Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **112**, 275–286, 2021

Article

James Croll and geological archives: testing astronomical theories of ice ages

Polychronis C. TZEDAKIS[1]* and Eric W. WOLFF[2]

[1] Environmental Change Research Centre, Department of Geography, University College London, London, UK.
[2] Department of Earth Sciences, University of Cambridge, Cambridge, UK.
*Corresponding author. Email: p.c.tzedakis@ucl.ac.uk

ABSTRACT: James Croll's Physical Theory of Secular Changes of Climate emerged during an age of revolution in geology that included the rise of the glacial theory and the search for its underlying causes. According to Croll, periods of high eccentricity are associated with the persistence of long glacial epochs, within which glaciations occur in alternate hemispheres when winter is at aphelion every ~11,000 years; however, astronomical forcing is only able to produce glaciation by means of physical agencies (climate feedbacks) that amplify the small effects of varying seasonal irradiation. Croll understood the importance of interglacial deposits because they provided evidence for the occurrence of multiple glaciations within his long glacial epochs. He was aware of the limitations of the terrestrial record and suggested that deep-sea sediments would contain a continuous succession of glacial-interglacial cycles. Contrary to a widespread view, however, Croll was not envisaging the advent of palaeoceanographic exploration *avant la lettre*, but instead was drawing attention to the inadequacy of the land record as a testbed of his astronomical theory. Yet, the marine record did eventually deliver a test of astronomical theories almost exactly 100 years after the publication of his 1875 book *Climate and Time in their Geological Relations*. Here, we provide an historical account of the technological and scientific developments that led to this and a summary of insights on astronomically paced climate changes from marine, terrestrial and ice core records. We finally assess Croll's ideas in the context of our current understanding of the theory of ice ages.

KEY WORDS: Croll, eccentricity, Foraminifera, glacials, ice sheets, interglacials, Milankovitch, obliquity, oxygen isotopes, precession.

1. Croll in the context of glacial and astronomical theories

During the course of the 'long 19th Century', the emergence of a novel perspective and novel method in geology radically transformed the view of Earth history in general, and of the physical character of the most recent major global change in particular (Rudwick 2005). Cuvier's revolutions (1812), representing a series of localised abrupt environmental changes, were transformed in the English translation by Jameson into universal catastrophes, the most recent of which was the biblical Flood, providing support for the diluvial theory (Buckland 1823). Erratics, large boulders lying unconformably on a terrain of different geological composition, presented a difficulty for the diluvial theory, which had to invoke transport by 'violently moving water' (de Saussure 1779–1796) or on ice rafts (Lyell 1840; hence the term 'drift' deposits). Von Buch (1815, 1818) undertook a systematic study of the distribution of erratics, in the Alps and the plains of northern Europe; he identified the sources of the erratics, refuted earlier conjectures for a physical cause and suggested mudslides or subaerial turbidity currents as possible agents. In time, mounting evidence from Switzerland and Scandinavia for the dispersal of erratics and deposition of moraines by the greater extent of glaciers in the past (e.g., Venetz 1833; de Charpentier 1841) led to the emergence of the glacial theory and the coining of the term Ice Age (*Eiszeit*) (Schimper 1837; Agassiz 1838).

Various theories attempted to account for the occurrence of multiple revolutions and also a gradual cooling during recent geological ages that led to an ice age. Lyell (1830–1832) proposed a geographical theory based on recurring changes in the distribution of land and sea, and tectonic vertical motions of the continents; he pointed to a gradual uplift of land areas of the northern hemisphere and an increase of land area at higher latitudes to account for global cooling since the early Tertiary. Another family of theories invoked celestial mechanics. Poisson (1835) suggested that during its geological history the Earth had passed through warmer and cooler regions in space. An early allusion to the occurrence of glaciation as a result of Earth occupying an orbital position farthest from the Sun was by Esmark (1827), who described evidence of glaciation in Norway and was aware of von Buch's work on erratics. In a paper read to the Geological Society in 1830, Herschel (1832) assessed the possible effects of changes in the Earth's orbit on geological revolutions. He thought that changes in the eccentricity would be too small to have an appreciable effect on the mean annual amount of solar radiation, but the combined effects of axial precession and apsidal precession could enhance seasonality, leading to changes in climate. Adhémar (1842) proposed a theory based on precessional variations with alternating glaciations in the two hemispheres caused by differences in the lengths of the seasons. According to Adhémar (1842), the southern hemisphere is in a glacial period, as implied by the presence of the newly

doi:10.1017/S1755691021000177

discovered Antarctic ice sheet, because its winters are longer by almost 8 days as a result of austral winter occurring at the point of the Earth's orbit farthest from the Sun (aphelion). However, von Humboldt (1821) and Herschel (1832) had pointed out that seasonal differences arising from precession are in fact balanced over the course of a year and both hemispheres receive the same amount of annual radiation.

Croll proposed that evidence for the recurrence of colder and warmer periods through geological time required 'some great, fixed, and continuously operating cosmical law' (Croll 1864, p. 129). He developed an astronomical theory that included the effects of both climatic precession and eccentricity, using calculations of orbital variations by Le Verrier; he was also aware of the effects of changes in the inclination of the Earth's rotational axis (obliquity) (Croll 1867), though accurate calculations were not available at that time. The main tenets of his theory (Croll 1875) were (1) high eccentricity produces on the hemisphere with winter solstice at aphelion long and cold winters and the accumulation of snow and ice; (2) changes in eccentricity lead to long glacial epochs, when the orbit is more elliptical and seasonal differences are accentuated (as from 240–80 thousand years ago (ka)), and to long interglacial epochs with a more circular orbit and subdued seasonal differences (e.g., 80 ka to present); (3) within glacial epochs, precession leads to glaciations alternating between hemispheres every ~11 thousand years (kyr) and in the same hemisphere every ~22 kyr (but only near local maxima in eccentricity; thus during the glacial epoch from 80 to 240 ka, three interglacials would have occurred near 200 ka and not more than two near 100 ka [Croll 1884]); (4) changes in obliquity accentuate the effects of precession; and (5) the direct effect of seasonal changes in irradiation is too small and therefore *physical agencies* (amplifying feedbacks) are required: the cooling effects of snow and fogs on air temperature and ice albedo lead to an increase in the latitudinal temperature gradient and the strength of the trade winds in the colder hemisphere, which in turn lead to changes in ocean currents and interhemispheric heat transport, further amplifying snow and ice accumulation. Croll emphasised that 'the physical causes are far more powerful than the astronomical' and that 'it is the transference of heat by ocean currents from the hemisphere in aphelion to the one in perihelion which is the main reason why the former is cold and the latter warm' (Croll 1884, pp. 97–98). In this view, 'the main function of the astronomical agents is to keep the physical agencies in operation, and also to determine the character of their operations' (Croll 1884, p. 95). It is for this reason that Croll preferred to term his theory the Physical Theory of Secular Changes of Climate.

The Irish *savant* Joseph John Murphy (1869) was first to point to summer as the critical season for glaciation by proposing that a glacial period would occur in the hemisphere with aphelion near the summer solstice, though he agreed with Croll that glaciation would alternate between hemispheres every half-precession cycle. Lyell (1875) considered the effect of astronomical variations secondary to the influence of physical geography on climate. Moreover, he thought the geological evidence did not support the occurrence of glaciation in one hemisphere at a time and was also not convinced by Croll's (1864) argument that because melting would give rise to thick fogs, the heat in the hemisphere with summer at perihelion would not be sufficient to remove the winter snow accumulation. Croll (1875) dismissed Murphy's suggestion, but in in response to Lyell's criticism he accommodated geographical factors (e.g., land–sea distribution, bathymetry) more explicitly into his theory (Croll 1884), though he considered them as necessary conditions that enable the active causes (astronomical, physical) to produce glaciation.

The most damaging criticism of Croll's theory, however, centred on the timing of the last glaciation, using relative dating of erosional and depositional features. Dana (1896, p. 978) observed that Croll's theory 'is objected to by American geologists on the ground that the Glacial period closed…not more than 10,000, or at most 15,000 years ago, instead of…at least 80,000 years, as the eccentricity requires'.

While support for the astronomical theory waned, so-called geochemical theories provided an alternative explanation for changes in climate and the occurrence of an Ice Age (Paillard 2015). Tyndall (1861) had suggested that small changes in the atmospheric concentration of water vapour and carbon dioxide (CO_2) would suffice to account for changes in climate observed by geologists. Svante Arrhenius (1896) calculated the effect of changes in CO_2 concentration on global temperatures during the Ice Age and proposed that small imbalances between sinks and sources would be able to account for this. He also observed that the global nature of these changes would be in accordance with the emerging view in the geological community that glacial periods were simultaneous in both hemispheres, contrary to Croll's theory. Following Arrhenius' work, Chamberlin (1897) proposed a carbon–ice-sheet oscillatory model, with variations in ocean temperature, oxidation of organic matter and silicate weathering leading to changes in CO_2 concentration and climate.

The astronomical theory was revived in the first part of the 20th Century by Milankovitch (and promoted by Köppen and Wegener). Milankovitch (1920, 1930, 1941) was able to use the Stockwell – Pilgrim numerical values (and later also those of Le Verrier–Miskovitch) of all three astronomical elements (eccentricity, precession and obliquity) to compute changes in insolation at different latitudes over the past 600,000 years before 1800 AD (Berger & Yin 2021). This showed that the impact of changes in obliquity on insolation is symmetrical across the hemispheres, while that of precession is opposite; the effect of obliquity variations is more important at high latitudes, while that of precession is more important at low latitudes. Echoing Murphy and following Brückner *et al.* (1925), Milankovitch considered that the distribution of summer insolation at 65°N would be critical for changes in ice sheets. However, defining summer insolation is not a trivial problem as the length of astronomical seasons varies with Earth's orbital position (Berger & Yin 2021). Given that ice ablation depends both on total irradiation and the length of the summer season, Milankovitch introduced the concept of caloric summer insolation, which is the energy integrated over the caloric summer half of the year (where any day of the summer half receives more insolation than any day of the winter half). The variance of this metric contains a strong obliquity component, whose influence Milankovitch considered crucial for the timing of glaciations. Thus, instead of glaciations alternating between hemispheres, he proposed synchronous global climate changes, which were further amplified by the effect of large northern hemisphere ice sheets on planetary albedo. According to the Milankovitch formulation of the astronomical theory, periodic expansions of northern hemisphere ice sheets are driven by variations in the Earth's orbital geometry and axial inclination that influence the amount of summer isolation received at northern high latitudes.

