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# A Punctuated Equilibrium Analysis of the Climate Evolution of Cenozoic: Hierarchy of Abrupt Transitions

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## FRONT MATTER

### Title

- Full title: A Punctuated Equilibrium Analysis of the Climate Evolution of Cenozoic: Hierarchy of Abrupt Transitions
- Short title: Hierarchy of Transitions in the Cenozoic

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### Abstract

The Earth's climate has experienced numerous critical transitions during its history, which have often been accompanied by massive and rapid changes in the biosphere. Such transitions are evidenced in various proxy records covering different timescales. The goal is then to identify, date, and rank past critical transitions in terms of importance, thus possibly yielding a more thorough perspective on climatic history. To illustrate such an angle, which inspired the punctuated equilibrium angle on the theory of evolution, we have analyzed 2 key high-resolution datasets: the CENOGRID marine compilation (past 66 Myr), and North Atlantic U1308 record (past 3.3 Myr). By combining recurrence analysis of the individual time series with a multivariate representation of the system based on the theory of the quasi-potential, we identify the key abrupt transitions associated with major regime changes that differentiate various clusters of climate variability. This allows interpreting the time-evolution of the system as a trajectory taking place in a dynamical landscape, whose multiscale features are associated with a hierarchy of tipping points.

### Teaser

A hierarchy of Tipping Points shaped the Cenozoic: the time evolution of the system can be understood as a motion in a multiscale dynamical landscape

**MAIN TEXT (The manuscript should be a maximum of 15,000 words)**

## INTRODUCTION

Early evidence of abrupt transitions in Camp Century and Dye 3 Greenland ice cores (1, 2) attracted a lot of attention from the paleoclimatic community before being well acknowledged and understood. They have indeed introduced the evidence of a sequence of abrupt climatic variations that at the time were unknown. Nonetheless, such transitions did not seem to find an agreement with other marine and terrestrial records, which led to considerable debate in the field (3–5). After decades spent retrieving and studying more detailed paleorecords, the evidence for such rapid climatic variations, named Dansgaard-Oeschger events (DO), has been well accepted since then. They have been recently reinforced by the identification of additional abrupt transitions from the NGRIP ice core, which have been made possible by the increased time-resolution of the record (6). These additional events correspond to changes of either short duration or amplitude in  $\delta^{18}\text{O}$  that visual or standard statistical inspections do not necessarily flag. The Earth climate has experienced numerous abrupt and critical transitions during its long history, well beyond the specific examples above (7, 8). Such transitions are often referred to as climatic tipping points (TPs), associated with possibly irreversible changes in the state of the system. The term TP was originally introduced in social sciences (9) and made more recently popular thanks to (10). The study of TPs has recently gained broad interest and perspective in Earth and Environmental sciences, especially with regard to the future of our societies under the present climate warming scenarios (11–14). The term Tipping Elements (TE) was introduced by (13, 15), and subsequently adopted by others (12, 16) to characterize the particular components of the Earth System that are likely to experience a TP in the near future (14, 17–19). Recently, the concept of TP has been used to define, in turn, rapid societal changes that might lead to positive impacts in terms of addressing the climate crisis (20, 21).

Here, we want to investigate critical transitions in the Earth history by looking at 2 key high-resolution datasets that show evidences of abrupt transitions. The first dataset is the CENOGRID benthic  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  record corresponding to the compilation of 14 marine records over the past 66 Myr, from the Cretaceous-Paleogene (K–Pg) extinction event till present (22). The second dataset comprises the North Atlantic U1308 benthic  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  bulk carbonate time series covering the past 3.3 Myr (23).

While visual evidences of abrupt transitions have already been discussed for these datasets, we wish to identify key abrupt thresholds by applying the recurrence

81 quantification analysis (RQA) to the individual time series and supplementing it with  
82 the Kolmogorov-Smirnov (KS) test (24), see below. Then, the selected transitions are  
83 discussed in the context of the Earth climate history allowing the definition of  
84 dynamical succession of abrupt transitions. Such transitions are then interpreted taking  
85 into account the evolution of key climate factors such as CO<sub>2</sub> concentration, average  
86 global sea level, and depth of the carbonate compensation.

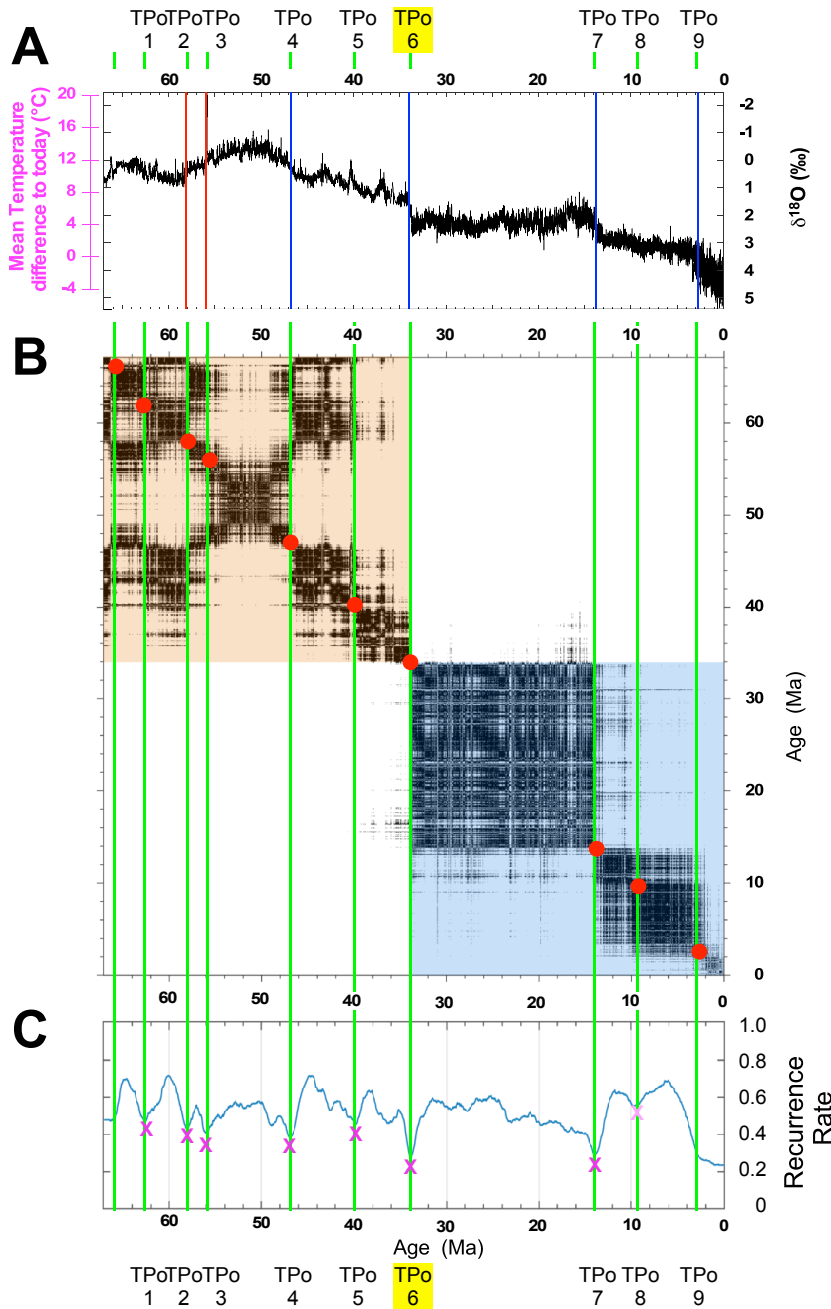
87 The existence of TPs is intimately related to the multistability properties of the climate  
88 system, which have long been recognised in different contexts; see e.g. (25–28) and  
89 discussion in (29) and (30). The multistability of the climate system is associated with  
90 the presence of more than one possible climate states for a given set of boundary  
91 conditions (31). While earlier analyses have mostly evidenced the possibility of  
92 bistable behaviour, multistability can indeed include multiple competing states (32–  
93 35). Recently, it has been proposed that the metastability properties of the climate  
94 system can be understood by taking a different angle that, rather than focusing on the  
95 actual succession of TPs, interprets the climate evolution as a diffusion process taking  
96 place in an effective dynamical landscape (36, 37), the Graham’s quasi-potential (38).  
97 Such a viewpoint mirrors earlier proposals for interpreting biological evolution,  
98 namely the Waddington’s epigenetic landscape (39–43), and foresee the rapid climatic  
99 transitions associated with the TPs as a manifestation of a dynamics characterized by  
00 punctuated equilibria (44, 45); see also relevant literature associated with synthetic  
01 evolution models like Tangled Nature (46, 47). We will test whether the RQA  
02 identifies candidate TPs that come hand in hand with saddles of the quasi-potential,  
03 and whether TPs featuring faster characteristic time scales are associated with smaller-  
04 scale decoration of the quasi-potential (36). The analysis of the benthic  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$   
05 suggests that the evolution of the climate in Cenozoic is characterized by a hierarchy of  
06 TPs due to an underlying multiscale quasi-potential.

