriving in Australia by 60,000 to 50,000 years ago. Migration into north Asia and then into the Americas occurs only when glacial conditions start to wane after around 20,000 years ago.

Timmermann and Friedrich explored the sensitivity of these model results to changes in several climate and dispersal parameters. They found that the orbital pacing of human dispersal events out of Africa is a robust result, as is the importance of MIS4 aridification in cutting off the exchange between the populations in northeastern Africa and the rapidly eastward-spreading group in southern Asia. The authors also show that millennial-scale climate oscillations, comparable to rapid warming or cooling episodes known as Dansgaard–Oeschger events, had little effect on migration times.

How well do the estimated migration-wave timings match previous archaeological, fossil and genetic data? For Arabia, archaeological evidence indicative of modern human presence does suggest modern human dispersals from Africa or the Levant between about 120,000 and 75,000 years ago)[9,12], whereas only the potentially oldest dating evidence for Skhul and Qafzeh (in the Levant)[13] falls earlier than the age ranges modelled by Timmermann and Friedrich (although an ancient jawbone found in Tabun Cave[14] raises the possibility that modern humans had an even earlier presence). For the Indian subcontinent, there is only limited archaeological evidence for a modern human presence before 50,000 years ago, although a partial cranium and jawbone are known from Laos at this time[15]. In China, there are several claims from fossil evidence for a modern human presence before 80,000 years ago, but these may require further confirmation[16].

The most obvious discrepancy in Timmerman and Friedrich's results is their suggestion that southern Europe experienced a low-density wave of occupation by modern humans before 80,000 years ago, which is more than 35,000 years earlier than the generally accepted evidence from archaeology and fossil remains[17]. The authors suggest that these earliest modern pioneers could have been assimilated by the more numerous Neanderthals. However, genetic signatures of these proposed early pioneers have not yet been detected in the genomes of subsequent Neanderthal individuals in Europe, and it could also be argued that, as with later Siberian and Romanian fossils[18], these early modern humans and their lineages simply went extinct. However, it seems unlikely that such early modern dispersals would not have left at least some distinctive archaeological traces, something that has not yet been detected.

Although such human–climate interactions may seem too complex to model with any fidelity, ancient population dynamics across north Africa provide an instructive example. Between 12,000 to 5,000 years ago, the vast Sahara was nearly completely vegetated with wooded grasslands, permanent lakes and rivers[19]. This region was alive with people and cultural activity until about 5,000 years ago, when the monsoon rains weakened and retreated as a result of changes in Earth's orbit. The archaeological record documents the massive and rapid depopulation of the north African interior around 5,000 years ago, at the same time as the establishment of the present-day Sahara Desert[20]. This well-documented case study illustrates just how effectively climate can shape life, including the peopling of the planet. ■

Peter B. deMenocal *is at the Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA.*
Chris Stringer *is in the Department of Earth Sciences, Natural History Museum, London SW7 5BD, UK.*
e-mails: peter@ldeo.columbia.edu; c.stringer@nhm.ac.uk

1. Groucutt, H. S. *et al. Evol. Anthropol.* **24,** 149–164 (2015).
2. Goebel, T., Waters, M. R. & O'Rourke, D. H. *Science* **319,** 1497–1502 (2008)
3. Timmermann, A. & Friedrich, T. *Nature* http://dx.doi.org/10.1038/nature19365 (2016).
4. Ambrose, S. H. *J. Hum. Evol.* **34,** 623–651 (1998).
5. Carto, S. L., Weaver, A. J., Hetherington, R., Lam, Y. & Wiebe, E. C. *J. Hum. Evol.* **56,** 139–151 (2009).
6. Castañeda, I. S. *et al. Proc. Natl Acad. Sci. USA* **106,** 20159–20163 (2009).
7. Eriksson, A. *et al. Proc. Natl Acad. Sci. USA* **109,** 16089–16094 (2012).
8. Osborne, A. H. *et al. Proc. Natl Acad. Sci. USA* **105,** 16444–16447 (2008).
9. Armitage, S. J. *et al. Science* **331,** 453–456 (2011).
10. Jennings, R. P. *et al. Quat. Int.* **382,** 181–199 (2015).
11. Pausata, F. S. R., Messori, G. & Zhang, Q. *Earth Planet. Sci. Lett.* **434,** 298–307 (2016).
12. Groucutt, H. S. & Petraglia, M. D. *Evol. Anthropol.* **21,** 113–125 (2012).
13. Grün, R. *et al. J. Hum. Evol.* **49,** 316–334 (2005).
14. Rak, Y., Ginzburg, A. & Geffen, E. *Am. J. Phys. Anthropol.* **119,** 199–204 (2002).
15. Demeter, F. *et al. PLoS ONE* **10,** e0121193 (2015).
16. Michel, V. *et al. J. Hum. Evol.* http://dx.doi.org/10.1016/j.jhevol.2016.07.008 (2016).
17. Svoboda, J. in *Emergence and Diversity of Modern Human Behavior in Palaeolithic Asia* (eds Kaifu, Y., Izuho, M., Goebel, T., Sato, H. & Ono, A.) 23–33 (Texas A&M Univ. Press, 2015).
18. Fu, Q. *et al. Nature* **534,** 200–205 (2016).
19. deMenocal, P. B. & Tierney, J. E. *Nature Educ.* **3,** 12 (2012).
20. Manning, K. & Timpson, A. *Quat. Sci. Rev.* **101,** 28–35 (2014).