

## ASTRONOMY AND CLIMATE: OLD AND NEW IDEAS

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**Abstract.** The idea that climate is strongly linked to astronomical cycles can be traced back to antiquity and the invention of the calendar. Still, if the effect of daily and annual cycles on temperatures are obvious, the role of longer cycles on climate was strongly disputed during the 19<sup>th</sup> and the beginning of the 20<sup>th</sup> centuries in the context of Quaternary glaciations. Milanković's genius allowed to establish a strong foundational theoretical background, that ultimately allowed to demonstrate the influence of astronomy on glaciation cycles. Today, some pieces are still missing in the puzzle of ice age cycles, most notably the mechanisms and the role of atmospheric pCO<sub>2</sub> changes and the transition towards larger and slower cycles after the Mid-Pleistocene transition.

The links between astronomy and climate are certainly not restricted to the question of ice-sheet changes, and Milanković was also pointing at the important role of the precessional forcing at lower latitudes. It is now well-known that the hydrological cycle in many semi-arid and monsoon areas is strongly linked to precession. These climatic changes are largely independent of glaciations, and it is worth underlining that the stratotype for the Quaternary is in fact linked to Mediterranean sapropels. Cyclostratigraphy is now a standard tool for geologists, but the many links between astronomy and climate are still not well understood. For instance, the strong 400-ka periodicity found in carbon isotopic records during the last 200 million years has probably far-reaching consequences on the Earth's climate dynamics.

**Key words:** Milutin Milanković, History of science, Climatology

### 1. INTRODUCTION

The discovery of ice ages in the nineteenth century was the starting point of scientific discussions on the mechanisms of climatic change. Indeed, after geologists found clear evidences of glaciations in many different places in the world, some physical explanations for such large-scale climatic changes were needed. Astronomers were actually quite reticent to discuss this topic and the very first astronomical theories were developed by non-academic people like Joseph Adhémar in 1842 or James Croll in 1864. Geologists like Archibald Geikie in 1863 or James Geikie in 1874 observed that a succession of glaciations occurred in the past [15]. Though this was in agreement with an astronomical theory of ice ages, other scientists were more in favour of a mechanism involving internal oscillations in the Earth system between climate and the carbon cycle. For instance, Chamberlin in 1897 suggested such an oscillator and Svante Arrhenius attempted the very first computation of the effect of atmospheric CO<sub>2</sub> on the Earth temperature, in order to reinforce this theory.

In this context, Milanković was the first to provide a solid mathematical framework to explain the role of the variations of the orbital parameters of the Earth on our climate. This proved to be critical to the understanding of Quaternary paleoclimatic records, in particular when the chronology of ice ages became sufficiently robust in the 1970's. The famous paper by Hays et al., 1976 [5] is therefore often presented as a "proof" of Milanković's theory, though the situation is in fact significantly more complex. Indeed, it is now well established that the pace of Quaternary glaciations is directly linked to orbital

forcing, but the main periodicity observed during the last million years is not associated to obliquity changes at 41 kyr, as expected by a simple interpretation of Milanković's theory, but it appears strongly linked to eccentricity changes at 100 kyr. Over the last 40 years, many scientific publications attempted to address this so-called "100-kyr problem" (see for instance [15]). On the other hand, before the Mid-Pleistocene transition (MPT) that occurred about 1 Myr BP, the dominant periodicity of glaciations was indeed 41-kyr, just as expected by Milutin Milanković. It can therefore be stated that the Milanković's theory of ice ages, in its simplest version, works quite well during the early Pleistocene, but no so well after the MPT. In order to account for ice ages during the late Pleistocene (a time period sometimes called the "100-kyr world"), it is necessary to specify some internal dynamics for the ice-sheet and climate system, that may possibly also involve the carbon cycle. Over this time period, ice ages are more easily understood in terms of an internal oscillator forced by the astronomy, a view that tends to provide a synthesis between the two different opinions expressed in the 19<sup>th</sup> century on this topic: either an external astronomical forcing or an internal oscillation.

