

scars, which are special states that do not reach thermal equilibrium with their environment¹³.

Graham *et al.* developed a complementary method for entangling multiple qubits. Instead of changing the positions of the atoms to entangle pairs of quantum states, the authors used tightly focused laser beams to drive the gates. This allowed them to keep the array static and to perform gate operations on specified pairs of atoms (Fig. 1b). They used this technique to prepare a system of up to six qubits in what is known as the Greenberger–Horne–Zeilinger state, or cat state, which many consider to be the gold-standard test for proving that a platform is capable of quantum computation.

The authors then demonstrated that they could calculate the molecular energy of a hydrogen molecule using a well-established quantum algorithm. Finally, they implemented a hybrid quantum–classical algorithm – the quantum approximate optimization algorithm – to solve the problem of how to maximize the number of edges that are cut when a graph (network) is divided in two. This is called the MaxCut problem, and it is ‘NP-hard’, which is the most complex class of problem in computer science.

A combination of the techniques presented by these two groups would lead to a robust and versatile platform for quantum computing. Because Bluvstein and colleagues’ atom shuffling connects atoms that are not adjacent, their approach allows the creation of complicated quantum circuits, with the drawback that the time between gate operations is long. Graham and co-workers’ platform enables sequential gates to be implemented very rapidly and allows independent, parallel gate operations, which makes larger circuits a possibility.

The next challenge for the field is to improve the gate fidelity, which describes the probability of correctly preparing the desired state. Although the gate fidelities reported are currently comparable to those of other platforms^{14,15}, they must still be increased to achieve the threshold for correcting the errors that arise naturally in any quantum computer.

The two groups’ results represent a key step towards realizing a quantum computer using neutral atoms. The extension of the techniques demonstrated here to large numbers of atoms should, in theory, be straightforward. But scaling up to a practical quantum computer would require many improvements. The atoms would need to be cooled until they were almost at a standstill, and the shape of the laser pulses used would need to be optimized and the laser power increased. The prospect of realizing a quantum circuit using hundreds, or even thousands, of atoms therefore presents a tantalizing new goal – but one that now seems within reach.

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1. Kandala, A. *et al.* *Nature* **549**, 242–246 (2017).
2. Arute, F. *et al.* *Nature* **574**, 505–510 (2019).
3. Pino, J. M. *et al.* *Nature* **592**, 209–213 (2021).
4. Scholl, P. *et al.* *Nature* **595**, 233–238 (2021).
5. Ebadi, S. *et al.* *Nature* **595**, 227–232 (2021).
6. Graham, T. M. *et al.* *Phys. Rev. Lett.* **123**, 230501 (2019).

7. Bluvstein, D. *et al.* *Nature* **604**, 451–456 (2022).
8. Graham, T. M. *et al.* *Nature* **604**, 457–462 (2022).
9. Barredo, D., de Léséleuc, S., Lienhard, V., Lahaye, T. & Browaeys, A. *Science* **354**, 1021–1023 (2016).
10. Endres, M. *et al.* *Science* **354**, 1024–1027 (2016).
11. Omran, A. *et al.* *Science* **365**, 570–574 (2019).
12. Gullion, T., Baker, D. B. & Conradi, M. S. *J. Magn. Reson.* **89**, 479–484 (1990).
13. Bernien, H. *et al.* *Nature* **551**, 579–584 (2017).
14. Satzinger, K. J. *et al.* *Science* **374**, 1237–1241 (2021).
15. Erhard, A. *et al.* *Nature* **589**, 220–224 (2021).

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Migration

A lengthy look at climate and hominin evolution

Michael D. Petraglia

Climate effects on ecosystems shaped the evolution of our hominin relatives in the human family tree. A modelling study examines these habitat changes and the various ways in which they influenced hominin species. **See p.495**

Changes in terrestrial ecosystems are inextricably linked to the evolution of humans and that of our ancestors and relatives in the genus *Homo*. Timmermann *et al.*¹ show on page 495 how climatic shifts over the past two million years shaped hominin habitats, dispersal patterns and species diversity. The work addresses crucial questions about the evolution of *Homo*, including the evolution of our own species.