2. Croll and the geological record

In a paper on the Post-Tertiary and Quaternary formations of Switzerland, Morlot (1855) drew attention to evidence for two separate glacial periods, with an intervening diluvial period of considerable length, but of unclear character that included remains of wood and shells of recent freshwater species, but also mammoth. A few years later, Archibald Geikie reported the presence of stratified deposits within the glacial drift of

Scotland, providing 'good evidence to show that even during the accumulation of the Scottish till, this extreme [glacial] rigour was not the constant and universal condition of the climate' (Geikie 1863, p. 92). However, the length of the temperate interval was unclear. Around the same time, Oswald Heer, Professor of Palaeobotany in Zürich, presented evidence for the development of mixed forest and temperate fauna in beds sandwiched between glacial deposits at Dürnten, Switzerland and proposed the term 'interglacial formation' (Heer 1865). To our knowledge, this is the first time the term 'interglacial' was introduced in the literature. Within a few years, a substantial number of interglacials deposits had been identified in the British Isles, Scandinavia, Central Europe and North America (Geikie 1874). It is worth noting, however, that the term interglacial (or 'inter-glacial', as distinct from 'pre-glacial' and 'post-glacial') was often used loosely to denote an interruption of glacial conditions. While some of these deposits would likely be considered 'interstadials' today, the fossil remains of others provided clear evidence of the temperate climatic character and considerable duration of interglacial periods.

Croll (1869, p. 344) drew attention to intercalated deposits within glacial drift in Scotland as '…bearing decided testimony to the existence of interglacial warm periods', because he understood the implications for his Physical Theory: '…the glacial epoch did not, as has hitherto been generally supposed, consist of one long unbroken period of cold and ice. Neither did it consist, as some have concluded, of two long periods of ice with an intervening mild period, but it must have consisted of a long succession of cold and warm periods' (Croll 1875, p. 236).

In principle, the geological record could provide a test of Croll's Physical Theory: 'Here we have the grand crucial test of the truth of the foregoing theory of the cause of the glacial epoch. That the glacial epoch should have consisted of a succession of cold and warm periods is utterly inconsistent with all previous theories which have been advanced to account for it. What, then, is the evidence of geology on this subject?' (Croll 1875, p. 237). But Croll (1868, 1875) was aware of the limitations of the terrestrial sedimentary sequence to preserve a complete record of glacials and interglacials: 'It is upon the present land surface that we find the chief evidence of the last glacial epoch, but the traces of the warm periods of that epoch are hardly now to be met with in that position since they have nearly all been obliterated or carried into the sea…In regard to former glacial epochs, however, ice-marked rocks, scratched stones, moraines, till, &c, no longer exist; the land-surfaces of those old times have been utterly swept away.' (Croll 1875, p. 287).

And then, as Imbrie & Imbrie (1979) have suggested, he famously appears to be anticipating the advent of palaeoceanographic exploration: 'The only evidence, therefore, of such ancient glacial epochs, that we can hope to detect, must be sought for in the deposits that were laid down upon the sea-bottom; where also we may expect to find traces of the warm periods that alternated during such epochs with glacial conditions.' (Croll 1875, p. 287).

In fact, Croll was not advocating a research programme in deep-sea sediment sampling, but was juxtaposing the marine and terrestrial geological records to draw attention to the imperfections of the latter, and by extension its inadequacy to test his hypothesis: 'But our limited knowledge of former glacial epochs must no doubt be attributed chiefly to the actual imperfection of the geological records. So great is this imperfection that the mere absence of direct geological evidence cannot reasonably be regarded as sufficient proof that the conclusions derived from astronomical and physical considerations regarding former ice-periods are improbable.' (Croll 1875, p. 267).

And: 'Nothing that does not lie buried in the deeper recesses of the ocean will escape complete disintegration and appear imbedded in those formations. It is only those objects which lie in our existing sea-bottoms that will remain as monuments of the glacial epoch of the Post-tertiary period. And, moreover, it will only be those portions of the sea-bottoms that may happen to be upraised into dry land that will be available to the geologist of future ages.' (Croll 1875, p. 271). Thus, was the proper testing of the astronomical theory consigned to remote posterity.

3. The marine record – testbed of astronomical theories

Around the same time, the Royal Society sponsored the *Challenger* expedition of 1872–76, the first oceanographic expedition of its kind. In addition to investigating the physical conditions of the deep sea and the chemical composition of seawater, the expedition undertook a systematic investigation of deep-sea sediments to examine their physical and chemical character and origin. When the scientific results were eventually published by John Murray, deep sea sediments were described as having either an organic origin, precipitated by organisms, or an inorganic origin, derived from terrestrial and extra-terrestrial sources and products synthesised in the deep sea. While diatom and radiolarian remains were abundant in deposits of the Southern Ocean and of the North Pacific, sediments in temperate and tropical seas above 4000 m depth were dominated by an ooze composed of remains of pelagic Foraminifera (Challenger Expedition 1880–1895). The *Challenger* results showed that the deep-sea floor was covered by sediments, but obtaining the archives that enabled the testing of the astronomical theory would have to await for technological and scientific developments to fall into place.

The initial sea floor samples of the *Challenger* expedition were small samples of surface sediment, recovered by means of the sounding instrument. In the early 20th Century, gravity corers were able to obtain continuous sediment cores about 1 m long. Wolfgang Schott analysed the relative abundance of planktic Foraminifera in cores raised by the German *Meteor* expedition of 1925–27 from the floor of the equatorial Atlantic; he plotted their present-day geographical distribution on the seafloor and found that downcore variations in the abundance of *Globorotalia menardii* indicated alternations of cold and warm climates (Schott 1935). A major development was the invention of the Kullenberg piston corer which allowed the recovery of longer 10–15 m cores and was used on the Swedish deep-sea expedition of the *Albatross*, 1947–49 (Pettersson 1948). Cores raised from the Pacific on the *Albatross* were sent to Gustaf Arrhenius (Svante Arrhenius' grandson) at the Scripps Institution of Oceanography. Arrhenius (1952) showed the presence of cyclical variations in the concentration of calcium carbonate ($CaCO_3$) and suggested that these were related to glacial-interglacial changes in Pacific Ocean circulation. In that same publication, Arrhenius introduced the system of notation, with odd-numbers corresponding to warm stages and even numbers to cold stages, starting with the Holocene as no. 1.

In 1949, Maurice Ewing established the Lamont Geological Observatory of Columbia University as a centre of oceanographic and geophysical research. Recognising the potential of deep-sea cores, Ewing directed its research vessels to raise a piston core every day, irrespective of other research activities, reaching a rate of 200 cores per year (Imbrie & Imbrie 1979). The Lamont core collection quickly became the largest in the world and provided critical material for reconstructing past climate variability. Using Lamont cores, Ericson & Wollin (1956) produced qualitative estimates of sea surface temperature (SST) variations over several cycles by calculating the relative abundances of planktic foraminifer indicator species that were sensitive to climate changes, such as *G. menardii*. Radiocarbon dating showed

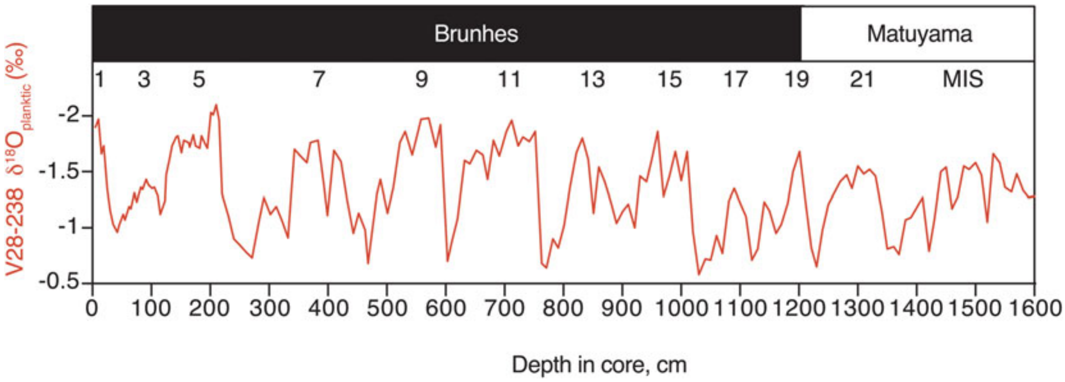

Figure 1 Magnetic stratigraphy and oxygen isotopic composition of planktic foraminifer *G. sacculifera* in core V28–238 (Shackleton & Opdyke 1973). Marine Isotope Stages (MIS) are indicated.

that the most recent cold-to-warm transition in their cores occurred ~11,000 years ago, in line with dating of terrestrial records (Ericson *et al.* 1956).

While records of faunal variations contributed to the body of evidence on past warm–cold cycles, advances in chemistry would revolutionise the field of palaeoclimate and eventually provide a more rigorous test of astronomical theories. In a lecture on the thermodynamic properties of isotopic substances delivered before the Chemical Society in 1947, Harold Urey proposed to use the temperature dependence of oxygen isotope fractionation in the CO_2–H_2O–$CaCO_3$ system to determine the temperature of precipitation of $CaCO_3$ by measuring its $^{18}O/^{16}O$ isotopic composition (Urey 1947). In Urey's laboratory at the University of Chicago, Cesare Emiliani applied this approach to the isotopic composition of planktic foraminiferal shells in Caribbean and equatorial Atlantic piston cores from Lamont. He suggested that SSTs varied by ~6°C during glacial–interglacial cycles and used the Arrhenius notation to define what are now called Marine Isotopic Stages (MIS) (Emiliani 1955). Emiliani was aware that the isotopic composition of carbonate does not only depend on temperature, but also on the isotopic composition of seawater. He therefore applied a small correction (0.4 ‰) to his palaeotemperature equation for glacial samples, representing the enrichment of seawater after extraction of water with the lighter isotope that is then locked in ice sheets. The relative contribution of changes in the isotopic composition of seawater, however, would remain uncertain, until Nick Shackleton, a PhD student at the University of Cambridge, modified a mass spectrometer to analyse much smaller samples with improved precision. This enabled him to measure the $\delta^{18}O$ content in much rarer bottom-dwelling benthic Foraminifera, which yielded the same glacial–interglacial isotopic range as planktic Foraminifera from the same samples. Since bottom water temperatures vary little, Shackleton (1967) reasoned that variations in oxygen isotope curves do not primarily reflect sea-water temperatures, but rather the extraction of large amounts of water from the oceans during glacial periods. In 1997, John Imbrie spoke about the significance of this development in an interview for the American Institute of Physics:

> "[Shackleton] then went to…the Pacific Ocean, took a core, and he went down, let's say a hundred and fifty thousand years with the sediment. And he measured the ^{18}O ratio in the plankton, and he also…measured the ^{18}O ratio of the benthics. Now there's a famous picture in one of his papers [Shackleton & Opdyke 1973] where he plotted both of these together. And it was that picture that he brought…[to] a lecture to the CLIMAP group and said, look at this. The benthic record [to a] first approximation has exactly the same amplitude of change as the surface one does. So he showed that graph. Right away a cheer goes up from our audience…Because what that shows is that the temperature effect is very small. Because the temperature at the bottom of the Pacific Ocean can't change by more than a degree Centigrade. So that says right away that the basic feature of the [δ]^{18}O record is…an ice volume record".[1]

A central issue in exploring the presence of astronomical frequencies embedded in marine palaeoclimatic archives was the derivation of a robust chronology. The deep sea represented a stable depositional environment, so to a first approximation the assumption of linear sedimentation rates was not entirely unrealistic. Emiliani (1955, 1972) had derived a timescale for his Caribbean cores by using ^{14}C and $^{230}Th/^{231}Pa$ measurements for the last 150,000 years and beyond that extrapolation using a constant sedimentation rate or alignment to the 65°N insolation curve. Equatorial Pacific core V28–238 was a gamechanger because it extended beyond the Matuyama/Brunhes (M/B) palaeomagnetic boundary (Fig. 1), which had been independently K-Ar dated on land to 700 ka. Shackleton & Opdyke (1973) generated a $\delta^{18}O$ record from planktic Foraminifera, showing a regular succession of glacial–interglacial cycles back to MIS 22; they identified the M/B boundary in MIS 19 and used its age to anchor their chronology. Applying a uniform sedimentation rate for the entire core yielded an age of 123 ka for MIS 5e, very close to independent estimates for that interval (Broecker *et al.* 1968; Shackleton 1969). Comparison with Emiliani's Caribbean $\delta^{18}O$ records showed that the original timescales beyond 60 ka had been wide of the mark, with the age of MIS 19 underestimated by ~250,000 years (Emiliani & Shackleton 1974).

The scene was finally set for testing the astronomical theory. Hays *et al.* (1976) selected two high-accumulation and continuous sequences spanning the last 450 kyr in the southern Indian Ocean, whose locations and properties were suited to testing astronomical hypotheses. They derived records of planktic foraminiferal $\delta^{18}O$, SST from radiolarian assemblages and the abundance of a radiolarian species *Cycladophora davisiana*, reflecting variations in global land ice, subantarctic SST and Antarctic surface water structure, respectively. Spectral analysis revealed that the variance of these records was concentrated

---

[1] Interview of John Imbrie by Ronald Doel on 1997 May 21, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA, www.aip.org/history-programs/niels-bohr-library/oral-histories/6924

in peaks at 100 kyr, 42 kyr and 23–19 kyr. The 42-kyr and 23–19-kyr components had the same period as variations in obliquity and precession, respectively, indicating that the climate system responds quasi-linearly to astronomical forcing. However, the dominant 100-kyr component had a period close to, and in phase with, eccentricity, which, given its very small effect on insolation, was not predicted by astronomical theory and therefore required non-linear responses. Hays *et al.* (1976, p. 1131) concluded that 'changes in the Earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages', providing support for the Milankovitch hypothesis. Although they did not refer to Croll's theory explicitly, their analyses showed that changes in northern hemisphere ice volume and subantarctic SST were nearly synchronous, and therefore glaciations did not alternate between hemispheres.

4. Astronomical frequencies in marine records

Over time, longer and higher resolution foraminiferal δ^{18}O records were obtained and these were eventually combined to produce composite (Shackleton 1995) or stacked records (e.g., Imbrie *et al.* 1984; Lisiecki & Raymo 2005) that were astronomically tuned to derive detailed chronologies spanning the Pleistocene and Pliocene, and eventually reaching to the base of the Cenozoic (Zachos *et al.* 2001; Westerhold *et al.* 2020). Time-series analyses of these records revealed a steadily increasing contribution by obliquity over the last 15 million years (Myr) (Westerhold *et al.* 2020), underlining the sensitivity of ice sheets to high-latitude insolation changes associated with changes in the Earth's axial inclination. The intensification of northern hemisphere glaciation ~2.8 million years ago (Ma) is marked by an increase in the amplitude of the 41-kyr glacial cycles, without a significant concentration of variance in the precession band (Ruddiman *et al.* 1986; Shackleton *et al.* 1995). Between 2.8 and 0.92 Ma, maximum ice volumes ranged between one half and one third of the LGM value, with the first extensive glaciation recorded during MIS 22, around 0.9 Ma (Elderfield *et al.* 2012). A prolongation and intensification of glacial cycles took place over the so-called Middle Pleistocene Transition (MPT, ~1.25–0.70 Ma [Clark *et al.* 2006]), after which δ^{18}O records became dominated by the 100-kyr cycle along with a precession component (Imbrie *et al.* 1984; Shackleton *et al.* 1990; Lisiecki & Raymo 2005) (Fig. 2). Dating of Barbados coral terraces representing a series of sea-level highstands also showed precessional changes in ice volume in MIS 5 and 7 (Broecker *et al.* 1968; Mesolella *et al.* 1969).

Milankovitch had suggested that precession would dominate climate variability at low latitudes. Lithological changes in Atlantic, Arabian Sea and Mediterranean Sea cores have indeed revealed that aeolian dust deposition varied at the 23–19-kyr period before 2.8 Ma, reflecting the influence of precession on monsoonal precipitation (Larassoaña *et al.* 2003; deMenocal 2004). After 2.8 Ma variability in the dust record shifted to the 41-kyr period and after 1 Ma to the 100-kyr period, indicating a coupling of high- and low-latitude climates. However, precession remained a fundamental driver of African climate variability throughout the Quaternary (deMenocal 2004). In addition, marine records from deep-sea cores and exposed sections on land in the Mediterranean spanning the last 13.5 Myr, also show the effects of precession on the quasi-periodic deposition of organic-rich sapropel layers as a result of increased surface water freshening, reduced deep water ventilation and increased export production (e.g., Rossignol-Strick *et al.* 1982; Hilgen *et al.* 2015; Rohling *et al.* 2015). Sapropels are associated with precession minima and boreal insolation maxima, leading to the intensification of the African monsoon, northward penetration of the rain belt beyond the central Saharan watershed at ~21°N, and increased freshwater input into the Mediterranean Sea via northward draining catchments and the Nile (Rohling *et al.* 2015). In addition to precession, complex orbital effects are detected in the character of sapropels, with small- and large-scale bundles of sapropels corresponding to maxima in the 100-kyr and 400-kyr eccentricity cycles (Larrasoaña *et al.* 2003), while sapropel thickness appears to be related to obliquity, with thick (thin) sapropels corresponding to obliquity maxima (minima) (Lourens *et al.*

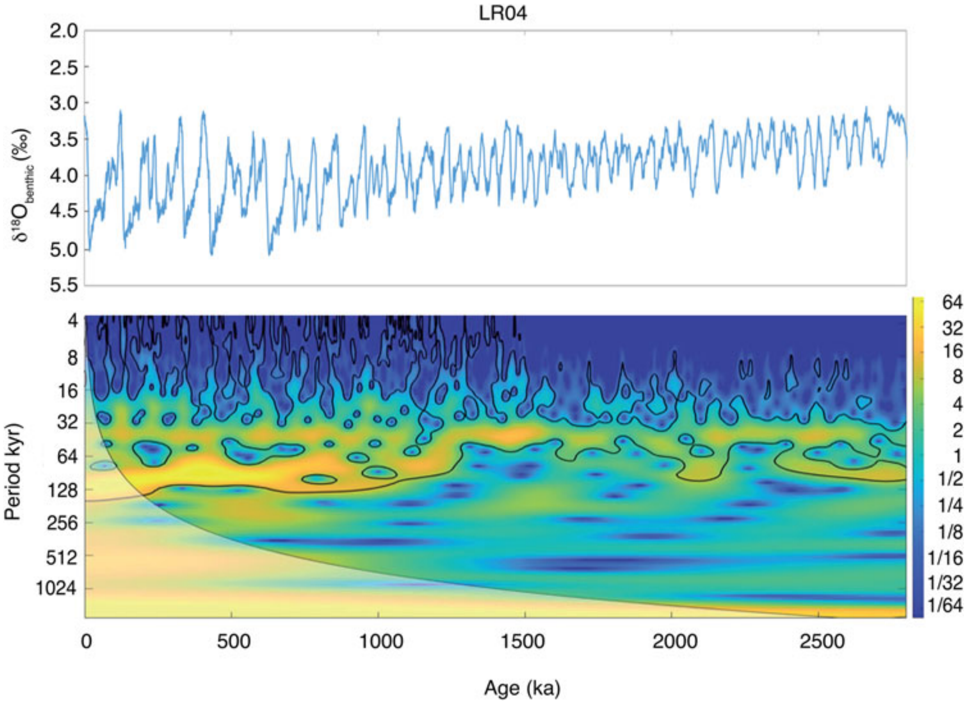

Figure 2 Oxygen isotope composition of benthic Foraminifera in the LR04 stack (Lisiecki & Raymo 2005) (upper panel) and its continuous wavelet power spectrum (lower panel). Colour scale represents the relative wavelet power and the thick black contour designates the 5 % significance level against red noise (Grinsted *et al.* 2004).