But geologists have now considerably enlarged their knowledge since the 19<sup>th</sup> century and it is today much too restrictive to limit the role of astronomy to the ice age problem of the Quaternary. Indeed, the astronomy is clearly impacting climate even when no ice-sheet is present, through many different mechanisms, some being rather well understood and others being still rather mysterious. The best known example is the low latitude precessional forcing of monsoons and more generally of low latitude precipitations. Such a signal was expected by Milanković, since he clearly stated that precession should have a much larger role at low latitudes, while ice-sheet and high-latitude climate should depend mostly on obliquity. The basic mechanism is also quite well understood, since monsoons are directly affected by the summer heating of the continents, itself linked to the insolation forcing. More generally, the inter-tropical convergence zone (ITCZ) moves globally according to precession, since continents are more abundant in the northern hemisphere. In some specific areas, this leads to spectacular results. The best example is probably the Mediterranean sapropels that provide a precise chronology over the last 10 to 15 million years [10].

Based on these successes, cyclo-stratigraphy is now a standard tool in geo-chronology. But when looking at longer periodicities, it becomes a challenge to identify the physical mechanisms linking the recorded geochemical or climatic changes with astronomy. An intriguing example is the pervasive 400-kyr oscillation found in carbon isotopes over at least the last 200 million years, and the possibility that these cycles are further modulated by longer periodicities, most notably 2,4 Myr and also 8 to 9 Myr [2, 12]. The persistence of these orbitally-forced oscillations over such a long time period may point towards some fundamental connection between our Earth climate and astronomy that remains to be deciphered.

## 2. QUATERNARY GLACIATIONS

Astronomical theories of climatic changes were first applied to the problem of glaciations in the 19<sup>th</sup> century. The early theories of Adhémar and Croll were based mostly on precession. Indeed, scientists were quite aware that the duration and intensity of seasons should change in relation with the precession of equinoxes, also known as "the third movement of the Earth" since the Antiquity. Milanković mathematically demonstrated that obliquity had a much more important effect on high latitude and that the summer season should be considered as the most critical one. But astronomical seasons have varying durations and it is not entirely trivial to choose a "summer insolation" in a relevant way for the ice age problem. For this purpose, Milanković defined "caloric seasons", with the caloric summer being the half year receiving the largest amount of solar radiation at the top of the atmosphere. This forcing is largely dominated by obliquity. In the 1970's, it became more usual to use the summer solstice daily insolation (usually taken at 65°N, the latitude of northern ice-sheets). This forcing has a more important amount of precessional content, a feature that may be more favorable to explain the recent glaciation cycles. Interestingly, it was also suggested recently to use the sum of the insolation forcing above a given threshold, as a surrogate of a "positive degree day" forcing classically used by glaciologists [8]. This new definition of "summer insolation" is again dominated by the 41-kyr obliquity cycle and happens to be quite similar to the original suggestion of Milanković.

Still, choosing the right forcing is not sufficient. As explained in Hays et al. [5], glaciations are “paced” by the astronomy. We now can go further and state that Milanković did correctly predict the “41-kyr world” that is observed between about 3 Myr BP and 1 Myr BP, when ice ages are clearly driven by obliquity changes. But after the MPT, the main cyclicality appears to be linked to eccentricity [5]. There is currently no consensus on the mechanisms behind these longer and larger oscillations, but the concept of relaxation oscillations has many advantages (see eg. [3]). Indeed, in such a framework, it becomes easier to explain the rather stable amplitude of glacial oscillations while the astronomical forcing is strongly modulated by eccentricity at 400-kyr. In such a framework, it is rather natural to switch from one astronomical frequency (41-kyr) to another one (100-kyr) when some other external parameter varies slowly [14] and thus to explain the MPT.