It has long been understood that large-scale shifts in the global climate correspond to changes in terrestrial ecosystems as a result of alterations in available habitats. Accordingly, researchers from a range of fields, including Earth science, palaeoanthropology and archaeology, have theorized that major habitat changes might have profoundly affected hominin populations by altering the availability of resources, and thereby influencing biological and behavioural pressures^{2,3}.

In investigations of habitat variability over millions of years, one of the most notable problems is that terrestrial records of habitat information – such as that obtained from sedimentary outcrops and palaeolake drill cores – are often limited in terms of the time frames of data available. Moreover, fieldwork to gather such records is geographically biased, with only partial coverage of the regions that hominins inhabited. Furthermore, the existing records demonstrate temporal, spatial and complex regional variation^{4,5}, supporting the view that researchers need to examine the full range of habitats in which hominins resided⁶.

Timmermann and colleagues took a sophisticated modelling approach, examining the relationship between simulated predictions of ancient habitats and the presence of hominin-fossil localities and archaeological sites. The authors’ habitat predictions for a location correspond to a time frame of 1,000 years for each piece of data, and are based on a range of climate variables, such as precipitation, temperature and net primary productivity (the generation of plant biomass). These predictions are mapped on a spatial scale corresponding to 1° of latitude by 1° of longitude. Timmermann *et al.* also compiled a comprehensive data set of hominin fossil and archaeological sites across Africa and Eurasia, comprising 3,245 data entries, with dated samples ranging from 2 million to 30,000 years ago.

The authors examined five hominin groups comprising six species – early African *Homo* (combining *Homo habilis* and *Homo ergaster*), Eurasian *Homo erectus*, *Homo heidelbergensis*, *Homo neanderthalensis* (Neanderthals) and *Homo sapiens*. Timmermann *et al.* note that certain groupings are contentious, such as that of *H. heidelbergensis*⁷, and that species, such as the Neanderthals and *H. sapiens*, are better understood in comparison with the other hominin species. Among the limitations of this study is the exclusion of the hominins Denisovans, *Homo naledi*, *Homo floresiensis* and *Homo luzonensis*, owing to the small number of relevant fossils or fossil locations available. Also missing are newly proposed species, such as *Homo longi* and *Homo bodoensis*.