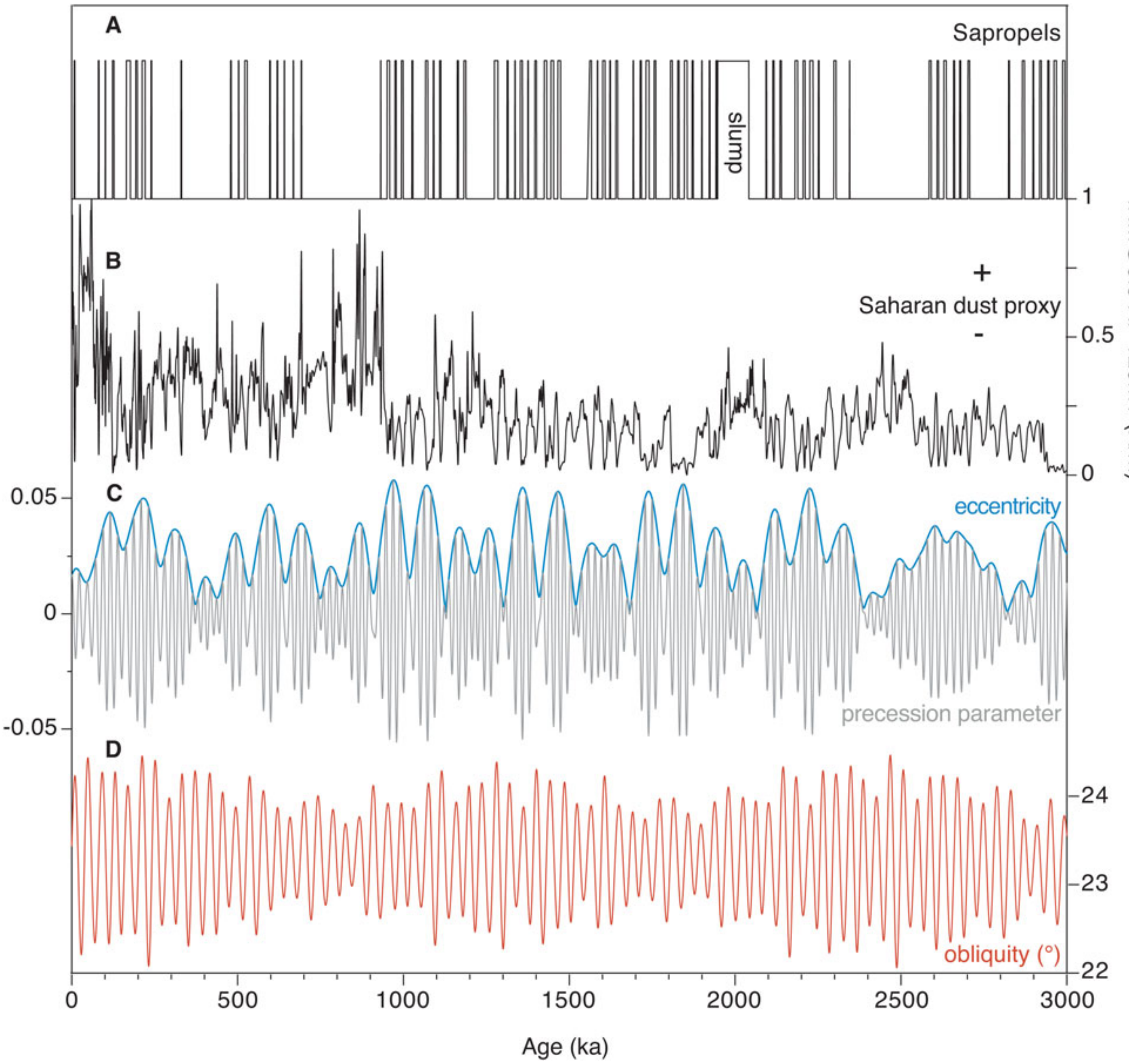

Figure 3 Occurrence of sapropels and Saharan dust at ODP Site 967, eastern Mediterranean, in relation to changes in astronomical parameters. (a) position of sapropels in ODP Site 967 (Kroon *et al.* 1998). (b) variations in IRM0.9 T@AF120 mT in ODP Site 967, indicating changes in haematite concentration as a proxy for Saharan dust supply (Larrasoaña *et al.* 2003). (c) variations in eccentricity and precessional parameter (Laskar *et al.* 2004); (d) variations in obliquity (Laskar *et al.* 2004).

1996). Figure 3 shows the relationship between sapropel occurrence and astronomical parameters and its antiphase relation with Saharan dust deposition at ODP Site 967 SW in the eastern Mediterranean.

5. Astronomical frequencies in terrestrial records

In principle, Croll was correct that evidence of past glacial–interglacial cycles would not be recovered from land surfaces where erosion or intermittent deposition predominate. But in places beyond glaciated terrains or continuous permafrost areas, favourable geological contexts have occasionally led to the uninterrupted deposition of sediment sequences that have gradually provided a picture of changes on land over long timescales. The first terrestrial sequences extending continuously from present over multiple glacial-interglacial cycles were pollen records obtained in the 1960s and 1970s from the Bogotá basin, Colombia (Van der Hammen & González 1960; Van der Hammen 1974) and the Tenaghi Philippon fen, Greece (Wijmstra 1969; Wijmstra & Smit 1976), and loess records from central Europe (e.g., Kukla 1977). The pollen records from Bogotá and Tenaghi Philippon were later extended to cover the last 2.2 Myr (Hooghiemstra 1984; Hooghiemstra *et al.* 1993; Torres *et al.* 2013) and 1.35 Myr (Wijmstra & Groenhart 1983; van der Wiel & Wijmstra 1987a, b; Tzedakis *et al.* 2006), respectively. Gradually, a number of long pollen sequences emerged from southern Europe, showing expansions and contractions of forest communities associated with variations in ice volume, although glacial-interglacial transitions in the marine and terrestrial records were not always synchronous (Tzedakis *et al.* 1997, 2004; Shackleton *et al.* 2003). These records also revealed recurring patterns of characteristic vegetation communities associated with specific astronomical configurations: expansion of Mediterranean sclerophylls, expansion of heathland vegetation and collapse of forest communities at times of boreal summer solstice, vernal equinox and winter solstice at perihelion, respectively (Magri & Tzedakis 2000; Margari *et al.* 2014). Analyses of the spectral evolution in pollen records from Bogotá basin (Torres *et al.* 2013), Tenaghi Philippon (Tzedakis *et al.* 2006; Fig. 4), Lake Ohrid, Albania/FYROM (Wagner *et al.* 2019) and Heqing basin, SW China (An *et al.* 2011) show a shift from 41-kyr

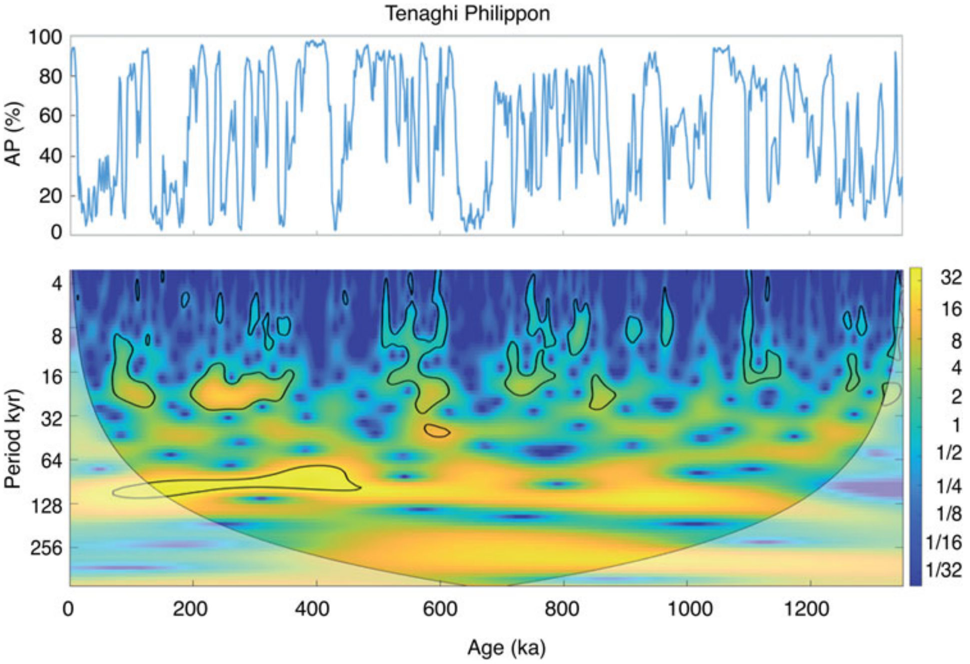

Figure 4 Arboreal pollen (AP) percentages in the Tenaghi Philippon record, Greece (Tzedakis *et al*. 2006) (upper panel) and its continuous wavelet power spectrum (lower panel). Colour scale represents the relative wavelet power and the thick black contour designates the 5 % significance level against red noise (Grinsted *et al*. 2004).

cyclicity to 100-kyr cyclicity during the MPT, reflecting high-latitude effects. However, clusters of precession cycles appear throughout the entire interval covered in these records, reflecting the effect of local insolation changes on moisture availability (see for example Fig. 4). Speleothem records from China also indicate the pervasive influence of precession on the intensity of the Asian Monsoon during the last 640 kyr (Cheng *et al*. 2016). What emerges is that although high-latitude effects were superimposed on low- to mid-latitude climate variability, precession remained a fundamental driver of precipitation and vegetation changes during the course of the Quaternary.

Analyses of pollen and sediment records from Zoige Basin, eastern Tibetan Plateau (Zhao *et al*. 2020), show shifts in the dominant periodicity, from precession cycles (1.74–1.54 Ma), to precession and obliquity cycles (1.54–0.62 Ma) and finally 100-kyr cycles (0.64–0 Ma). On the other hand, Chinese loess records show only one major transition at ~0.9–0.7 Ma from ~40-kyr to ~100-kyr cycles (e.g., Guo *et al*. 2000; Ding *et al*. 2002). At higher latitudes, changes in the abundance of biogenic silica in lake Baikal over the last 1.8 Myr (Prokopenko *et al*. 2006), and sediment grain size in lake El'gygytgyn, Far East Russian Arctic over the last 2.6 Myr (Francke *et al*. 2013), show cyclicities in all three astronomical components, with a shift from 41-kyr to 100-kyr cyclicity during the MPT. As in lower latitudes, these records reflect the influence of glacial cycles, but the presence of precession cycles indicates the effect of local insolation changes.

6. Astronomical frequencies in ice core records

Croll could certainly not have envisaged that the remaining ice sheets on Earth would also provide evidence about the climate, and especially provide a means of linking geochemical and astronomical theories.

