

News & views

Palaeontology

Earth's eccentricity shapes evolution

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Analysis of plankton fossils has revealed pulses of size diversity that are inextricably linked to the degree of circularity of Earth's orbits. Could this orbital variability provide a beat that dictates the rhythm of evolution? **See p.79**

When considering the factors that shape evolution over time, attention normally focuses on biological aspects. However, on page 79, Beaufort *et al.*¹ present the case for variations in Earth's orbit as being implicated in determining the outcome of evolution.

Earth's annual orbit around the Sun is not always perfectly circular; instead, it displays variations in what is known as eccentricity – in which the planet's orbit varies between a more-circular and a more-elliptical path. Nearly half a century ago, the unmistakable frequencies of such variations were identified within evidence from glacial cycles (discerned through isotopic signals), captured in microfossils preserved in marine sediments². These deviations in the circularity of Earth's annual orbit (resulting in cycles of eccentricity approximately every 100,000 and 400,000 years) are caused by the gravitational pull of other orbiting planets in the Solar System. Further notable changes include variation in the tilt of Earth's rotational axis (every 40,000 years) and alterations every 23,000 and 19,000 years in the timing of the seasons around the orbit, called precession.

Curiously, in the past 400,000 years, cycles between an ice age (glacial) and a non-ice age (interglacial) period are in sync with the 100,000-year frequency of eccentricity, despite this change in Earth's orbit exerting approximately ten times less influence on the amount of annual sunlight received compared with the other, higher-frequency orbital cycles³. A key unanswered question is how the seemingly minor perturbations of eccentricity might drive the large climatic swings of glacial cycles. By providing fresh insights into a consequence of Earth's eccentricity on the planet's biosphere and carbon cycle, Beaufort and colleagues' findings hint at an elusive

feedback mechanism that could contribute to the amplification of these climatic swings.

The authors have uncovered a phenomenon that challenges our understanding of the effects of Earth's orbital eccentricity. They pioneered new types of a machine-learning tool called a neural network⁴ that enabled them to automate and thereby speed up the process of characterization of intricate, micrometre-scale structures called calcite liths (or coccoliths), which are formed of

calcium carbonate. Calcite liths are produced intracellularly by single-celled phytoplankton termed coccolithophores (Fig. 1), which are found in marine sediments⁴. Beaufort *et al.* show that the size diversity of the Noelaerhabdaceae, the dominant coccolithophore group found in the ancient ocean of the Pleistocene period (from 2.6 million to 11,700 years ago), displays a changing pattern that tracks with variations in the eccentricity of Earth's orbit.

Time-consuming microscopy work had previously established that the size of fossil coccoliths of the Noelaerhabdaceae grouping underwent three 'pulses' of increased size, punctuated by episodes of size reduction, in the past 1.8 million years⁵. Beaufort and colleagues developed an index that could capture a snapshot of the size characteristics of coccoliths, described as the morphological divergence index (MDI). This is cleverly designed to be independent of varying species abundance, because such variation might otherwise result, for example, in a highly prevalent species dominating the signal of the average coccolith size. The metric is based on the difference in the average mass of Noelaerhabdaceae coccoliths that are assigned to one of two groups: either longer or shorter than 3 micrometres.