In this concept, a key element is that the triggering of deglaciations is in some way linked to the ice-sheet being sufficiently large [14, 23]. Several possible underlying mechanisms have been suggested to explain [17]. One possibility is that larger ice-sheet might be less stable than smaller ones. In particular, the ice near the base of the ice-sheet will be warmer or will even start to melt. This will significantly accelerate the flow of ice and it is possible that such a large ice sheet could disintegrate rather rapidly. This dynamical process was actually one of the first suggestion made by glaciologists to explain the so-called “100-kyr problem”. Another option was suggested by climate modelers [4] involving the surface albedo of large ice sheets. Indeed, the larger the ice-sheet, the drier the climate above it and the surface ice will receive little fresh snow, but possibly higher amounts of dusts. If the albedo of fresh snow is very high, it becomes much lower through aging and, of course, even lower when loaded with dusts. It is therefore possible that the glacial maximum favours a rapid surface melting of such an ice-sheet thanks to lower surface albedo. Another suggestion to explain a causal link between large ice sheets and deglaciations happens through deep ocean circulation and atmospheric CO<sub>2</sub> [18]. Indeed, bottom waters are currently formed mainly on the Antarctic continental shelf, with brine rejection of sea ice having an important role. If this mechanism should be enhanced during glacial times because of stronger sea ice formation and stronger winds, it should nevertheless completely break down when the Antarctic ice-sheet covers the whole continental shelf, as suggested by geological reconstructions, a few thousands of years after the last glacial maximum. This stop of the “sea ice factory” allows for a de-stratification of the ocean and the release of CO<sub>2</sub> in the atmosphere, thus favouring global warmer climates as observed just before the last deglaciation. Finally, it is also important to mention the possible role of rapid climatic variability in the terminations. Indeed, if the deep ocean circulation has several equilibria as suggested by numerous studies, then there might be a connection between the deglacial “switch” mentioned above and the oceanic abrupt changes. Obviously, it is also possible that each one of the above processes has some important role in the dynamics of ice ages and that they should all be accounted for in a more realistic description of ice ages.

Glaciations are “paced” by astronomy, but obviously the dynamics involved in the recent ice age cycles is far from being understood as a simple response to this forcing. Whatever the detailed mechanism, it appears now that some internal dynamics of the Earth system has a critical role in the ice age problem, in particular in order to explain the 100-kyr cycles and the MPT. During the 19<sup>th</sup> century, scientists disagreed on the nature of ice ages, being either externally induced by the astronomical forcing or being an internal oscillation of the Earth system. Today, both views have gained some value and the idea of an externally forced “internal” relaxation oscillator has gained some credibility [18, 20]. An open question remains the exact role of CO<sub>2</sub> changes in these cycles. If Milanković has correctly predicted the “41-kyr world” many decades before it was observed, it should also be reminded that Arrhenius correctly predicted the last glacial maximum CO<sub>2</sub> to be about 30 to 40% lower than preindustrial levels, almost a century before it was measured in Antarctic ice cores. Furthermore, during deglaciation, there is a clear lead of a few millenia of the CO<sub>2</sub> rise with respect to the melting of ice sheets [15]. It is therefore difficult to avoid the idea that pCO<sub>2</sub> might have some role during terminations.

Unfortunately, current climate models are not well suited to address these questions. A key difficulty in simulating ice-sheets is the long time-scales involved (at least tens of thousands of years) and the small spatial scales for a good representation of ice flows (kilometers or smaller). These ice-sheet models need furthermore to be coupled with the atmosphere above, in order to provide a climate consistent with the evolution of the ice sheet, but also these need to be coupled with the ocean below, since large ice sheets like Antarctica today also have ice-shelves that are key elements of their dynamics. A fully coupled model of the atmosphere, the ocean, the carbon cycle and ice sheets with all these

relevant processes is still not feasible today, though some interesting progresses have been obtained with Earth Models of Intermediate Complexity (EMICs) [4, 25].