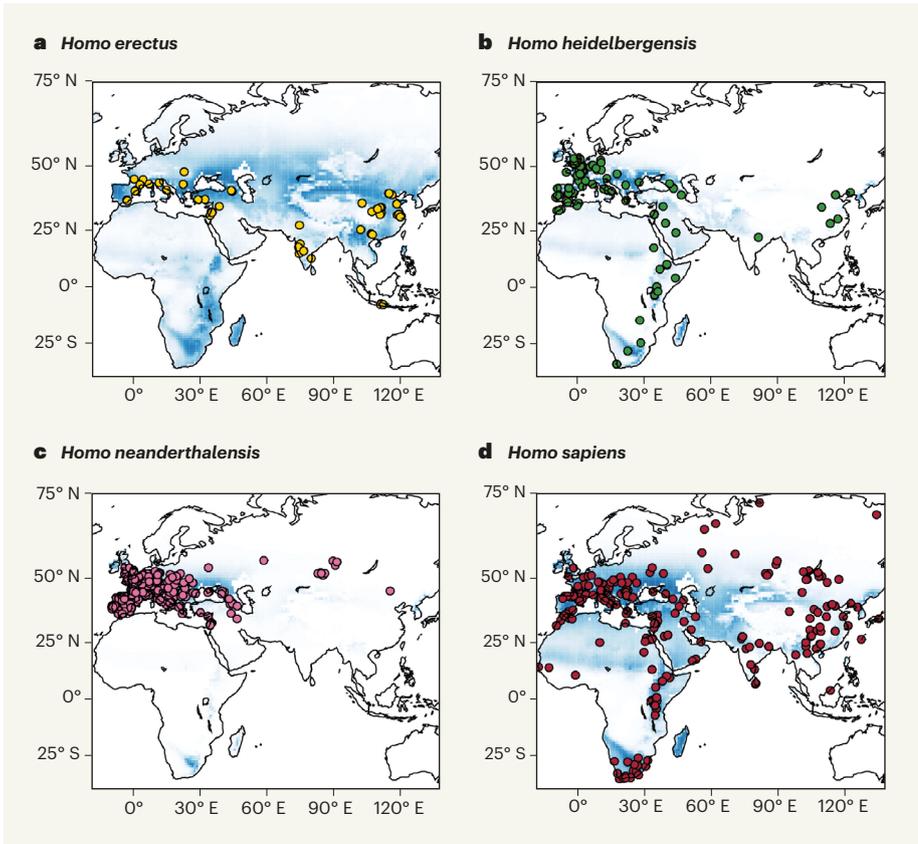


Figure 1 | Habitat suitability and the distribution of early humans and our close relatives. Timmermann *et al.*¹ used a modelling approach to estimate the probable climate over the past 2 million years, in 1,000-year intervals, for locations corresponding to an area of 1° of latitude by 1° of longitude. The authors also mapped sites (circles) associated with remains or artefacts linked to various hominin species belonging to the genus *Homo*. The authors estimated the habitat suitability, as indicated by blue shading, with darker blue corresponding to sites of greater suitability. **a–d**, Each panel presents the data for the relevant time frame between 2 million and 30,000 years ago that correspond to the existence of each species. Panels are ordered from the most-ancient species, *Homo erectus* (only *H. erectus* in Eurasia are shown) (**a**), to the most-modern species, humans (**d**). (Figure based on Fig. 1 of ref 1.)

Probably one of the most debated parts of the study will be that the authors link the presence of hominin species to particular stone-tool industries, in the absence of hominin fossils. More than one species can be responsible for producing similar types of stone tool – as shown, for example, for Neanderthals and *H. sapiens*⁸.

Timmermann *et al.* developed habitat-suitability models for each of the six hominin species, quantifying the probability of finding archaeological and fossil evidence of the species at a given time and place. A series of maps of habitat suitability for each hominin group over time shows some interesting patterns (Fig. 1).

For early African *Homo*, the results point to narrow corridors of suitable habitats across southern Africa and the East African rift valley, characterized by high spatial and temporal variability (the location of these small areas of suitable habitat varies and the habitats' change over time), consistent with the environmental specialization (restricted habitat range) of *H. habilis* and *H. ergaster*.

The predicted habitat-suitability data for Eurasian *H. erectus* is spatially extensive in comparison with that of the other species examined, consistent with the argument that this species was a flexible generalist that inhabited widely different environments (Fig. 1a). In contrast to results for earlier hominins, such as *H. erectus*, the habitat-suitability patterns for *H. heidelbergensis* and the Neanderthals were both overlapping and more restricted (Fig. 1b,c). The authors argue that *H. sapiens* contrasts with all other hominin species with respect to a widening of the presence of our species into generally drier landscapes (Fig. 1d).

The habitat-suitability maps provide a basis for identifying possible locations of the formation of new species, and of species succession and overlap. Timmermann *et al.* find the highest values of overlap in Europe for *H. heidelbergensis* and *H. neanderthalensis*, corresponding to the wealth of fossils and archaeology in that region, and consistent with a view that it is the 'birthplace' of the Neanderthals. The authors also identify two

key areas with climatic conditions suitable for joint occupancy by *H. heidelbergensis* and *H. sapiens* in Africa – central eastern Africa and southern Africa. They argue that climatic stress and a decline in habitat suitability in southern Africa between 415,000 and 310,000 years ago led to the eventual demise of *H. heidelbergensis* and the rise of *H. sapiens* sometime between 310,000 and 200,000 years ago. This time frame is matched by potential fossil and archaeological overlap and high habitat suitability, consistent with the idea that *H. heidelbergensis* evolved into *H. sapiens*.

By contrast, the central eastern African record is viewed as having gaps in the availability of fossils and in archaeological data, suggesting to the authors that this region is less likely to have harboured a gradual species transition or diversification compared with southern Africa. This single southern African 'homeland' interpretation by Timmermann *et al.* might be controversial⁹, because it challenges the African multi-regional model, which contends that our species evolved within a set of interlinked groups of *H. sapiens*, whose connectivity was fluid over time¹⁰.