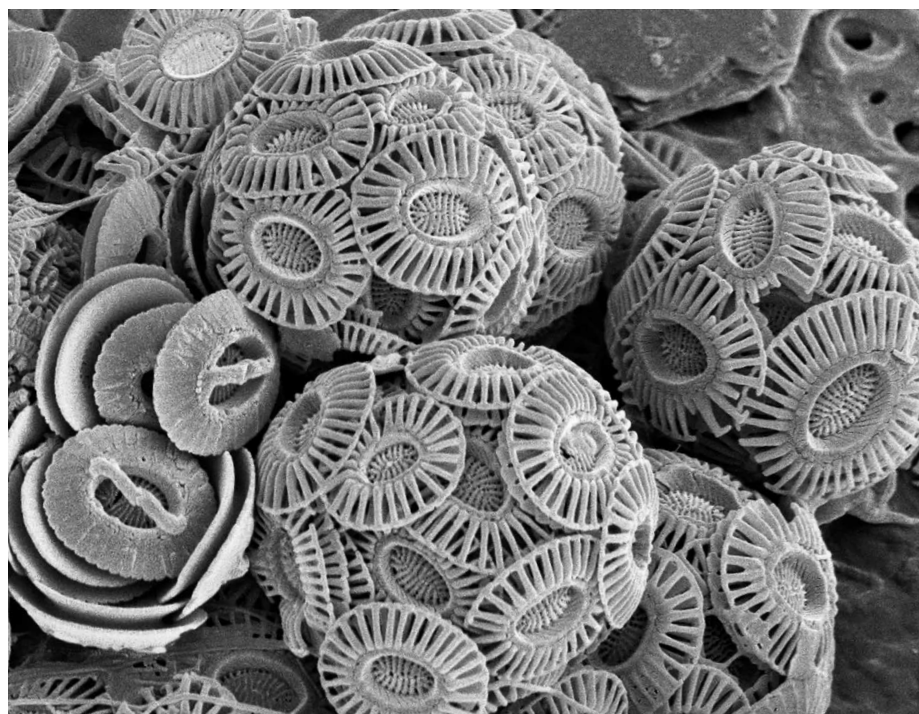


Figure 1 | Coccolithophores. These marine phytoplankton make intricate oval structures intracellularly – called coccoliths – that are then extruded to surround the organism's surface (the species shown is *Emiliania huxleyi*). Beaufort *et al.*¹ analysed coccoliths in ancient marine sediments, and their findings indicate that eccentricity in Earth's orbit had a role in shaping phytoplankton evolution.

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This measurement is sensitive to both size and the degree of calcite incorporation (calcification), which might be sensitive to environmental parameters.

Whether MDI is a signature that is truly representative of genetic diversity is open to question. Nonetheless, genomic analyses⁶ have confirmed that the size increase of coccolithophores over the past 600,000 years was a consequence of rapid diversification of species (a phenomenon called radiation, typically associated with the availability of new environmental niches). And another type of analysis indicates that the pulses older than 600,000 years were associated with distinct species that could be defined by their shape (morphologically defined)⁶. This suggests that genetic diversity does underpin the size variance of coccoliths.

Armed with their tool, Beaufort and colleagues rattled through multiple samples of marine-sediment cores. This work resulted in the statistically robust observation that a high eccentricity of Earth's orbit leads to high diversity of phytoplankton, and vice versa, as observed over the past 2.8 million years. Intuitively, and as validated by Earth-system modelling, the more eccentric the orbit, the more extreme were the seasonal contrasts and the greater the diversity of ecological niches and thus the associated phytoplankton diversity. By contrast, a more circular orbit caused a decline in diversity, perhaps even extinctions, presumably through diminishing niche availability and the creation of a genetic 'bottleneck' that allowed more-opportunistic species to flourish ubiquitously and outcompete the existing diversity of phytoplankton.

Although biodiversity is heralded as the harbinger of a healthy ecosystem, from the perspective of carbon storage in the ocean, low phytoplankton diversity seemed to be more productive and to have accelerated the flow of carbon from the surface to the deep, as indicated by Beaufort and colleagues' evidence. Opportunistic, mid-size phytoplankton species at low Earth eccentricity led to the greatest burial rates of coccolith-derived carbon in the form of calcium carbonate. Notably, each of these highs in productivity occurred just before a step increase in the size of the climatic swings of the glacial cycles: approximately 900,000 years ago and 400,000 years ago.

Might high burial rates of coccoliths have reduced the ocean reservoir of alkalinity or carbon, causing the marine carbonate system to be more susceptible to fluctuations, and thus accentuating a carbon-cycle feedback for larger-amplitude glacial cycles? An overwhelming challenge in climate science is to understand how the very weak influence of eccentricity on the receipt of sunlight on Earth can cause massive-amplitude glacial cycles. Perhaps Beaufort and colleagues' findings

indicate a response to the 400,000-year cycle of eccentricity in the carbon cycle that could then help to amplify the system towards the more-extreme glacial cycles that happen subsequently. And how might these high burial rates of coccoliths with their specific chemistries^{7,8} influence seawater chemistry? The answer has implications for the interpretation of a number of indirect measurements (proxies) that are used to understand the past ocean.