### 3. ASTRONOMY AND CARBON CYCLE

But as outlined above, the influence of the astronomical forcing is not limited to ice-sheets. An intriguing enduring feature of geological records is the pervasive 400-kyr oscillation observed in Earth  $^{13}\text{C}$  records over much of the Cenozoic and possibly before [6, 19]. These oscillations are often used as a cyclo-stratigraphic target to build age scales and the international geological time scale now relies on these  $^{13}\text{C}$  cycles at several specific time periods. These cycles are also clearly visible during the last few millions of years as shown on figure 1, though their connection with eccentricity appears more complex during the last part of the Quaternary than during the preceding millions of years. Indeed, most of the time during the Cenozoic, high values of eccentricity are associated with low values of  $^{13}\text{C}$  on Earth. Over the last million years, this connection is perturbed, probably as a result of the large glaciations that occur during this time.

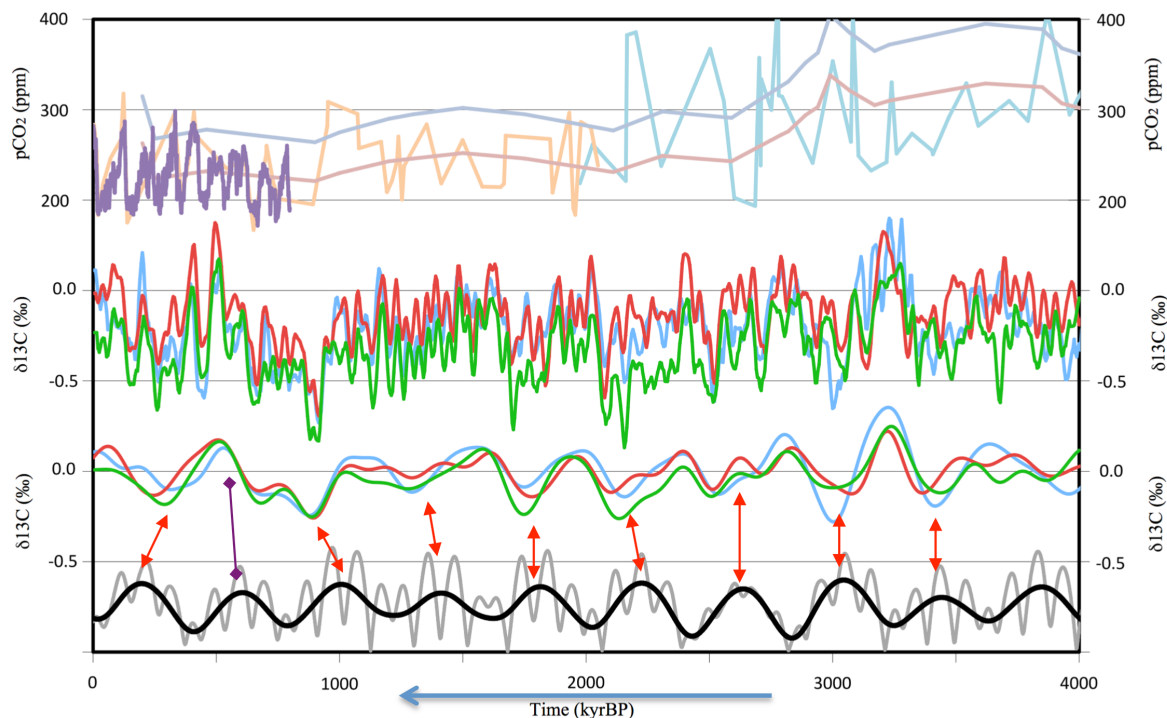


Fig. 1 At the top :  $\text{pCO}_2$  data from Antarctic ice cores in purple [11], boron isotopes. In orange and light blue [7, 1] and the envelope of alkenone isotopes [21]. Middle : marine  $^{13}\text{C}$  records from [24, 13, 22] and the corresponding filtered values at 400 kyr (bandpass =  $2.5 \text{ Myr}^{-1}$ ). Bottom : eccentricity [9] and the corresponding filtered values. Adapted from [16].