## 07 **RESULTS**

### 08 **Detecting Critical Transitions of the past 66 Myr – 3 Myr history of the Earth** 09 **Climate**

10 The KS augmented test of the benthic  $\delta^{18}\text{O}$  record of the past 66 Ma identifies seven  
11 major abrupt transitions corresponding to two major warming events at about 58 Ma  
12 and 56 Ma, followed by five major coolings at 47 Ma, 34 Ma, 14 Ma and 2.8 Ma  
13 respectively (Fig. 1A). Such transitions are characterized by a long-time scale in terms  
14 of permanence in the competing states (a long time-window of 1-4 Ma is used, see  
15 Suppl. Mat.). These events are classical ones described from the literature (48), where  
16 the first two transitions led to warmer conditions, while the latter four led to colder

17 conditions. The same transitions are identified by employing the recurrence plot (RP)  
 18 and recurrence rate (RR) analyses (49), which also identify two more events, occurring  
 19 at around 63 Ma, 20 Ma, and 9.7 Ma, see Fig. 1C, Suppl. Tab. 1. We have  
 20 chronologically labeled these TP<sub>0</sub>1 to TP<sub>0</sub>9, where the lower index refers to the used  
 21 proxy data. As shown in Fig 1B, TP<sub>0</sub>5 separates the climate variability in two separate  
 22 macroclusters prior and after 34 Ma, the well-known Eocene-Oligocene Transition  
 23 (EOT) (50), which is a key step in the Cenozoic climate history and is associated with  
 24 a major extinction event (51, 52).



25  
 26 **Fig. 1. KS test and Recurrence Quantitative Analysis (RQA) of CENOGRID benthic  $\delta^{18}\text{O}$ .** A) Time series  
 27 in Ma BP with difference of the reconstructed and present Mean Global Temperature in pink). KS test identifying  
 28 abrupt transitions towards warmer conditions in red and cooler or colder conditions in blue; B) Recurrence plot  
 29 (RP) with identification of the main two clusters prior and after 34 Ma. The main abrupt transitions identified are  
 30 highlighted by red circles, and C) Recurrence rate (RR). The pink crosses and vertical green lines indicate the  
 31 abrupt transitions (TP<sub>0</sub>) detected by the RQA. CENOGRID benthic  $\delta^{18}\text{O}$  data are from (22)

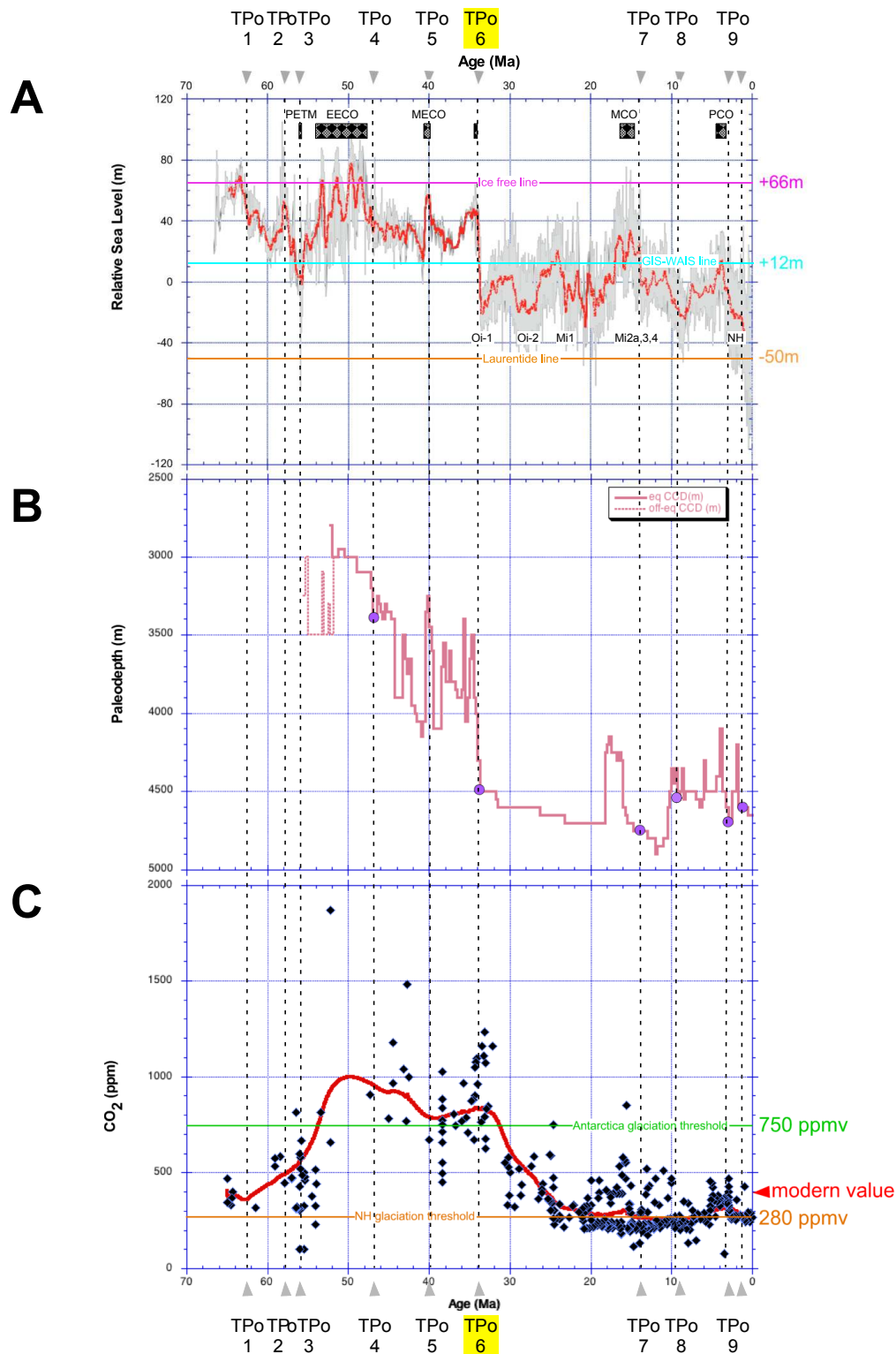
32  
33 The older macrocluster shows a disrupted variability, according to Marvan et al.'s  
34 nomenclature (49). One finds very large negative values of the benthic  $\delta^{18}\text{O}$ , which  
35 correspond to the very warm climate conditions. The average global temperature was  
36 estimated to be between 8°C and 16°C above the present day one, with no apparent  
37 presence of any major continental ice bodies (22) (Fig. 1A). Four major transitions are  
38 found within this period. They include the 2 major abrupt warmings at 58 Ma (TP<sub>O2</sub>)  
39 and 56 Ma (TP<sub>O3</sub>). These two transitions correspond to thresholds towards much  
40 warmer oceanic deep water corresponding to the first late Paleocene-Eocene  
41 hyperthermal (53, 54) and Paleocene-Eocene Thermal Maximum (PETM) (55, 56)  
42 respectively. The third one at about 47 Ma (TP<sub>O3</sub>) corresponds to a transition towards  
43 cooler deep waters and named the Early-Middle Eocene cooling (54). The last one at  
44 about 40 Ma (TP<sub>O4</sub>) inaugurates the period of continuous cooling due to decrease of  
45 CO<sub>2</sub> concentration that eventually leads to the TP<sub>O6</sub> event (57), which leads to the build-  
46 up of the Antarctica ice sheets. TP<sub>O5</sub> clearly separates two fundamentally different  
47 modes of operation of the climate system. From 34 Ma to present day the records  
48 features more positive values of benthic  $\delta^{18}\text{O}$  associated with prevailing colder climate  
49 conditions. After TP<sub>O6</sub>, the climate featured mostly stationary conditions with a slight  
50 warming until the Middle Miocene Climate Transition (TP<sub>O7</sub>) that occurred around 14  
51 Ma (58, 59). The last major transition (TP<sub>O9</sub>) occurred around 2.8 Ma, leading to the  
52 Pleistocene and the onset of glaciations in the Northern Hemisphere.