Aside from diversity, the advent of new species (speciation) might also be sensitive to orbit, because such large populations of opportunistic coccolithophores, at low Earth eccentricity, enhance the potential for the emergence of advantageous mutations. Barriers to gene flow, which are also needed for speciation, are altered by the advance and retreat of glaciers and ice sheets, segregating ecosystems, at least on land, such that the tempo of terrestrial species turnover seems sensitive to orbital cycles⁹. Even though the open ocean is devoid of such apparent mechanisms of physical isolation, an analysis of

"A high eccentricity of Earth's orbit leads to high diversity of phytoplankton."

Noelaerhabdaceae genomes demonstrates that extended periods of complete genetic isolation occurred during all the recent speciation events for this grouping¹⁰.

Furthermore, all individual speciation events coincided with glacial periods, suggesting that the low-latitude glacial ocean during low Earth eccentricity might have been the birthing pool for new phytoplankton species, perhaps owing to stronger isolation between ocean basins and increased segregation of ecological niches. The growth of diversity happens through the emergence of individual species in the 100,000-year paced eccentricity lows (glacials), gradually building up over subsequent cycles until diversity reaches a maximum roughly every 400,000 years.

Such a link between orbital change, climate and phytoplankton evolution could be an intrinsic beat that underscores the Earth system. There are hints that orbital frequencies have provided the metronome for the carbon cycle¹¹ and for coccolith size over the past 190 million years¹², and reports of a link between Earth's orbital forcing and speciation in plankton stretch back to data obtained from samples dating back 450 million years ago^{13,14}.

A future challenge will be to understand how the weakest variance in annual sunlight from the eccentricity cycles is amplified to exert such a disproportionate impact on evolution and climate. The extent to which evolution is

influenced by cycles in climate or exposure to changing intensity of solar radiation as a result of orbital change is itself a key issue to be resolved. Exploring the rhythm of orbital variations across the evolution of the tree of life will undoubtedly unveil greater detail regarding the intricate feedbacks between life, the carbon cycle and climate.

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1. Beaufort, L. et al. *Nature* **601**, 79–84 (2022).
2. Hays, J. D., Imbrie, J. & Shackleton, N. J. *Science* **194**, 1121–1132 (1976).
3. Imbrie, J. et al. *Paleoceanogr. Paleoclimatol.* **8**, 699–735 (1993).
4. Beaufort, L. & Dollfus, D. *Mar. Micropaleont.* **51**, 57–73 (2004).
5. Matsuoka, H. & Okada, H. *Proc. Ocean Drill. Prog.* **115**, 255–270 (1990).
6. Bendif, E. M. et al. *Nature Commun.* **10**, 4234 (2019).
7. McClelland, H. L. O., Bruggeman, J., Hermoso, M. & Rickaby, R. E. M. *Nature Commun.* **8**, 13511 (2017).
8. Rickaby, R. E. M. et al. *Earth Planet. Sci. Lett.* **253**, 83–95 (2007).
9. van Dam, J. A. et al. *Nature* **443**, 687–691 (2006).
10. Filatov, D. A., Bendif, E. M., Archontikis, O. A., Hagino, K. & Rickaby, R. E. M. *Curr. Biol.* <https://doi.org/10.1016/j.cub.2021.09.073> (2021).
11. Herbert, T. D. *Proc. Natl Acad. Sci. USA* **94**, 8362–8369 (1997).
12. Suchéras-Marx, B., Mattioli, E., Pittet, B., Escarguel, G. & Suan, G. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **295**, 281–292 (2010).
13. Crampton, J. S. et al. *Proc. Natl Acad. Sci. USA* **115**, 5686–5691 (2018).
14. Crampton, J. S. et al. *Proc. Natl Acad. Sci. USA* **113**, 6868–6873 (2016).

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