Global  $^{13}\text{C}$  reflects the balance between volcanic or kerogen sources, and biogenic or carbonate sinks. It appears very difficult to explain such a large amplitude oscillation through changes in inorganic processes alone while organic carbon burial or kerogen release might more easily account for such an oscillation. A reasonable hypothesis is therefore that the precessionnal forcing has a direct impact on the net balance of organic matter burial and kerogen release, with high forcing leading to enhanced monsoonal precipitations and kerogen erosion, thus explaining the carbon isotopic signal. This was demonstrated in the conceptual model [16] whose results are presented on figure 2. Interestingly, such a mechanism induces changes in Earth carbon cycle that might account for a long-term oscillation in the atmospheric  $\text{pCO}_2$  of about 20 ppm, a magnitude compatible with our knowledge from Antarctic ice cores. As a consequence of this astronomical forcing, the 2 – 2,4 Myr amplitude modulation of the eccentricity is clearly appearing in the carbon model results, in agreement with observations from long marine  $\delta^{13}\text{C}$  records [2, 19]. In particular, according to this concept, it is worth mentioning that the long-term modulation of eccentricity may thus induce a drop in the surface Earth carbon content, and therefore

a drop in atmospheric CO<sub>2</sub> and in temperature, at to specific times over the last millions of years: at about 2.8 MyrBP, roughly in correspondence with the start of Quaternary glaciations, and also at about 0.8 MyrBP, in close connection to the MPT and the enhancement of glaciation cycles.