53  
54 In this work, we will prioritize the information coming from the  $\delta^{18}\text{O}$  record because of  
55 its very strong link to the Earth's temperature. Nonetheless, the analysis of the Benthic  
56  $\delta^{13}\text{C}$  record performed along the same lines as above provides separate pieces of  
57 information on the critical transitions of the Earth's Climate. Benthic  $\delta^{13}\text{C}$  values  
58 characterize deep-water ventilation with high  $\delta^{13}\text{C}$  values in regions close to deep-water  
59 formation area. The KS analysis performed over a time window of 1-4 Myr individuates  
60 14 TPs, with the RP suggesting an additional one, located at around 34 Ma and  
61 associated with the EOT. We refer to these 15 TPs associated with the  $\delta^{13}\text{C}$  record as  
62 TP<sub>C</sub> 1 to 15; see Suppl. Fig. 1, Suppl. Tab. 1. The interval 56.15 Ma – 7.15 Ma is well  
63 characterized, showing some subclusters distributed around 34 Ma. The 56.15 Ma date  
64 groups  $\delta^{13}\text{C}$  values above 1‰, at the base of the record, while 7.15 Ma gathers the  
65 negative  $\delta^{13}\text{C}$  values which mainly occurs on top of the record. The two periods are  
66 characterized by very different climatic conditions. The earlier climate regime features

67 more input of carbon in the ocean while the later climate, instead, is characterized by  
68 higher presence of carbon in the atmosphere.

### 69 **Critical Transitions in other Proxy Data**

71 We next want to analyze TP<sub>O</sub> 1-9 in relation to different reconstructed paleoclimatic  
72 data, namely the global mean sea level (GMSL), the Pacific carbonate compensation  
73 depth (CCD), and CO<sub>2</sub> concentration (Fig. 2). Using benthic foram  $\delta^{18}\text{O}$  and Mg/Ca  
74 records from high-resolution Pacific cores different from CENOGRID ones, (54) have  
75 reconstructed the variations of the GMSL of the past 66 Ma. Measuring the carbonate  
76 content in sediment Pacific cores and applying transfer functions, (60) have computed a  
77 detailed Cenozoic record of the Pacific CCD below which carbonates dissolve. Finally,  
78 compiling estimates from various proxies including foram  $\delta^{13}\text{C}$ , boron isotopes, stomata,  
79 paleosols. (61) have released a comprehensive Cenozoic record of the CO<sub>2</sub>  
80 concentration. One clearly observes the signature of the TP<sub>O</sub>6 in the three records, as it  
81 corresponds to an abrupt decrease of the GMSL by about 70m and of the CCD by  
82 around 1000m. Additionally, TP<sub>O</sub>6 signals the start of the progressive decrease of the  
83 CO<sub>2</sub> from values of the order of 750 ppm to values of the order of 280 ppm.



84  
85 **Fig. 2. Variation through time of three main climate factors and comparison with the identified**  
86 **abrupt transitions (TP) in the CENOGRID benthic  $\delta^{18}\text{O}$ .** A) Global Mean Sea Level in meters from  
87 (54). Identification of specific warm and of glaciation events. The Laurentide, GIW-WAIS and Ice free  
88 lines are from (54); B) Carbonate Compensation Depth (CCD) in meters from (60). The purple circles  
89 identify the TPs on this record; C) Estimate of the CO<sub>2</sub> concentration in parts per million volume (ppmv)  
90 from (61). The Antarctica glaciation threshold at 750 ppmv and the NH glaciation threshold at 280 ppmv  
91 lines respectively are from (62)

92 One can identify four competing states, "Warmhouse" (66 Ma-TP<sub>01</sub> and TP<sub>03</sub>- TP<sub>05</sub>)  
93 and "Hothouse" (TP<sub>01</sub>-TP<sub>03</sub>) climates in the earlier, warmer period, followed by the  
94 "Coolhouse" (TP<sub>05</sub>-TP<sub>06</sub>) and "Icehouse" climates (TP<sub>06</sub> to present); see Fig. 1.



95 The first two states alternated in a warm-hot-warm sequence under extremely high CO<sub>2</sub>  
96 concentrations (61) as compared to those measured over the past 800 Kyr in the  
97 Antarctic ice cores, which represent the reference states for the IPCC potential scenarios  
98 of climate change warming (63) (Fig. 2C). Before 34 Ma, one finds substantially larger  
99 values for GMSL, CCD depth, and CO<sub>2</sub> concentration whose average values are: +38 ±  
00 15 m, 4600 ± 150 m, and 630 ± 300 ppmv respectively (Suppl. Tab. 2). Note that the  
01 CO<sub>2</sub> concentration is much higher than what observed in the past 800 kyr in the  
02 Antarctic ice cores, which represent the reference states for the IPCC potential scenarios  
03 of climate change warming (63). Conversely, from 34 Ma until present, under much  
04 lower CO<sub>2</sub> concentrations and GMSL, thus generating the classical climate trend  
05 towards the recent ice-age conditions (8, 22, 48) (Fig. 2A,C). Indeed the last 34 Myr  
06 show average values in GMSL, CO<sub>2</sub> concentration and CCD depth of -3.5 ± 13 m, 330 ±  
07 160 ppmv and 3500 ± 400 m respectively (Tab. 2), which are much lower than in the  
08 older interval. This second set of means are underestimated values because the final  
09 values of (54) dataset ending at 0.9 Ma,

10 These GMSL, CCD and CO<sub>2</sub> reconstructions show key transitions that fit with the  
11 CENOGRID thresholds deduced from the KS and RR analysis of the benthic δ<sup>18</sup>O as  
12 they signal increase or a decrease in the global mean sea level corresponding roughly to  
13 warming or cooling episodes of the Earth history or strong variations in the  
14 concentration of atmospheric CO<sub>2</sub>. The variations observed in CO<sub>2</sub>, CCD and GMSL at  
15 the 9 identified TPs from the benthic δ<sup>18</sup>O record indicate heterogeneous characteristics  
16 prior to the TP6 major threshold (Suppl. Tab. 3). On the contrary, more homogenous  
17 features are noticed in the three climate proxies after TP<sub>O6</sub>, translating the occurrence of  
18 major reorganizations in the climate system, which become interesting to test at shorter  
19 timescales; see discussion below.