While the first shallow cores were drilled in the 1950s (Jouzel 2013), the potential of ice cores to address questions of climate on the timescales of astronomical frequencies had to wait for a series of technical and scientific breakthroughs. The scientific advances include the establishment of water isotopes (δ^{18}O and δD) as a proxy for temperature (Dansgaard 1964), and the development of an ability to measure correctly the concentration of CO_2 in air bubbles within the ice (Delmas *et al*. 1980). The technical advances led to the ability to drill to the bottom of the Greenland and Antarctic ice sheets, initially at Camp Century (Greenland) (Hansen & Langway 1966) where a 1366-m core was completed in 1966 and then at Byrd Station (Antarctica) where the bed at 2164 m was reached in 1968 (Gow *et al*. 1968).

However, even these cores were not enough to penetrate a complete glacial cycle. Only with the Vostok record (Lorius *et al*. 1985), eventually reaching 420 ka (Petit *et al*. 1999), did it become possible to consider several glacial cycles in ice cores, and to assess their frequency content. Such work remains confined to Antarctica, because the oldest reliable Greenland ice core record still only reaches 128 ka (NEEM Community Members 2013). In Antarctica, cores drilled at Dome C (EPICA Community Members 2004; Jouzel *et al*. 2007) and Dome Fuji (Kawamura *et al*. 2007; Dome Fuji Ice Core Project Members 2017) have extended beyond the age of the Vostok core. Because the pattern of glacial–interglacial change seems to be close to uniform across the East Antarctic plateau and CO_2 is well mixed in the atmosphere, we can use these three cores interchangeably to discuss the imprint of astronomical cycles on local and global climate.

Analysis of the record extending to MIS 11 in the Vostok core showed that the signature of water isotopes in the ice (interpreted as a proxy for temperature at Vostok) has strong power in the 100-kyr and 41-kyr bands, but little in the precessional bands (Petit *et al*. 1999). Some caution must be used in assessing this result because the timescale (based on glaciological modelling and named GT4) derived in that work has been superseded by better age models that are constrained by absolute dating ties. Nonetheless, it is noteworthy that the Vostok record (Petit *et al*. 1999) allowed an assessment for the first time of the frequency content of the CO_2 concentration. This has the same frequencies, but with an even larger proportion of variance concentrated in the 100-kyr band, reflecting the role of CO_2 as a key amplifier of the glacial-interglacial climate changes. The role of CO_2 helps to explain why glacial cycles are in phase across

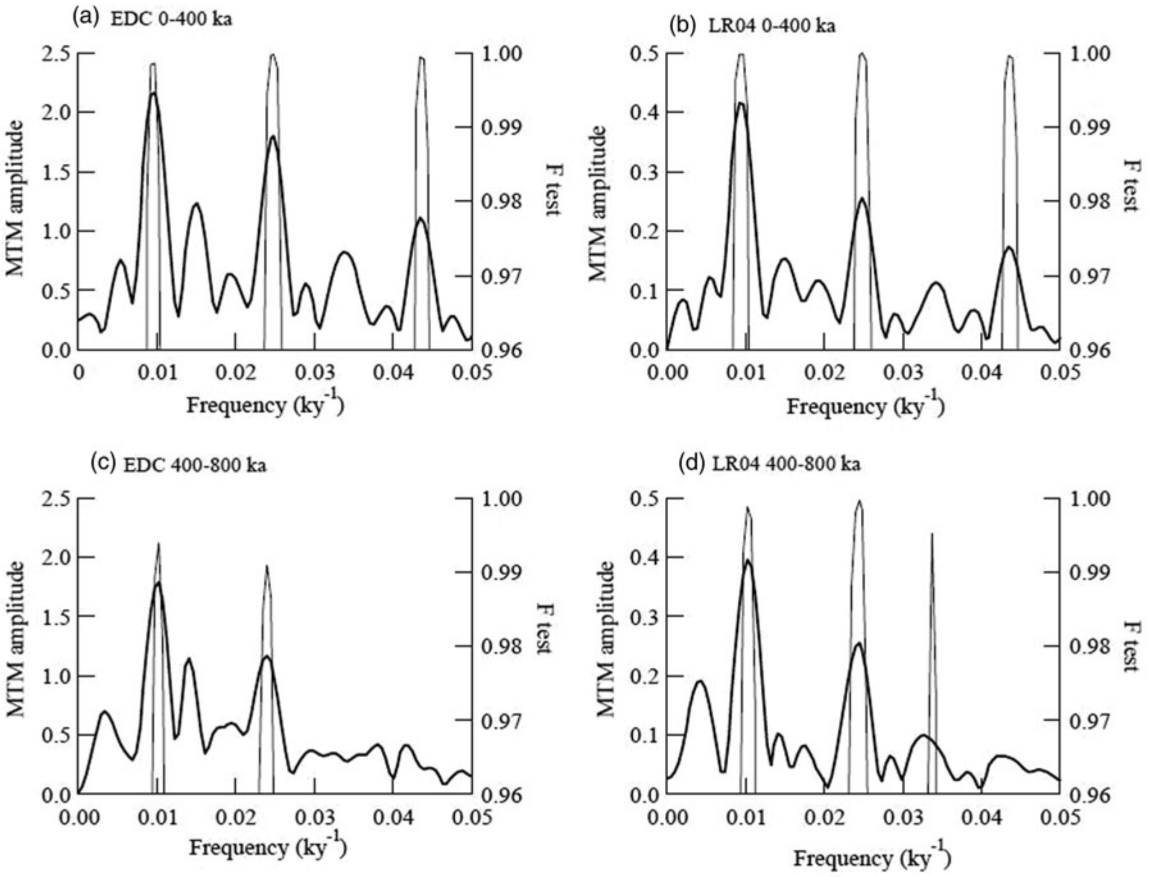

Figure 5 Power spectra for 0–400 ka (upper panels) and 400–800 ka (lower panels) for Antarctic temperature at Dome C (Jouzel *et al.* 2007) (left panels) and for the benthic oxygen isotope LR04 stack (Lisiecki & Raymo 2005) (right panels). Site temperature (T_s) is calculated from δD measured on the EPICA Dome C ice core. The thick lines are the power spectrum amplitudes calculated using the multi-taper method (MTM). The thin lines show the significance of peaks at particular frequencies estimated from an F-test. Both records show clear power at ~100 kyr and 40 kyr. The 20-kyr period is significant only in the most recent 400 ka. From Jouzel *et al.* 2007. Orbital and millennial Antarctic climate variability over the last 800,000 years. *Science* **317**, 793–796. Reprinted with permission from AAAS.

the hemispheres, because CO_2 acts globally as a radiative forcing agent. A final noteworthy observation from the Vostok record was that $\delta^{18}O_{atm}$ (the isotopic ratio of oxygen in air bubbles), a signal that is particularly affected by low latitude terrestrial productivity, shows a strong precessional frequency. In detail, $\delta^{18}O_{atm}$ closely mirrors (but with a phase lag) mid-June northern hemisphere insolation, providing both evidence of the role of insolation on tropical climate, and a useful tool that was later used to provide fixed tie-points for dating ice cores.

The 800-kyr record of EPICA Dome C (Jouzel *et al.* 2007) has a much improved age model, in particular constrained by the ^{10}Be signal that marks the Matuyama–Brunhes boundary at ~780 ka (Raisbeck *et al.* 2006). Spectral analysis of the temperature proxy confirms that the dominance of the 100- and 41-kyr periods extends back to 800 ka. However, in contrast to what was deduced from Vostok, there is some power in the precessional band from 0 to 400 ka, though it is not observed between 400 and 800 ka (Fig. 5). Methane records also exhibit 100-kyr, 41-kyr and 23-kyr frequencies throughout the 800-kyr record (Loulergue *et al.* 2008).

A final interesting finding specific to the local climate in Antarctica is the existence of cycles in the ratio of O_2/N_2 in the air trapped in ice in Antarctica (Kawamura *et al.* 2007). This ratio shows a strong resemblance to local summer insolation at the Antarctic site (such as Dome Fuji). This is believed to arise from the effect of insolation on snow structure at the surface that later influences the amplitude of a small fractionation between oxygen and nitrogen that occurs during the bubble closure process. Again, this can be used to aid in dating cores but it also provides another demonstration that astronomically forced variability is imprinted in a variety of climate indicators.

The ice core record clearly exhibits similar frequencies to the marine record. However, it adds to the story by showing directly the influence on polar temperatures, and that the astronomical frequencies are passed to climate not only directly but also through the amplifying effect of greenhouse gases.

7. Croll in the context of the modern synthesis of a theory of ice ages

As Croll predicted, testing of the astronomical theory would require long and undisturbed archives, though his own version of the theory has not fared well under the weight of accumulating evidence. Glaciations do not only occur when eccentricity is high, they do not alternate between hemispheres every ~11 kyr and the critical season for the initiation of glaciation is not winter, but summer. Drawing attention to the flaws of early theories from today's vantage point may be regarded as the epitome of bad taste, but it is of interest to explore how different aspects of Croll's theory fit in the context of the modern theory of ice ages.

The 'heroic' age of palaeoclimate research (~1950–2000) and subsequent attempts to develop a synthesis have transformed our understanding of the nature of glacial cycles. In the Early Pleistocene, deglaciations occurred every 41 kyr and climate resided mostly in an interglacial state. Over the course of the MPT, secular cooling or a change in ice dynamics led to a rise in the deglaciation threshold, a decrease in the frequency of interglacials after 1 Ma and the emergence of the 100-kyr glacial cycle (e.g., Berger *et al.* 1999; Clark *et al.* 2006; Tzedakis *et al.* 2017), though the temporal spacing of deglaciations is not always 100 kyr (Past Interglacial Working Group of PAGES 2016). The distinction between the more symmetric cycles of the '41-kyr world' of the Early Pleistocene and the more saw toothed-shaped cycles of the '100-kyr world' in the Middle and Late Pleistocene is thought to reflect a difference between a quasi-linear and a strongly nonlinear climate–cryosphere response to the same astronomical forcing, respectively. Although there is no consensus on the origin and mechanism of the 100-kyr cycle, a key element appears to be the critical size of ice sheets in triggering deglaciations (e.g., Raymo 1997; Paillard 1998; Tzedakis *et al.* 2017). Over time the glacial system accumulates instability (MayAyeal 1979) that makes ice sheets more sensitive to insolation increases as a result of (i) ice-sheet physics and glacio-isostatic adjustments (e.g., Birchfield *et al.* 1981; Abe-Ouchi *et al.* 2013); (ii) dust deposition and changes in ice-sheet albedo (Ganopolski & Calov 2011); (iii) extent of Antarctic ice sheet, bottom-water formation and ocean carbon storage (Paillard & Parrenin 2004). In addition, during glacial terminations the interaction of orbital and millennial-scale climate variability may promote deglaciation via the operation of the bipolar seesaw, whereby weakening of the meridional overturning circulation leads to changes in interhemispheric heat transport and CO_2 degassing from the Southern Ocean (e.g., Paillard 2001; Barker *et al.* 2011). In this context, Croll's recognition of the crucial role of changes in the transference of heat by ocean currents remains relevant to the present day.