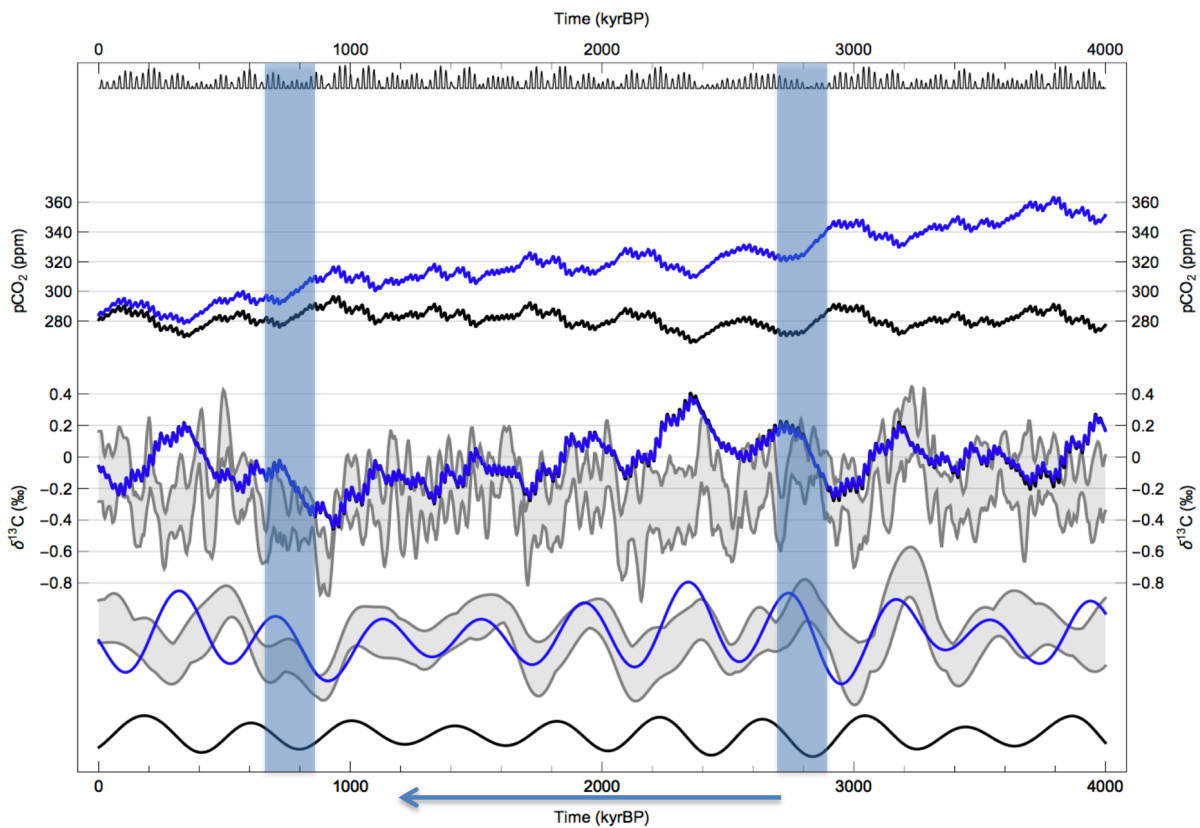


Fig. 2 Top : Top : precessionnal forcing used as an input of the model. In black, the model results in terms of pCO<sub>2</sub> and δ<sup>13</sup>C for the standard simulation, and in blue, the results when a downward trend is added in the carbon content of the Earth. The range of the <sup>13</sup>C data from figure 1 is shown in grey shading. Bottom : the filtered δ<sup>13</sup>C results and data and in black the filtered eccentricity. The blue vertical areas indicate the start of the Quaternary glaciations (about 2.6 or 3 MyrBP) and the Mid-Pleistocene transition (0,7 or 1 MyrBP). These two time periods seem to be linked to the long-term modulation of the carbon cycle model, and therefore could be linked to long-term eccentricity modulation. Adapted from [16]

This model is obviously much too crude to represent faithfully the intricate mechanisms involved in the astronomical forcing of the carbon cycle. Still, it highlights that finding new connections between the astronomy and climate are not only a possibility, but a necessity. Furthermore, this could pave the way towards explaining many important questions on longer-term climate variations during the Cenozoic or even the Mesozoic. In any case, the 400-kyr cycles in the carbon cycle are a reality that deserve a much closer attention from the climate and geochemistry modelling community.

## 5. CONCLUDING REMARKS

Milanković's contribution to Earth Science was tremendous and actually went far beyond the astronomical theory of ice ages. Interestingly, he was neither a geologist, nor an astronomer. He was trained as a civil engineer and started his early career by building bridges and dams. One of his major scientific achievements can be described as building the first bridge between two rather separate areas of science: geology and meteorology on one side, which were very empirical at that time; and mathematics and physics on the other side, with a strong mathematical background. We need to follow his tracks and continue to build such bridges between communities.