## 20 21 **A Historical Account of the Critical Transitions**

22 Added to the Chicxulub meteor impact previously mentioned, which injected a  
23 considerable amount of CO<sub>2</sub> into the atmosphere (64, 65), Deccan traps were already  
24 spreading at the beginning of the Cenozoic, contributing to the release of massive  
25 amount of CO<sub>2</sub> (8). CO<sub>2</sub> concentration continued raising until about 500 ppmv with the  
26 North Atlantic Igneous province very active at about 58 Ma – 56 Ma (TP<sub>O2</sub> and TP<sub>O3</sub>)  
27 in relation with the opening of the North Atlantic Ocean (66). The Northern Hemisphere  
28 plates were connected and not facing the present Arctic conditions allowing faunal and  
29 vegetal dispersion. Other plates were on the contrary reorganizing like India moving  
30 northeastward toward the Asian continent. Equatorial Pacific carbonate compensation

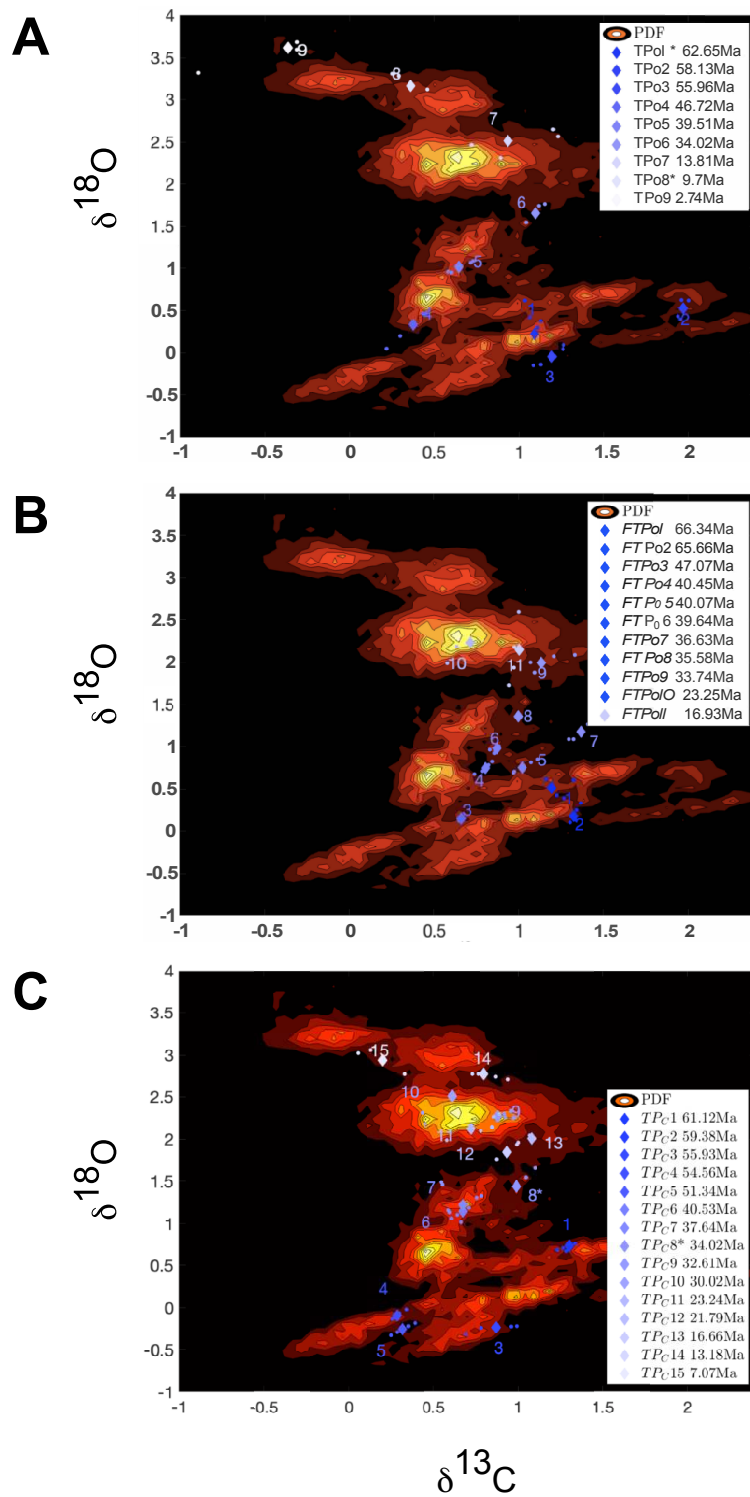
31 depth (CCD) reached a minimum value a bit later at about 54 Ma when CO<sub>2</sub>  
32 concentration reached its maximum of the whole Cenozoic above 1,100 ppmv (61). The  
33 lowering of the GMSL and of the CCD at TP<sub>O</sub>4 (about 40 Myr) has been interpreted as  
34 the start of the icing of Antarctica through mountain glaciers deposits dates by K-Ar  
35 dating of lava flows (67), supported by other glacial evidences i.e., from the Gamburtsev  
36 subglacial mountains (68), while Northern Hemisphere plates remained connected. By  
37 TP<sub>O</sub>4 India is approaching the Asian plate while Northern Hemisphere ones were still  
38 connected, allowing northern continental migrations of mammals at high latitudes (69,  
39 70). About 34 Ma, the EOT (TP<sub>O</sub>6) is associated with the opening (in several steps) of  
40 the Drake and Tasmanian passages (71), which lead to a drastic change in the global  
41 ocean circulation. The effect is a decrease in the South Hemisphere water formation  
42 strength, a deep-sea temperature drop associated with the deep fall in relative sea level  
43 and CCD (see Fig. 2). According to paleoaltimetry estimates based on oxygen isotopes,  
44 (72) indicate that the Tibetan Plateau had an elevation of about 4000m, favoring  
45 therefore the physical weathering of rocks, consuming CO<sub>2</sub>, and the burial of carbon  
46 through high sedimentation rates in the adjacent seas. This may have contributed to the  
47 major threshold in the variation of the CO<sub>2</sub> concentration, which also drops very strongly  
48 ((61); Fig. 2).