By comparison to the 100-kyr world, the Early Pleistocene of smaller ice sheets and reduced non-linearity provides a simpler testbed for understanding the response of the climate system to astronomical forcing. Before 1 Ma, interglacials occurred every time the amount of energy reaching northern high latitudes exceeded a simple threshold, approximately every 41 kyr (Huybers 2006; Tzedakis *et al.* 2017). Near 65°N, the variance of the caloric summer half year insolation has almost equal contributions from precession and obliquity and insolation peaks are spaced every ~21 kyr, yet deglaciations skipped nearly every other insolation peak in the Early Pleistocene (the so-called '41-kyr problem' of Raymo & Nisancioglu 2003). The simplest explanation is that the 41-kyr glacial cycle arises because every second insolation peak is boosted by above-average obliquity (Tzedakis *et al.* 2017).

Raymo *et al.* (2006), however, proposed that in the Early Pleistocene ice volume changes occurred not only in the northern hemisphere, but also in the southern hemisphere, where a land-based East Antarctic ice sheet with melting margins was contributing to sea-level changes. Since precession is out of phase between hemispheres but obliquity is in phase, the contribution of each hemisphere to ice-volume variations cancelled each other in the globally integrated benthic $\delta^{18}O$ record for the 21-kyr cycle, but were additive for the 41-kyr cycle. In essence, the possibility of additional 'cryptic' ice volume variations occurring on precessional timescales represents a 'Croll–Murphy' model of alternating glaciations between hemispheres every ~11 kyr when summer solstice is at aphelion.

Recent analysis of high-resolution benthic records (Liautaud *et al.* 2020), however, has revealed a larger precession contribution in ice volume variance in the Early Pleistocene than previously recognised, which steadily increases over the course of the Quaternary. If anti-phased precessional variations in ice volume did occur in the earliest Pleistocene in the mode of Raymo *et al.* (2006), then the gradual increase in the amplitude of precession might reflect the expansion of northern hemisphere ice-sheets and a growing imbalance in northern and southern contributions to sea level, such that they would no longer cancel each other in the benthic $\delta^{18}O$ record (Liautaud *et al.* 2020). Alternatively, the steady intensification of the precession signal through the Quaternary simply reflects the gradual southward extension of northern hemisphere ice-sheet margins to lower latitudes, where the influence of precessional insolation changes is stronger (Liautaud *et al.* 2020).

On a more abstract level, Paillard (2015) noted that the Milankovitch theory is a theory of ice sheets where astronomical changes lead to changes in ice sheets, which in turn drive global climate changes via the albedo effect; the geochemical theory, on the other hand, is a theory of climate, where changes in CO_2 concentration and climate drive ice volume changes. In this context, Croll's Physical Theory of Secular Changes of Climate, would probably lie somewhere in between, with climate feedbacks playing a central role in amplifying small variations in insolation and driving ice volume changes. In many ways, it is this aspect of Croll's theory that has contributed to his enduring legacy.

8. Acknowledgements

We thank Simon Crowhurst for wavelet analyses and assistance with figures and Richard Preece for discussions. We are grateful to John Lowe and James Scourse for their insightful reviews and guidance. Finally, we are indebted to Kevin Edwards for the invitation to contribute to this Croll volume, commemorating the life and work of an extraordinary individual.

9. References

Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J., Takahashi, K. & Blatter, H. 2013. Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature* **500**, 190–3.

Adhémar, J. 1842. *Révolutions de la Mer, Déluges Périodiques*. Paris: Carilian-Goeury et V. Dalmont.

Agassiz, L. 1838. Upon glaciers, moraines, and erratic blocks. Address delivered at the opening of the Helvetic Society at Neuchâtel, 24 1837 by its President M. L. Agassiz. *The Edinburgh New Philosophical Journal* **24**, 364–83.

An, Z. S., Clemens, S. C., Shen, J., Qiang, X. K., Jin, Z. D., Sun, Y. B., Prell, W. L., Luo, J. J., Wang, S. M., Xu, H., Cai, Y. J., Zhou, W. J., Liu, X. D., Liu, W. G., Shi, Z. G., Yan, L. B., Xiao, X. Y, Chang, H., Wu, F, Ai, L. & Lu, F. Y. 2011. Glacial-Interglacial Indian summer monsoon dynamics. *Science* **333**, 719–23.

Arrhenius, G. 1952. Sediment cores from the east Pacific. Reports of the Swedish Deep-Sea expedition 1947–1948, v. 5, fasc. 1.

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **41**, 237–76.

Barker, S., Knorr, G., Edwards, L., Parrenin, F., Putnam, A.E., Skinner, L. C., Wolff, E. & Ziegler, M. 2011. 800,000 Years of abrupt climate variability. *Science* **334**, 347–51.

Berger, A., Li, X. S. & Loutre, M. F. 1999. Modelling northern hemisphere ice-volume over the last 3 Ma. *Quaternary Science Reviews* **18**, 1–11.

Berger, A. & Yin, Q. 2021. Orbital forcing (Astronomical Theory of Paleoclimates). In Alderton, A. & Elias, S. A. (eds) *Encyclopedia of geology*, 2nd edn, 435–43. London: Academic Press.

Birchfield, G. E., Weertman, J. & Lunde A. T. 1981. A paleoclimate model of northern hemisphere ice sheets. *Quaternary Research* **15**, 126–42.

Broecker, W. D., Thurber, D. L., Goddard, J., Ku, T.-L. & Matthews, R. K. 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep-Sea sediments. *Science* **159**, 297–300.

Brückner, E., Köppen, W. & Wegener, A. 1925. Über die Klimate der geologischen Vorzeit. *Zeitschrift für Gletscherkunde*, Vol. 14.

Buckland, W. 1823. *Reliquiae diluvianae; or, observations on the organic remains contained in caves, fissures, and diluvial gravel, and on geological phenomena, attesting the action of an universal deluge*. London: John Murray.

Challenger Expedition. 1880–1895. Report of the scientific results of the voyage of H.M.S. Challenger during the years 1873–76. London: Her Majesty's Stationery Office.

Chamberlin, T. C. 1897. A group of hypotheses bearing on climatic changes. *Journal of Geology* **5**, 653–83.

Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S. T., Kelly, M., Kathayat, G., Wang, X. F., Li, X. L., Kong, X. G., Wang, Y. J., Ning, Y. F. & Zhang, H. W. 2016. The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* **534**, 640–6.

Clark, P. U., Archer, D., Pollard, D., Blum, J. D., Rial, J. A., Brovkin, V., Mix, A. C., Pisias, N. G. & Roy, M. 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. *Quaternary Science Reviews* **25**, 3150–84.

Croll, J. 1864. On the physical cause of the change of climate during geological epochs, and *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **28**, 121–37.

Croll, J. 1867. On the change in the obliquity of the ecliptic, its influence on the climate of the polar regions and on the level of the sea. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **33**, 426–45.

Croll, J. 1868. On geological time, and the probable date of the glacial and the upper Miocene period. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **36**, 362–86.

Croll, J. 1869. On two river channels buried under drift, belonging to a period when the land stood several hundred feet higher than at present. *Transactions Edinburgh Geological Society* **1**, 330–45.

Croll, J. 1875. *Climate and time in their geological relations.* London: Daldy, Isbister, & Co.

Croll, J. 1884. Examination of Mr. Alfred R. Wallace's *Modification of the Physical Theory of Secular Changes of Climate. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **17**, 81–111.

Cuvier, G. 1812. Discours sur les révolutions de la surface du Globe et sur les changements qu'elles ont produits dans le règne animal. *In Recherches sur les ossemens fossils de quadrupèdes, ou l'on rétablit les caractères de plusieurs espèces d'animaux que les révolutions du globe paroissent avoir détruites.* 4 vols, 301 p. Paris: Deterville.

Dana, J. D. 1896. *Manual of geology*, 4th edn. New York: American Book Co.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus* **16**, 436–68.

de Charpentier, J. 1841. *Essai sur les Glaciers et sur le terrain erratique du bassin du Rhône.* Lausanne : M. Ducloux, 363 p.

de Saussure, H.-B. 1779–1796. *Voyages dans les Alpes, précédés d'un essai sur l'histoire naturelle des environs de Genève.* 4 volumes Neuchâtel: Samuel Fauche

Delmas, R. J., Ascencio, J.-M. & Legrand, M. 1980. Polar ice evidence that atmospheric CO_2 20,000 yr BP was 50% of present. *Nature* **284**, 155–7.

deMenocal, P. B. 2004. African climate change and faunal evolution during the Pliocene-Pleistocene. *Earth and Planetary Science Letters* **220**, 3–24.

Ding, Z. L., Derbyshire, E., Yang, S. L., Yu, Z. W., Xiong, S. F. & Liu, T. S. 2002. Stacked 2.6-Ma grain size record from the Chinese loess based on five sections and correlation with the deep-sea $\delta^{18}O$ record. *Paleoceanography* **17**, 1033.

Dome Fuji Ice Core Project Members: Kawamura, K., Abe-Ouchi, A., Motoyama, H., Ageta, Y., Aoki, S., Azuma, N., Fujii, Y., Fujita, K., Fujita, S., Fukui, K., Furukawa, T., Furusaki, A., Goto-Azuma, K., Greve, R., Hirabayashi, M., Hondoh, T., Hori, A., Horikawa, S., Horiuchi, K., Igarashi, M., Iizuka, Y., Kameda, T., Kanda, H., Kohno, M., Kuramoto, T., Matsushi, Y., Miyahara, M., Miyake, T., Miyamoto, A., Nagashima, Y., Nakayama, Y., Nakazawa, T., Nakazawa, F., Nishio, F., Obinata, I., Ohgaito, R., Oka, A., Okuno, J., Okuyama, J., Oyabu, I., Parrenin, F., Pattyn, F., Saito, F., Saito, T., Saito, T., Sakurai, T., Sasa, K., Seddik, H., Shibata, Y., Shinbori, K., Suzuki, K., Suzuki, T., Takahashi, A., Takahashi, K., Takahashi, S., Takata, M., Tanaka, Y., Uemura, R., Watanabe, G., Watanabe, O., Yamasaki, T., Yokoyama, K., Yoshimori, M. & Yoshimoto, T. 2017. State dependence of climatic instability over the past 720,000 years from Antarctic ice cores and climate modeling. *Science Advances* **3**, 10.1126/sciadv.1600446.

Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I. N., Hodell, D. & Piotrowski, A. M. 2012. Evolution of ocean temperature and ice-volume through the Mid-Pleistocene climate transition. *Science (New York, N.Y.)* **337**, 704–9.

Emiliani C. 1972. Quaternary paleotemperatures and the duration of the high-temperature intervals. *Science* **178**, 398–401.

Emiliani, C. & Shackleton, N. J. 1974. The Brunhes Epoch: isotopic paleotemperatures and geochronology. *Science* **183**, 511–4.

Emiliani, C. 1955. Pleistocene temperatures, *Journal of Geology* **63**, 538–78.

EPICA community members. 2004. Eight glacial cycles from an Antarctic ice core. *Nature* **429**, 623–8.

Ericson, D. B., Broecker, W. S., Kulp, J. L. & Wollin, G. 1956. Late-Pleistocene climate and deep-Sea sediments. *Science* **124**, 385–9.

Ericson, D. B. & Wollin, G. 1956. Micropaleontological and isotopic determinations of Pleistocene climates. *Micropaleontology* **2**, 257–70.

Esmark, J. 1827. Remarks tending to explain the geological history of the earth. *The Edinburgh New Philosophical Journal* **2**, 107–21.

Francke, A., Wennrich, V., Sauerbrey, M., Juschus, O., Melles, M. & Brigham-Grette, J. 2013. Multivariate statistic and time series analyses of grain-size data in quaternary sediments of Lake El'gygytgyn, *NE Russia. Climate of the Past* **9**, 2459–70.

Ganopolski, A. & Calov, R. 2011. The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles. *Climate of the Past* **7**, 1415–25.

Geikie, A. 1863. *On the phenomena of the glacial drift of Scotland.* Glasgow: John Gray.

Geikie, J. 1874. *The great ice age – and its relation to the antiquity of man.* London: W. Isbister.

Gow, A. J., Ueda, H. T. & Garfield, D. E. 1968. Antarctic Ice sheet: preliminary results of first core hole to bedrock. *Science* **161**, 1011.

Grinsted, A., Moore, J. C. & Jevrejeva, S. 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* **11**, 561–6.

Guo, Z., Biscaye, P., Wei, L., Chen, X., Peng, S. & Liu, T. 2000. Summer monsoon variations over the last 1.2 Ma from the weathering of loess-soil sequences in China. *Geophyical. Research. Letters* **27**, 1751–4.

Hansen, B. & Langway, C. C. 1966. Deep core drilling in Ice and core analysis at camp century, Greenland, 1961–1966. *Antarctic Journal of the United States* **1**, 207–8.

Hays, J. D., Imbrie, I. & Shackleton, N. J. 1976. Variations in the Earth's orbit: pacemaker of the ice ages. *Science* **194**, 1121–31.

Heer, O. 1865. *Die Urwelt der Schweiz*. Zürich, Schulthess.

Herschel, J. F. W. 1832. On the astronomical causes which may influence geological phenomena. *Herschel Transactions of the Geological Society of London* **S2**, 293–9.

Hilgen, F. J., Hinnov, L. A., Abdul Aziz, H., Abels, H. A., Batenburg, S., Bosmans, J. H. C., de Boer, B., Hüsing, S. K., Kuiper, K. F., Lourens, L. J., Rivera, T., Tuenter, E., Van de Wal, R. S. W., Wotzlaw, J.-F. & Zeeden, C. 2015. Stratigraphic continuity and fragmentary sedimentation: the success of cyclostratigraphy as part of integrated stratigraphy. In Smith, D. G., Bailey, R. J., Burgess, P.M. & Fraser, A. J. (eds) *Strata and time: probing the gaps in our understanding*. London: Geological Society. Special Publications 404, 157–97.

Hooghiemstra, H. 1984. *Vegetational and climatic history of the high plain of Bogotá, Colombia*. Dissertationes Botanicae 79, 368 p. Vaduz: J. Cramer.

Hooghiemstra, H., Melice, J.L., Berger, A. & Shackleton, N.J., 1993. Frequency spectra and palaeoclimatic variability of the high-resolution 30–1450 ka Funza-1 pollen record (Eastern Cordillera, Colombia). *Quaternary Science Reviews* **12**, 141–56.

Huybers, P. 2006. Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science* **313**, 508–11.

Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L. & Shackleton, N. J. 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine δ18O record. In Berger, A. Imbrie, J., Hays, J., Kukla, G. & Saltzman, B. (eds) *Milankovitch and climate, part 1*, 269–305. NATO ASI Series. Series C: Mathematical and Physical Sciences vol. 126. Dordrecht: D. Reidel Publishing.

Imbrie, J. & Imbrie, K. P. 1979. *Ice ages, solving the mystery.* London: Macmillan.

Jouzel, J. 2013. A brief history of ice core science over the last 50 yr. *Climate of the Past* **9**, 2525–47.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E., Schilt, A., Steffensen, J. P., Stenni, B., Stauffer, B., Stocker, T., Tison, J.-L., Werner, M. & Wolff, E. W. 2007. Orbital and millennial Antarctic climate variability over the last 800 000 years. *Science* **317**, 793–6.

Kawamura, K., Parrenin, F., Lisiecki, L., Uemura, R., Vimeux, F., Severinghaus, J. P., Hutterli, M. A., Nakazawa, T., Aoki, S., Jouzel, J., Raymo, M. E., Matsumoto, K., Nakata, H., Motoyama, H., Fujita, S., Azuma, K., Fujii, Y. & Watanabe, O. 2007. Northern hemisphere forcing of climatic cycles over the past 360,000 years implied by accurately dated Antarctic ice cores. *Nature* **448**, 912–6.

Kroon, D., Alexander, I., Little, M., Lourens, L. J., Matthewson, A., Robertson, A. H. F. & Sakamoto, T. 1998. Oxygen isotope and sapropel stratigraphy in the eastern Mediterranean during the last 3.2 million years. In Robertson, A. H. F., Emeis, K.-C., Richter, C., Camerlanghi, A. (eds) *Proceedings of the ocean drilling program*, Scientific Results 160, 181–90. College Station (TX): Ocean Drilling Program.

Kukla, G. J. 1977. Pleistocene land—sea correlations. *I. Europe. Earth-Science Reviews* **13**, 307–74.

Larrasoaña, J. C., Roberts, A. P., Rohling, E. J., Winklhofer, M. & Wehausen, R. 2003. Three million years of monsoon variability over the northern Sahara. *Climate Dynamics* **21**, 689–98.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M. & Levrard, B. 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* **428**, 261–85.

Liautaud, P. R., Hodell, D. A. & Huybers, P. J. 2020. Detection of significant precession variability in early Pleistocene cycles. *Earth and Planetary Science Letters* **536**, 116137.

Lisiecki, L. E. & Raymo, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography* **20**, PA1003.

Lorius, C., Jouzel, J., Ritz, C., Merlivat, L., Barkov, N. I., Korotkevich, Y. S. & Kotlyakov, V. M. 1985. A 150,000-year climatic record from Antarctic ice. *Nature* **316**, 591–5

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J. M., Raynaud, D., Stocker, T. F. & Chappellaz, J. 2008. Orbital and millennial-scale features of atmospheric CH_4 over the last 800,000 years. *Nature* **453**, 383–6.

Lourens, L. J., Antonarakou, A., Hilgen, F. J., Van Hoof, A. A. M., Vergnaud-Grazzini, C. & Zachariasse, W. J. 1996. Evaluation of the Plio-Pleistocene astronomical timescale. *Paleoceanography* **11**, 391–413.

Lyell, C. 1830–1832. *Principles of geology*, 1st edn. London: Murray.

Lyell, C. 1840. On the boulder formation, or drift and associated freshwater deposits composing the mud-cliffs of Eastern Norfolk. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **16**, 345–80.

Lyell, C. 1875. *Principles of geology*, 12th edn. London: Murray.

MacAyeal, D. R. 1979. A catastrophe model of the paleoclimate. *Journal of Glaciology* **24**, 245–57.

Magri, D. & Tzedakis, P. C. 2000. Orbital signatures and long-term vegetation patterns in the Mediterranean. *Quaternary International* **73/74**, 69–78.

Margari, V., Skinner, L. C., Hodell, D. A., Martrat, B., Toucanne, S., Grimalt, J. O., Gibbard, P. L., Lunkka, J. P. & Tzedakis, P. C. 2014. Land-ocean changes on orbital and millennial timescales and the penultimate glaciation. *Geology* **42**,183–6.

Mesolella, K. J., Matthews, R. K., Broecker, W. S. & Thurber, D. L. 1969. The astronomical theory of climatic change: Barbados data. *Journal of Geology*, **77**, 250–74.

Milankovitch, M. 1920. *Théorie Mathématique des Phénomènes Thermiques Produits par la Radiation Solaire*. Académie Yougoslave des Sciences et des Arts de Zagreb. Paris: Gauthier Villars.

Milankovitch, M. 1930. Mathematische Klimalehere und Astronomische Theorie der Klimaschwankungen. In Köppen W. & Geiger, R. (eds) *Köppen Geigersches Handbuch der Klimatologie*, Band I Teil A. Berlin: Borntraeger.

Milankovitch, M. 1941. *Kanon der Erdbastrahlung und seine Anwendung auf des Eiszeitenproblem*. Special Publication 132, Section of Mathematical and Natural Sciences, Vol. **33**. Belgrade: Royal Serbian Academy of Sciences.

Morlot, A. 1855. The post-tertiary and quaternary formations of Switzerland. *Edinburgh New Philosophical Journal* **ii** New Series, 14–29.

Murphy, J. J. 1869. On the nature and cause of the glacial climate. *Quarterly Journal of the Geological Society* **25**, 350–6.