Timmermann and colleagues' model also addresses relationships between environments and dispersals. Habitat overlaps and species successions are suggested for African early *Homo* and *H. erectus*, followed by the first major exodus of *H. erectus* out of Africa by 1.8 million years ago, culminating in hominins traversing a range of environments in Eurasia at both high and low latitudes. The authors' results indicate that, after the emergence of *H. heidelbergensis* by approximately 875,000 years ago, the dispersal of hominins into Eurasia was accompanied by moves into environments characterized by high and low net primary productivity, far exceeding the ranges of habitats experienced by their earlier ancestors. The wide range of environments and latitudes traversed by both *H. erectus* and *H. heidelbergensis* suggests that these dispersals were accompanied by hominin adaptive shifts in biology and culture^{11,12}. It is a reasonable suggestion that such shifts, in turn, boosted the ability of hominins to extend their geographical range even further, setting the stage for *H. sapiens* to migrate into new ecosystems¹³ and to adapt to spatial climatic extremes¹⁴.

There is still much to learn about the evolutionary implications of climatic variability over the past two million years. Timmermann and colleagues' study provides a starting point for testing a range of theories about how climatic and habitat shifts shaped the distribution, diversification and dispersal of hominin species. On-the-ground research, with close scrutiny of the palaeoenvironmental, fossil and archaeological records across the globe, will be crucial to such an endeavour.

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1. Timmermann, A. *et al.* *Nature* **604**, 495–501 (2022).
2. Potts, R. *Science* **273**, 922–923 (1996).
3. deMenocal, P. B. *Science* **331**, 540–542 (2011).
4. Cohen, A. *et al.* *Annu. Rev. Earth Planet. Sci.* **50**, 451–476 (2022).
5. Yang, S.-X. *et al.* *Quat. Sci. Rev.* **248**, 106614 (2020).
6. Patalano, R. *et al.* *Front. Earth Sci.* **9**, 787669 (2021).
7. Roksandic, M., Radović, P., Wu, X.-J. & Bae, C. J.

- Evol. Anthropol.* **31**, 20–29 (2022).
8. Blinkhorn, J. *et al.* *Sci. Rep.* **11**, 2869 (2021).
9. Schlebush, C. M. *et al.* *J. Archaeol. Sci.* **130**, 105374 (2021).
10. Scerri, E. M. L. *et al.* *Trends Ecol. Evol.* **33**, 582–594 (2018).
11. Faith, J. T. *et al.* *Trends Ecol. Evol.* **36**, 797–807 (2021).
12. Galway-Witham, J., Cole, J. & Stringer, C. *J. Quat. Sci.* **34**, 355–378 (2019).
13. Boivin, N., Fuller, D. Q., Dennell, R., Allaby, R. & Petraglia, M. D. *Quat. Int.* **300**, 32–47 (2013).
14. Roberts, P. & Stewart, B. A. *Nature Hum. Behav.* **2**, 542–550 (2018).

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Climate science

Marine heatwaves reliably forecast by climate models

Markus G. Donat

Climate models can provide accurate seasonal forecasts of unusually warm ocean temperatures, enabling the models’ predictions to guide decisions made by stakeholders in the marine industries and conservation. **See p.486**

Prolonged periods of anomalously warm ocean temperatures, known as marine heatwaves, can severely affect marine ecosystems, as well as industries such as fisheries and tourism. On page 486, Jacox *et al.*¹ report that these extreme events can be predicted several months into the future, offering valuable information for marine stakeholders seeking to mitigate such effects – or to benefit from them.

The frequency and duration of marine heatwaves have increased globally over the past century², and further increases are expected as Earth’s climate continues to warm³. Such long-term changes will require suitable adaptation and mitigation measures, but marine heatwaves are also affected by climatic variations between one season or year and the next. Predicting these short-term effects could aid operational decisions to manage their impact. For fisheries, for example, this could mean protecting populations from being overfished when heatwaves reduce productivity, or preparing to harvest more when productivity is enhanced.