49 This key transition is the major boundary between two different climate landscapes  
50 dominated by intensive plate tectonic and major volcanism for the older one, and by  
51 major ice sheets in both Southern and Northern Hemispheres, with plate tectonic  
52 (closure of seaways, orogenies) still very active, for the younger one (70). Immediately  
53 after the EOT, the climate witnessed the build-up of the East Antarctic ice sheet (Oi-1  
54 glaciation), which can be considered as the onset of the cold world in which we are still  
55 living. India has almost ended its transfer to the Asian plate. Between TP<sub>O</sub> 6 and TP<sub>O</sub> 7,  
56 i.e., 34 Ma and 14 Ma respectively, the East Antarctic ice sheet is waxing and vaning  
57 with several major glaciations occurring before the 17 Ma to 14.5 Ma interval during  
58 which sea level increases in association with a severe shoaling episode of CCD and  
59 higher values of the CO<sub>2</sub> concentration (Fig. 2). Such high CO<sub>2</sub> concentrations may have  
60 been fueled by the Columbia River major volcanism, which ended by TP<sub>O</sub> 7 at about 14  
61 Ma (8). Plate tectonics is still very active with the closure of both the Indonesian  
62 gateway and the Tethyan seaway, contributing to the start of the development of the  
63 Mediterranean (73), and. Eurasia is now separated from Northern America and  
64 Greenland, India colliding the Asian continent, and the Andes are uplifting modifying  
65 the geometry of the marine basins and the global oceanic circulation. West Antarctica is  
66 starting building up while East Antarctic ice sheet is reinforcing and expanding. TP<sub>O</sub>8 at

67 about 9 Ma sees a strong lowering of the GMSL and of the CO<sub>2</sub> concentrations (Fig. 2).  
68 TP<sub>O</sub>9 is associated with a final major tectonic event corresponding to the closure of the  
69 Panama Isthmus, which as a result of shutting down the exchange of water between the  
70 two oceans, led to re-routing large-scale flows in both the Pacific and the Atlantic  
71 Ocean, and configured a oceanic circulation that is very similar to present day (74). This  
72 is associated to a strong lowering of the global sea level, a deepening of the CCD and  
73 the CO<sub>2</sub> concentration (Fig. 2) that will preside the Earth climate history during the  
74 Quaternary, associated to the build-up of the Northern Hemisphere glaciers and ice  
75 sheets. It is interesting to notice that all the major transitions that have been identified  
76 during the interval between 66 Ma and 2.9 Ma - 2.5 Ma are linked to the build-up,  
77 waxing, and vaning of the Northern and Southern Hemisphere ice sheets.

### 78 79 **Quasi-potential Landscape and Critical Transitions**

80 As discussed in detail in the Methods section, taking inspiration from the use of the  
81 Waddington epigenetic landscape to describe evolution (39–43) and from the theory of  
82 punctuated equilibrium (44, 45), it has been proposed in (36, 37) to study the global  
83 stability properties of the climate system by introducing an effective quasi-potential  
84 (38), which generalizes the classical energy landscape framework often used to study  
85 metastable stochastic system. The quasi-potential formalism allows one to study general  
86 nonequilibrium system and to associate local maxima of the probability distribution  
87 function (pdf) of the system stable states. Additionally, saddles of the pdf are associated  
88 with Melancholia (M) states (31), which are unstable states living in the boundary  
89 between different basins of attraction. In the weak-noise limit, noise-induced transitions  
90 between competing stable states are expected to go through such M states. What we  
91 have done here is to construct the empirical bivariate pdf of climate system in the  
92 projected ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) and check whether TP<sub>O</sub> 1-9 indicated in Fig. 1 correspond, at  
93 least approximately, to saddles of the pdf. We find – see Fig 3A – that, indeed, this is  
94 the case of TP<sub>O</sub>s 1, 2, 4, 5, 6, 8, 9, whereas no agreement is found for TP<sub>O</sub>s 3 and 7,  
95 which seem to take place in regions where the density is very small and very large,  
96 respectively. The pdf shown here had already been used in (22) to identify the Icehouse,  
97 the Coolhouse, the Warmhouse, and the Hothouse states. Our angle here, instead, allows  
98 to better identify the transitions between such states, and the special role played by  
99 TP<sub>O</sub>6, which basically breaks the pdf into two separate parts. Note that the transitions  
00 shown in Fig. 1 are associated, because of the choice of a long time-window, with  
01 events that occur over long periods and that lead to persistent changes in the state of the  
02 system.



03  
 04 **Fig. 3. Probability density of the climate system in the projected CENOGRID benthic  $\delta^{18}\text{O}$  and**  
 05  **$\delta^{13}\text{C}$ . space.** Panel a) Chronologically ordered TP<sub>O</sub>s (diamonds) selected according to the KS  
 06 methodology for  $\delta^{18}\text{O}$  with time window 1-4 Myr are shown. The two extra TP<sub>O</sub>s found via RP  
 07 are indicated with a \*. Panel b) Chronologically ordered fast TP<sub>O</sub>s (FTP<sub>O</sub>s, diamonds) selected  
 08 according to the KS methodology for  $\delta^{18}\text{O}$  with time window 0.25-1 Myr are shown. Panel c) Same as a),  
 09 but for the  $\delta^{13}\text{C}$  record. The approximate timing of the TPs is indicated (rounded to .01 Myr). The 5 Ky-long  
 10 portions of trajectories before and after each TP are also plotted.  
 11

12 It is natural to ask ourselves what happens if, instead, we consider a catalogue of  
 13 transitions for the  $\delta^{18}\text{O}$  record that are detected by considering shorter time windows  
 14 (0.25 Ma-1Ma) in the KS procedure. One finds – see Fig. 3B - 11 of such transitions

(see Suppl. Mat.). Once we report such fast TP<sub>OS</sub> (FTP<sub>OS</sub>) into the empirical bivariate pdf of the climate system in the projected ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) space, we find that they correspond to finer and smaller structures of the pdf as opposed to the case of the TPs. Hence, events that are associated with faster time scales are associated with smaller jumps between secondary maxima in the pdf belong to a hierarchically lower rung than those occurring over longer time scales. This seems to support the proposal made in Ref. (38).

As additional step, we repeat the same analysis leading to Fig 3A by using, instead, the  $\delta^{13}\text{C}$  record, which features, as mentioned above, a total of 15 TP<sub>CS</sub>. Figure 3C shows clearly that the TP<sub>CS</sub> correspond for the most to saddles that had not been flagged by the TP<sub>OS</sub>. We have evidence that the same saddle is crossed more than once in a back-and-forth fashion few millions of years apart (e.g. TP<sub>C</sub> s 4 & 5; TP<sub>CS</sub> 6 & 7; TP<sub>CS</sub> 12 & 13), which supports the dynamical interpretation discussed here. Comparing Figs 3A and 3C, one discovers that the same saddle is responsible for TP<sub>O</sub>8 and for TP<sub>C</sub>15 even if the dating is different. Similarly, the same saddle is responsible for TP<sub>O</sub>5 and TP<sub>CS</sub> 6 & 7. Two key climatic features that appear as TPs in both records: the PETM corresponds to TP3 in both records, while the EOT corresponds to TP<sub>O</sub>6 and TP<sub>C</sub>8.

### **The recent past**

The past 3.3 Myr record from North Atlantic core U1308, can be considered as a blow-up of the CENOGRID dataset (Fig. 4). As previously mentioned, the last 3.3 Myr have been defined as an Icehouse climate state, with the appearance, development, and variations of the NHIS (22), with the Antarctic ice sheets already reached mostly their maximal expansion. The variations in the deep-water temperature, as expressed by the benthic  $\delta^{18}\text{O}$ , are interpreted as an indicator of the continental ice volume with clear interglacial-glacial successions (75–77). The Icehouse state is characterized by a change of the interplay between benthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , which corresponds to a new relationship between the carbon cycle and climate (78). Indeed, one finds a very strong correlation between the two records (Pearson's coefficient being approximately -0.6). The correlation mainly results from the fact that the time series have approximately a common quasi-periodic behaviour due to resonant response to the astronomical forcing, as discussed below. Note that that the presence of such almost regular resonant oscillations makes the use of the quasi-potential framework not particularly useful for describing the dynamics of the system.