NEEM Community Members. 2013. Eemian interglacial reconstructed from a Greenland folded ice core. *Nature* **493**, 489–94.

Paillard, D. 1998. The timing of Pleistocene glaciations from a simple multiple- state climate model. *Nature* **391**, 378–81.

Paillard, D. 2001. Glacial cycles: toward a new paradigm. *Reviews of Geophysics* **39**, 325–46.

Paillard, D. 2015. Quaternary glaciations: from observations to theories. *Quaternary Science Reviews* **107**, 11–24.

Paillard, D. & Parrenin, F. 2004. The Antarctic ice-sheet and the triggering of deglaciations. *Earth and Planetary Science. Letters* **227**, 263–71.

Past Interglacial Working Group of PAGES. 2016. Interglacials of the last 800,000 years. *Reviews of Geophysics* **54**, 162–219.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E. & Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**, 429–36.

Pettersson, H. 1948. The Swedish deep-sea expedition. *Pacific Science* **2**, 231–8.

Poisson, S. D. 1835. *Théorie Mathématique de la Chaleur*. Paris: Bachelier Imprimeur-Libraire.

Prokopenko, A. A., Hinnov, L. A., Williams, D. F. & Kuzminc, M. I. 2006. Orbital forcing of continental climate during the Pleistocene: a complete astronomically tuned climatic record from Lake Baikal, SE Siberia. *Quaternary Science Reviews* **25**, 3431–57.

Raisbeck, G. M., Yiou, F., Cattani, O. & Jouzel, J. 2006. ^{10}Be Evidence for the Matuyama-Brunhes geomagnetic reversal in the EPICA Dome C ice core. *Nature* **444**, 82–4.

Raymo, M. E. 1997. The timing of major climate terminations. *Paleoceanography* **12**, 577–85.

Raymo, M., Lisiecki, L. & Nisancioglu, K. 2006. Plio-Pleistocene ice volume, Antarctic climate, and the global δ18O record. *Science* **313**, 492–5.

Raymo, M. E. & Nisancioglu, K. 2003. The 41 kyr world: Milankovitch's other unsolved mystery. *Paleoceanography* **18**, PA2011.

Rohling, E. J., Marino, G. & Grant, K. M. 2015. Mediterranean Climate and oceanography, and the periodic development of anoxic events (sapropels). *Earth-Science Reviews* **143**, 62–97.

Rossignol-Strick, M., Nesteroff, W., Olive, P. & Vergnaud-Grazzini, C. 1982. After the deluge, Mediterranean stagnation and sapropel formation. *Nature* **295**, 105–10.

Ruddiman, W. F., Raymo, M. & McIntyre, A. 1986. Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets. *Earth and Planetary Science Letters* **80**, 117–29.

Rudwick, M. 2005. *Bursting the limits of time*. London: The University of Chicago Press Ltd.

Schimper, K. F. 1837. Über die Eiszeit. *Actes de la Société helvétique des sciences naturelles* 22e Session, Neuchâtel, 38–51.

Schott, W. 1935. Die Foraminiferen in dem aequatorialen Teil des Atlantischen Ozeans. Deutsch. Atlant. Exped. "Meteor" 1925–1927. *Wissenschaftliche Ergebnisse* **3**, 43–134.

Shackleton, N. J. 1967. Oxygen isotope analyses and Pleistocene temperatures re-assessed. *Nature* **215**, 15–7.

Shackleton, N. J. 1969. The last interglacial in the marine and terrestrial records. *Proceedings of the Royal Society B* **174**, 135–54.

Shackleton, N. J. 1995. New data on the evolution of Pliocene climatic variability. In Vrba, E. S., Denton, G. H., Partridge, T. C. & Burckle, L. H. (eds) *Paleoclimate and evolution*, 242–8. New Haven: Yale University Press.

Shackleton, N. J., Berger, A. & Peltier, W. R. 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of The Royal Society of Edinburgh: Earth Sciences* **81**, 251–61.

Shackleton, N. J., Hall, M. A. & Pate, D. 1995. Pliocene stable isotopic stratigraphy of Site 846. In Pisias, N. G., Mayer, L. A., Janecek, T. R. & van Andel, T. H. (eds) *Proceedings of the ocean drilling program*, Scientific Results 138, 337–55. College Station (TX): Ocean Drilling Program.

Shackleton, N. J., Sánchez Goñi, M. F., Pailler, D. & Lancelot, Y. 2003. Marine isotope substage 5e and the Eemian interglacial. *Global and Planetary Change* **757**, 105.

Shackleton, N. J. & Opdyke, N. D. 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial pacific core V28–238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quaternary Research* **3**, 39–55.

Torres, V., Hooghiemstra, H., Lourens, L. & Tzedakis, P. C. 2013. Astronomical tuning of long pollen records reveals the dynamic history of montane biomes and lake levels in the tropical high Andes during the quaternary. *Quaternary Science Reviews* **63**, 59–72.

Tyndall, J. 1861. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption and conduction. *Philosophical Transactions of the Royal Society* **151**, 1–6.

Tzedakis, P. C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N. J. & Wijmstra, T. A. 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. *Earth and Planetary Science Letters* **150**, 171–6.

Tzedakis, P. C., Roucoux, K. H., de Abreu, L. & Shackleton, N. J. 2004. The duration of forest stages in Southern Europe and interglacial climate variability. *Science* **306**, 2231–5.

Tzedakis, P. C., Hooghiemstra, H. & Pälike, H. 2006. The last 1.35 million years at Tenaghi Philippon, revised chronostratigraphy and long-term vegetation trends. *Quaternary Science Reviews* **25**, 3416–30.

Tzedakis, P. C., Crucifix, M., Mitsui, T. & Wolff, E. W. 2017. A simple rule to determine which insolation cycles lead to interglacials. *Nature* **542**, 427–32.

Urey, H. C. 1947. The thermodynamic properties of isotopic substances. *Journal of the Chemical Society* **1947**, 562–81.

Van der Hammen, T. 1974. The Pleistocene changes of vegetation and climate in tropical South America. *Journal of Biogeography* **1**, 3–26.

Van der Hammen, T. & González, E. 1960. Upper Pleistocene and Holocene climate and vegetation of the Sabana de Bogotá. *Leidse Geologische Mededelingen* **25**, 261–315.

van der Wiel, A. M. & Wijmstra, T. A. 1987a. Palynology of the lower part (78–120 m) of the core Tenaghi Philippon II, Middle Pleistocene of Macedonia, Greece. *Review of Palaeobotany and Palynology* **52**, 73–88.

van der Wiel, A. M. & Wijmstra, T. A. 1987b. Palynology of 112.8–197.8 m interval of the core Tenaghi Philippon III, Middle Pleistocene of Macedonia. *Review of Palaeobotany and Palynology* **52**, 89–117.

Venetz, I. 1833. Mémoire sur les variations de la température des Alpes de la Suisse (rédigé en 1821). *Mémoires de la Société Helvétique des Sciences Naturelles* **1**, 1–38.

von Buch, L. 1815. Ueber die Ursachen der Verbreitung grosser Alpengeschiebe. *Abhandlungen der Physicalischen Klasse der Königlich-Preussischen Akademie der Wissenschaften*, Jahren 1804–1811, 161–181.

von Buch, L. 1818. Sur les causes auxquelles on peut attribuer le transport des blocs de roches des Alpes sur le Jura. *Annales de chimie et de physique* [Paris] **7**, 17–32.

von Humboldt, A. 1821. On isothermal lines and distribution of heat over the globe. *Edinburgh Philosophical Journal* **iv**, 262–81.

Wagner, B., Vogel, H., Francke, F., Friedrich, T., Donders, T., Lacey, J., Leng, M., Regattieri, E., Sadori, L., Wilke, T., Zanchetta, G., Albrecht, C., Bertini, A., Combourieu-Nebout, N., Cvetkoska, A., Giaccio, B., Grazhdani, A., Hauffe, T., Holtvoeth, J., Joannin, S., Jovanovska, E., Just, J., Kouli, K., Kousis, I., Koutsodendris, A., Krastel, S., Leicher, N., Levkov, Z., Lindhorst, K., Masi, A., Melles, M., Mercuri, A.M., Nomade, S., Nowaczyk, N., Panagiotopoulos, K., Peyron, O., Reed, J.M., Sagnotti, L., Sinopoli, G., Stelbrink, B., Sulpizio, R., Timmermann, A., Tofilovska, S., Torri, P., Wagner-Cremer, F., Wonik, T. & Zhang, X. 2019. Mediterranean Winter rainfall in phase with African monsoons during the past 1.36 million years. *Nature* **573**, 256–60.

Westerhold, T., Marwan, N., Drury, A. J., Liebrand, D., Agnini, C., Anagnostou, E., Barnet, J. S. K., Bohaty, S. M., De Vleeschouwer, D., Florindo, F., Frederichs, T., Hodell, D. A., Holbourn, A., Kroon, D., Lauretano, V., Littler, K., Lourens, L. J., Lyle, M. W., Pälike, H., Röhl, U., Tian, J., Wilkens, R. H., Wilson, P. A. & Zachos, J. C. 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science* **369**, 1383–7.

Wijmstra, T. A. 1969. Palynology of the first 30 metres of a 120 m deep section in northern Greece. *Acta Botanica Neerlandica* **18**, 511–27.

Wijmstra, T. A. & Groenhart, M. C. 1983. Record of 700,000 years vegetational history in eastern Macedonia (Greece). *Revista de la Academia Colombiana Ciencias Exactas, Fisicas y Naturales* **15**, 87–98.

Wijmstra, T. A. & Smit, A. 1976. Palynology of the middle part (30–78 metres) of the 120 m deep section in northern Greece (Macedonia). *Acta Botanica Neerlandica* **25**, 297–312.

Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001. Trends, rhythms and aberrations in global climate 65 Ma to present. *Science* **292**, 686–93.

Zhao, Y., Tzedakis, P. C., Li, Q., Qin, F., Cui, Q., Liang, C., Birks, H. J. B., Liu, Y., Zhang, Z., Ge, J., Zhao, H., Felde, V.A., Deng, C., Cai, M., Li, H., Ren, W., Wei, H., Yang, H., Zhang, J. & Guo, Z. 2020. Evolution of vegetation and climate variability on the Tibetan Plateau over the past 1.74 Myr. *Science Advances* **6**, eaay6193.

MS received 23 January 2021. Accepted for publication 24 March 2021. First published online 10 May 2021