Seasonal climate predictions are made using numerical models that represent our understanding of the physical climate system consisting of the atmosphere, ocean, sea ice and land surface, and the interactions between those components. Simulations of such models typically start from our best estimate of the present climate state and forecast plausible climate trajectories for the coming months⁴. These simulations can be

used to compute the probability that a marine heatwave will occur.

Such seasonal predictions are now provided on a regular basis by a number of forecasting centres around the world. These centres also produce large sets of retrospective forecasts, which are initialized from conditions in the past. By comparing retrospective forecasts with past observations, researchers can assess

the quality of the predictions, and determine to what extent they provide trustworthy information.

Jacox *et al.* used a collection of retrospective seasonal climate predictions (made with multiple models)⁵ to analyse the occurrence of anomalously warm ocean surface temperatures, and to calculate the accuracy with which they can be predicted. They defined marine heatwaves as events in which monthly average sea surface temperatures were in the warmest 10% of those recorded between 1991 to 2020, taking into account seasonality and location.

Their analysis shows that the occurrence of marine heatwaves can be predicted up to four months in advance with high forecasting ‘skill’ (a metric that quantifies the quality of a forecast, including its accuracy and reliability) for large areas of the global ocean (Fig. 1). The predicted duration of these heatwaves is also closely correlated with their observed duration. In some regions affected by large-scale climate modes, such as the El Niño–Southern Oscillation, in which the surface waters of the tropical Pacific Ocean periodically warm and cool⁶, marine heatwaves can be predicted with even longer lead times, of up to 12 months.

The ability to make skilful forecasts of marine heatwaves on the basis of existing prediction systems is good news for climate scientists and model developers, because it provides evidence that such systems are accurate to some extent. But can the predictions be used to guide decisions in other areas of research and industry? The answer depends on the relative needs of the user – including their tolerance to the risk of marine heatwaves and the cost and probable impact of evasive action.

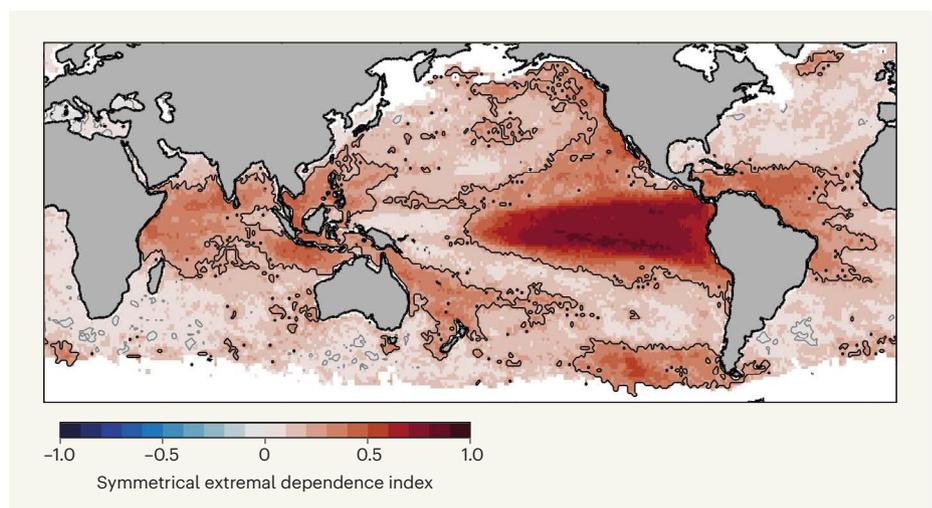


Figure 1 | Predicting marine heatwaves using seasonal climate forecasts. Jacox *et al.*¹ made predictions for prolonged periods of unusually warm ocean temperatures (marine heatwaves) using seasonal prediction models that simulate the climate several months into the future. The authors’ predictions were accurate for large areas of the global ocean, as shown by a measure known as the symmetrical extremal dependence index, which varies between –1 for poor forecasts and 1 for perfectly accurate forecasts, with a positive index indicating that the prediction is better than one made by chance. The predictions evaluated here are for forecast times 3.5 months into the future. (Adapted from Fig. 1b of ref. 1.)