The KS augmented test and the RQ of the benthic  $\delta^{18}\text{O}$  agree in identifying six abrupt transitions dated at approximately 2.93 Ma, at 2.52 Ma, at 1.51 Ma, at 1.25 Ma, at 0.61

51 Ma and at 0.35 Ma (Fig. 4, Suppl. Tab. 1). They characterize the dynamics of North  
52 Hemisphere ice sheets (elevation and spatial expansion) and agree with the classical  
53 transitions characterizing the Marine Isotope Stages (MIS) as already observed in  
54 numerous records covering the same interval (see (79) and Refs. therein).

55 The first two transitions broadly correspond with the previously discussed  
56 CENOGRID's TP<sub>O9</sub> associated with the onset of the Pleistocene (note that the interval  
57 between the two is much smaller than the resolution needed to separate to TP<sub>O8</sub>) and are  
58 followed by four more recent TPs associated with the benthic  $\delta^{18}\text{O}$  record (RTP<sub>O8</sub>).  
59 There is clear evidence of the Mid-Pleistocene (MPT) critical transition, between 1.25  
60 Ma and 0.8 Ma, during which a shift occurred from climate cycles dominated by a 40-  
61 kyr periodicity (due to obliquity) to 100-Kyr periodicity (due to eccentricity) dominated  
62 ones (80–84). The 1.25 Ma date is particularly significant, since it is followed by an  
63 Increase in the amplitude of glacial–interglacial fluctuations.

64 A complementary RQA of the  $\delta^{18}\text{O}$  bulk carbonate record from U1308, which  
65 characterizes episodes of iceberg calving into the North Atlantic Ocean IRD released  
66 into the North Atlantic Ocean (23), and therefore illustrates the dynamics of the  
67 Northern Hemisphere ice sheets (NHIS), yields similar dates to those obtained for the  
68 benthic  $\delta^{18}\text{O}$  record (see Suppl. Fig. 3, Suppl. Tab. 1) (79). Indeed, one finds abrupt  
69 transitions at 2.75 Ma, at 1.5 Ma, at 1.25 Ma, at 0.9 Ma and 0.65 Ma. Finally, as  
70 opposed to the CENOGRID  $\delta^{13}\text{C}$  RP, U1308  $\delta^{13}\text{C}$  RP shows a drifting pattern similar to  
71 that of benthic  $\delta^{18}\text{O}$ , with only 2 key transitions at 2.52 Ma and 0.48 Ma (see Suppl. Fig.  
72 3). Note that the 0.48 Ma transition does not have any equivalent in the benthic  $\delta^{18}\text{O}$   
73 records.

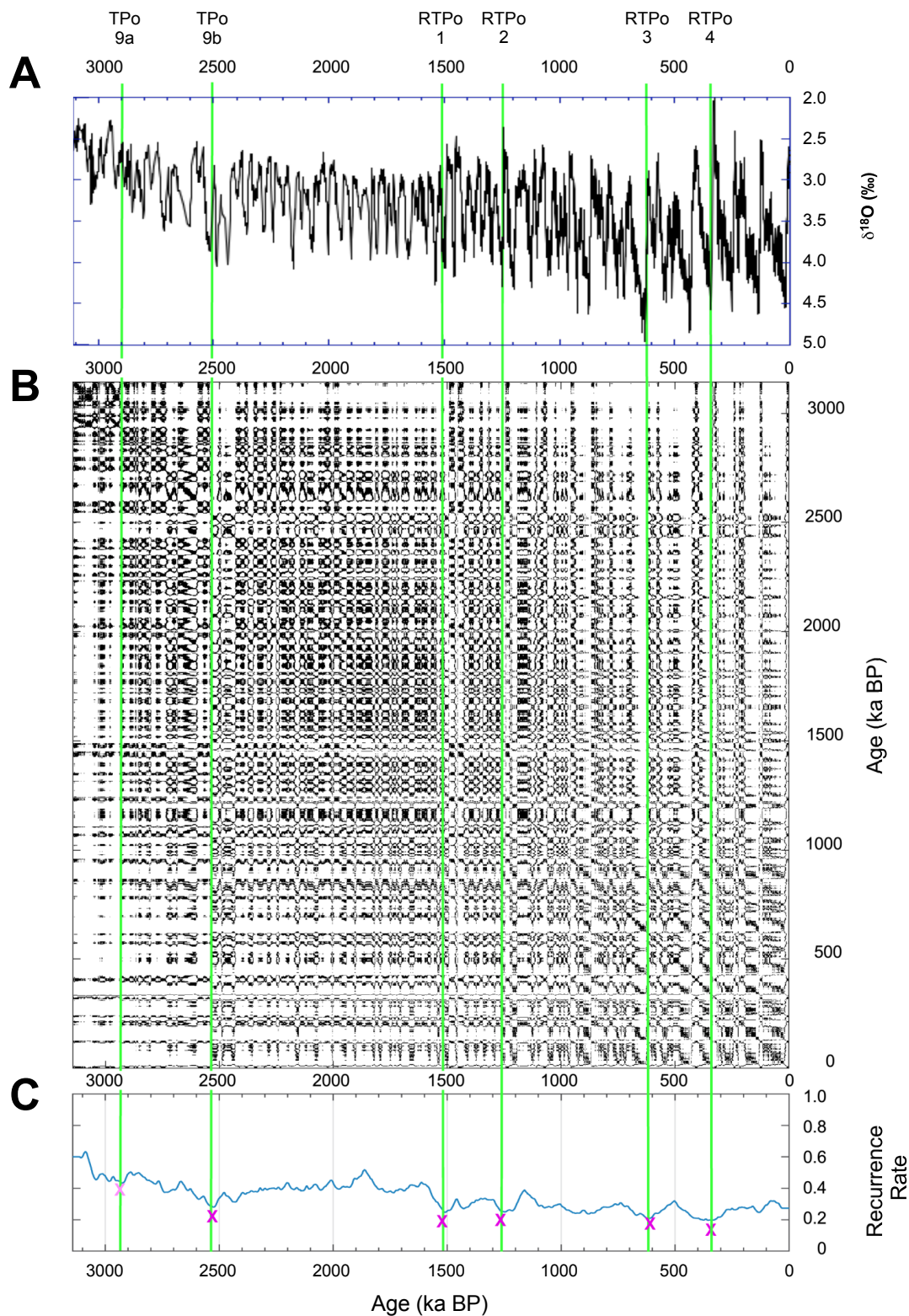


Fig. 4. **RQA of U1308 benthic  $\delta^{18}\text{O}$ .** A) Time series in Ma; B) RP; and C) RR. Crosses similar than Fig. S1. TP<sub>O</sub>9 and RTP<sub>O</sub>1-4 abrupt transitions identified in the RR. U1308 benthic  $\delta^{18}\text{O}$  data are from (23)

## DISCUSSION

Studying the same CENOGRID dataset, Ref. (85) identified 9 geological transitions at respectively 62.1 Ma, 55.9 Ma, 33.9 Ma, 23.2 Ma, 13.8 Ma, 10.8 Ma and 7.6 Ma. Four of them are indeed identical to those determined in the present study: 62.1 Ma, 55.9 Ma,

86 33.9 Ma and 13.8 Ma, the first two being preceded by a significant early warning signal  
87 (85), which is instead absent in the case for the EOT key transition.