## REFERENCES

1. Bartoli, G., Hönisch, B., Zeebe R.E. : 2011, Atmospheric CO<sub>2</sub> decline during the Pliocene intensification of Northern Hemisphere glaciations. *Paleoceanography*, 26 (4), PA4213 doi:10.1029/2010PA002055.
2. Boulila, S., Galbrun, B., Laskar, J., Pälike, H. : 2012, A ~9 myr cycle in Cenozoic  $\delta^{13}\text{C}$  record and long-term orbital eccentricity modulation: Is there a link ? *Earth and Planetary Science Letters*, 317, 273–281.
3. Crucifix, M. : 2012, Oscillators and relaxation phenomena in Pleistocene climate theory. *Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci.* 370, 1140-1165.
4. Ganopolski, A., Calov, R. : 2011. The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles. *Clim. Past*, 7, 1415-1425.
5. Hays, J., Imbrie, J., Shackleton, N. : 1976, Variations in the earth's orbit: pacemakers of the ice ages. *Science* 194, 1121-1132.
6. Hinnov, L., Ogg J.: 2007, Cyclostratigraphy and the astronomical time scale, *Stratigraphy*, 4, 239–251.
7. Hönisch, B., Hemming, N.G., Archer, D., Siddall, M., McManus, J., Atmospheric Carbon Dioxide Concentration Across the Mid-Pleistocene Transition. *Science* (2009) vol. 324 (5934) pp. 1551-1554
8. Huybers P., Wunsch C. :2005, Obliquity pacing of the late Pleistocene glacial terminations. *Nature*, 434, 491-494.
9. Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M. : 2004, A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics*, 428, 261-285.
10. Lourens, L.J., Antonarakou, A., Hilgen, F. J., VanHoof, A.A.M, Vergnaud-Grazzini, C., Zachariasse, W. J.: 1996. Evaluation of the Plio-Pleistocene astronomical timescale. *Paleoceanography*, 11(4), 391–413.
11. Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fisher, H., Kawamura, K., Stocker, T., High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* (2008) vol. 453 (7193) pp. 379-382
12. Martinez, M., Dera, G.: 2015, Orbital pacing of carbon fluxes by a ~9-My eccentricity cycle during the Mesozoic, *PNAS*, 112 (41), 12604-12609.
13. Mix, A. C., N. G. Pisias, W. Rugh, J. Wilson, A. Morey, and T. K. Hagelberg (1995), Benthic foraminifer stable isotope record from Site 849 (0 – 5 Ma): Local and global climate changes, *Proc. Ocean Drill. Program Sci. Results*, 138, 371 – 412.
14. Paillard D., The timing of Pleistocene glaciations from a simple multiple-state climate model, *Nature*, 391, 378-381, 1998.
15. Paillard, D.: 2015, Quaternary glaciations: from observations to theories, *Quaternary Science Reviews*, 107, 11-24
16. Paillard, D.: 2017, The Plio-Pleistocene climatic evolution as a consequence of orbital forcing on the carbon cycle. *Climate of the Past* 13, 1259–1267.
17. Paillard, D.: 2017, Predictable ice ages on a chaotic planet, *Nature*, 542, 419–420.
18. Paillard, D., Parrenin, F. :2004, The Antarctic ice-sheet and the triggering of deglaciations. *Earth Planet. Sci. Lett.* 227, 263-271.
19. Pälike, H., Norris R. D., Herrle J. O., Wilson P. A., Coxall H. K., Lear C. H., Shackleton N. J., Tripathi A. K., Wade B. S. : 2006, The heartbeat of the Oligocene climate system, *Science*, 314, 1894–1898.
20. Saltzman, B., Maasch, K. : 1990, A first-order global model of late Cenozoic climatic change. *Trans. R. Soc. Edinb Earth Sci.* 81, 315-325.
21. Seki, O., Foster, G.L., Schmidt, D.N., Mackensen, A., Kawamura, K., Pancost, R.D. : 2010, Alkenone and boron-based Pliocene pCO<sub>2</sub> records. *Earth Planet. Sci. Lett.*, 292 (1-2) 201-21.
22. Shackleton, N. J., M. A. Hall, and D. Pate (1995), Pliocene stable isotope stratigraphy of Site 846, *Proc. Ocean Drill. Program Sci. Results*, 138, 337–355.

23. Tzedakis, P. C., Crucifix M., Mitsui T., Wolff, E.W. : 2017, A simple rule to determine which insolation cycles lead to interglacials, *Nature*, 542 (7642), 427-432.
24. Wang, P., J. Tian, X. Cheng, C. Liu, and J. Xu (2004), Major Pleistocene stages in a carbon perspective: The South China Sea record and its global comparison, *Paleoceanography*, 19, PA4005, doi:10.1029/2003PA000991
25. Willeit, M. Ganopolski, A. Calov, R., Brovkin, V. :2019, Global mean CO<sub>2</sub>, temperature and sea level data from transient model simulations of Quaternary glacial cycles, *Science Advances*, 5(4), 7337.