88 Considering the results of both RQA, KS test of the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  time series  
89 considered in this study and the bivariate analysis performed using the framework of the  
90 quasi-potential theory, we propose a succession of critical transitions as described in  
91 Fig. 5. The critical transitions  $\text{TP}_{\text{O}1}$  to  $\text{TP}_{\text{O}9}$  shaped the Earth climate towards the onset  
92 and development of the Southern ice sheets and the later build-up of the NHIS.  $\text{TP}_{\text{O}9}$   
93 is followed by four more recent RTPs in the Quaternary, which steered the evolution of the  
94 ice sheets and of the climate as a whole until present day. The climatic evolution in the  
95 Cenozoic until about 3 Ma seem to conform to a punctuated equilibrium framework,  
96 where the  $\text{TP}_{\text{O}s}$  are associated with transitions between rather different modes of  
97 operation of the climate system. In particular, the key step that separates two rather  
98 diverse sets of climatic states occurred about 34 Ma at the EOT ( $\text{TP}_{\text{O}6}$ ). Without the  
99 major drop in GMSL, in  $\text{CO}_2$  concentration and in CCD, the Earth climate could have  
00 been different. However, after  $\text{TP}_{\text{O}6}$ , the Earth climate entered new dynamical regimes  
01 marked by much lower  $\text{CO}_2$  concentration, lower GMSL and CCD. The oceanic basin  
02 redesign and the mountain uplifts changed the marine and atmospheric circulations  
03 patterns, leading to the onset and development of the NHIS.

04 Interestingly, the analysis of the  $\delta^{13}\text{C}$  time series leads to identifying a different set of  
05 critical transitions – except for the case of the PET ( $\text{TP}_{\text{O}2}$  and  $\text{TP}_{\text{C}}$ ) and the EOT  
06 ( $\text{TP}_{\text{O}6}$  and  $\text{TP}_{\text{C}8}$ ), which are recovered for both proxy data. Looking into the bivariate  
07 pdf in the projected ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) space allows to better understand the nature and the  
08 origin of the TPs separately detected by studying the recurrence properties of the  
09 univariate time series. Indeed, we are in most cases able to associate both the  $\text{TP}_{\text{O}s}$  and  
10 the  $\text{TP}_{\text{C}s}$  to transitions across saddles of the effective quasi-potential. Clearly, some  
11 critical transitions might be better detectable when looking at one rather than the other  
12 time series, yet the angle taken here allows to put all TPs within a common ground.  
13 Additionally, TPs associated with faster processes and occurring between slower TPs  
14 correspond to transitions across smaller-scale saddles of the quasi-potential, hence  
15 revealing a correspondence between the hierarchy of TPs and the multiscale nature of  
16 the quasi-potential.



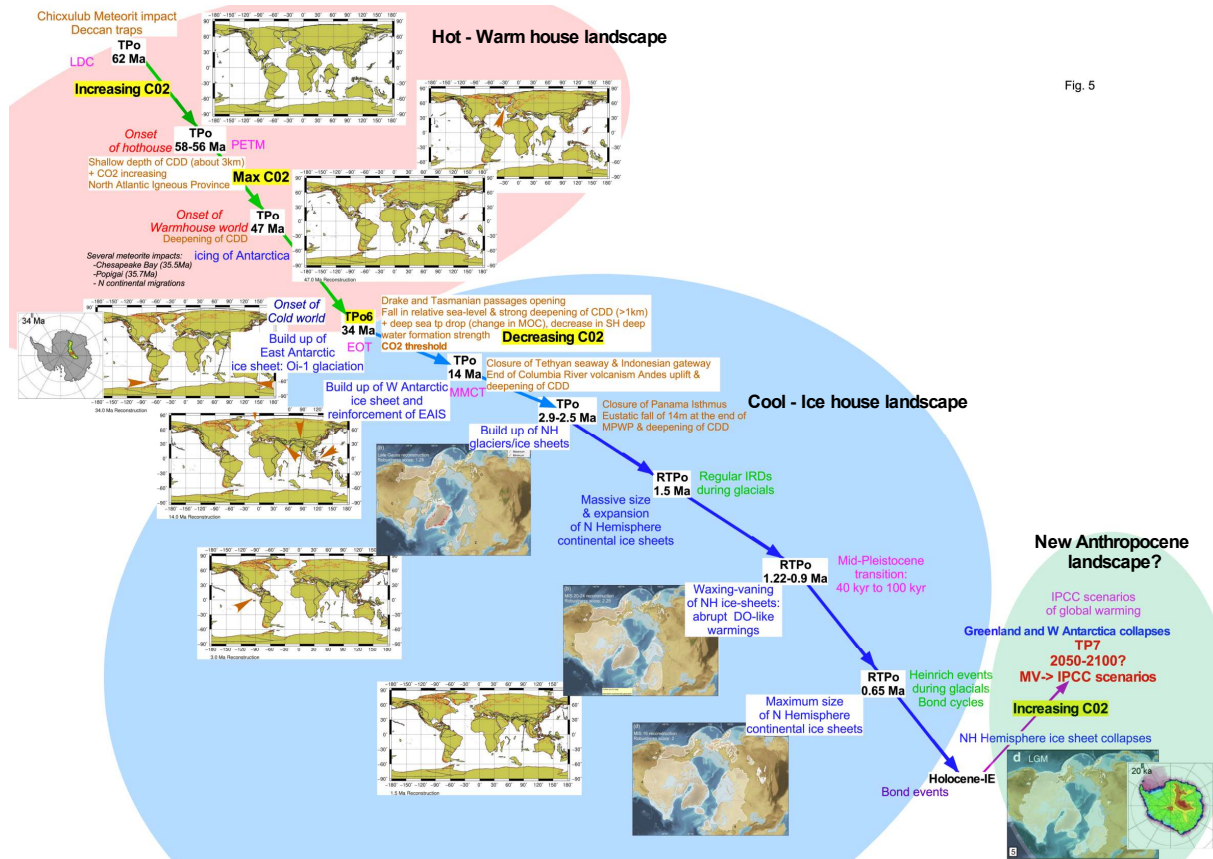


Fig. 5

Fig. 5. Evolution of the Earth Climate history among 2 different dynamical landscapes and proposal for a potential third one. The first dynamical landscape in light red, corresponds to the Hot-Warm House time interval. The second dynamical landscape in light blue corresponds to the Cold-Ice house time interval. The third landscape, in light green, corresponds to the potential new one represented by the Anthropocene time interval. The different abrupt transitions identified in the present study are reported as TPOs or RTPOs to differentiate the major tipping points up to the early Quaternary period from the more recent TPs characterizing less drastic climate changes in the Quaternary. Various plate tectonic and ice sheet events are indicated and supported by maps of plate movements and North and South Hemisphere ice sheets. The Antarctica maps are from (86), Northern Hemisphere ice sheet maps are from (87). The paleogeographic maps have been generated using the Ocean Drilling Stratigraphic Network (ODSN) plate tectonic reconstruction service: < <https://www.odsn.de/odsn/services/paleomap/paleomap.html>>. The red arrows on the tectonic maps indicate the key events at the identified abrupt transition.

More recently, variations in the NHIS extent and volume have contributed to the occurrence of the millennial variability marked by the Bond cycles as better described during the last climate cycle but, which onset has been proposed to be dated of 0.9 Ma (79). Human activity is now rapidly pushing the Earth system towards the limits of its safe operating space associated with the occurrence of TPs. This concern is supported by actual observations impacting numerous tipping elements (see (12) through very drastic tipping cascades (14). This paves the way for a possible upcoming major transition, which might be fundamentally different from what observed in the recent or more distant past, and, at the very least, could bring us into in perspective into a climate state with much reduced or absent NHIS. Hence, we can foresee the possibility of the Earth system exploring a rather different dynamical landscape. This potential major transition, leading to de factor irreversible changes for the climate and the biosphere, could be the

43 boundary between the Cenozoic icehouse and a new warmer and radically different  
44 climate state with respect to Pleistocene conditions.

## 45 **METHODS**

### 46 **Recurrence Plots and Kolmogorov-Smirnov Test**

47  
48 The augmented Kolmogorov-Smirnov test is a robust method for identifying  
49 discontinuities in a particular time series and is therefore a very precise way for timing  
50 the onset of abrupt transitions. It has been successfully applied to various geological  
51 time series (24, 79, 88). The method compares two samples taken before and after the  
52 potential transition point to test whether they come from the same continuous  
53 distribution. If they do not, the transition point is identified as a significant abrupt  
54 change indicative of a true climatic shift. (see for more details (24, 79))

55 To gain further insight like recurring patterns into the climate story the records tell us,  
56 we performed a quantitative, objective analysis of these time series of proxy variables,  
57 based on the recurrence plots (RPs) introduced by (89) into the study of dynamical  
58 systems and popularized in the climate sciences by (49, 90). The RP for a time series  
59  $\{x_i: i = 1, \dots, N\}$  is constructed as a square matrix in a cartesian plane with the abscissa  
60 and ordinate both corresponding to a time-like axis, with one copy  $\{x_i\}$  of the series on  
61 the abscissa and another copy  $\{x_j\}$  on the ordinate. A dot is entered into a position (i, j)  
62 of the matrix when  $x_j$  is sufficiently close to  $x_i$ . For the details — such as how  
63 “sufficiently close” is determined — we refer to (89) and (90). All the points on the  
64 diagonal  $i = j$  have dots and, in general, the matrix is rather symmetric, although one  
65 does not always define closeness symmetrically; to wit,  $x_j$  may be “closer to”  $x_i$  than  
66  $x_i$  is to  $x_j$  (89). An important advantage of the RP method is that it does apply to  
67 dynamical systems that are not autonomous, i.e., that may be subject to time-dependent  
68 forcing. The latter is certainly the case for the climate system on time scales of 10–100  
69 Kyr and longer, which is affected strongly by orbital forcing.

70 Ref. (89) distinguished between large-scale *typology* and small-scale *texture* in the  
71 interpretation of square matrix of dots that is the visual result of RP. Thus, if all the  
72 characteristic times of an autonomous dynamical system are short compared to the  
73 length of the time series, the RP’s typology will be homogeneous and, thus, not very  
74 interesting. In the presence of an imposed drift, a more interesting typology will appear.  
75 The most interesting typology in RP applications so far is associated with recurrent  
76 patterns that are not exactly periodic but only nearly so. Hence, such patterns are not that  
77 easily detectable by purely spectral approaches to time series analysis. Ref. (90)  
78 discussed how to render the purely visual RP typologies studied up to that point more

79 objectively quantifiable by recurrence quantification analysis and bootstrapping (91, 92).  
80 The RP exhibits, moreover, a characteristic texture — given by the pattern of vertical  
81 and horizontal lines that mark recurrences. These lines sometimes form recurrence  
82 clusters that correspond to specific periodic patterns.

### 84 **Quasi-potential, Melancholia States, and Critical Transitions**

85 Traditionally, tipping points are schematically represented as being associated with the  
86 bifurcation occurring for a system described by a one-dimensional effective potential  
87 when a change in the value of a certain parameter leads to a change in the number of  
88 stable equilibria. Hence, conditions describing the nearing of a tipping point can be  
89 related to the presence of slower decay of correlations (critical slowing down). This  
90 viewpoint, while attractive, suffers from many mathematical issues due to the fact that  
91 the true dynamics of the system occurs in a possibly very high dimensional space. Refs.  
92 (93, 94) have introduced a mathematically rigorous framework for the occurrence of  
93 tipping points that clarifies the link between rate of decay of correlations, sensitivity of  
94 the system to perturbations, and robustness of the unperturbed dynamics.

95 Here we wish to take a different angle on the problem, where, instead, of focusing on the  
96 approach to the individual tipping points, we try to capture the global stability properties  
97 of the system. Indeed, taking inspiration from the use of the Waddington epigenetic  
98 landscape to describe evolution (39–43) and from the theory of punctuated equilibrium  
99 (44, 45), Refs. (36, 37) proposed to describe the global properties of the climate system  
00 using the formalism of quasi-potential (38). Roughly speaking, assuming that the system  
01 lives in  $\mathbb{R}^N$ , and its dynamics is described by a stochastic differential equation the  
02 probability that its state is within the volume  $d\vec{x}$  around the point  $\vec{x} \in \mathbb{R}^N$  is given by

03  $P(\vec{x}, d\vec{x}) = \rho(\vec{x})d\vec{x}$  where  $\rho(\vec{x}) \approx e^{-\frac{2\Phi(\vec{x})}{\varepsilon^2}}$  is the probability distribution function (pdf)  
04 and  $\Phi(\vec{x})$  is the quasipotential. The function  $\Phi(\vec{x})$  depends in a nontrivial way on the  
05 drift term and noise law defining the stochastic differential equation. This setting  
06 generalizes the classical energy landscape and applies to a fairly large class of stochastic  
07 dynamical systems. One can see the dynamics of the system as being driven towards  
08 lower values  $\Phi(\vec{x})$  (plus an extra rotational effect that is typical of non-equilibrium  
09 systems), while the stochastic forcing noise makes sure that the system is erratically  
10 pushed around. Hence, the minima of  $\Phi(\vec{x})$  correspond to local maxima of the pdf, and  
11 the saddles (which coincide for both  $\Phi(\vec{x})$  and  $\rho(\vec{x})$ ) correspond to the Melancholia (M)  
12 states (31). Such M states are unstable states of the system that live at the boundary  
13 between basins of attraction and are the gateways for the noise-induced transitions

14 between competing stable states. Ref. (34) applied this angle to the investigation of the  
15 metastability properties of an intermediate complexity climate model and suggested that  
16 the presence of decorations of the quasi-potential at different scales could be interpreted  
17 as being associated with a hierarchy of tipping points. Indeed, passing near M states is  
18 intimately associated with the occurrence of critical transitions. Hence, the construction  
19 of the quasi-potential  $\Phi(\vec{x})$  can be seen as the structural counterpart of the investigation  
20 of the time-evolution of the system and of its critical transitions. Ref. (95) gives a  
21 complete overview of different methods applied to perform such analysis.

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**Data and materials availability:** All data generated by the present study from the main text or the supplementary materials will be submitted to PANGAEA data repository. U1308 marine data are available at <https://doi.org/10.1594/PANGAEA.871937> (Hodell and Channell, 2016b). CENOGRIID data are available at <https://doi.org/10.1594/PANGAEA.917503> (Westerhold, 2020).

## Figures and Tables

Fig. 1. **KS test and Recurrence Quantitative Analysis (RQA) of CENOGRID benthic  $\delta^{18}\text{O}$ .** A) Time series in Ma BP with difference of the reconstructed and present Mean Global Temperature in pink). KS test identifying abrupt transitions towards warmer conditions in red and cooler or colder conditions in blue; B) Recurrence plot (RP) with identification of the main two clusters prior and after 34 Ma. The main abrupt transitions identified are highlighted by red circles, and C) Recurrence rate (RR). The pink crosses and vertical green lines indicate the abrupt transitions (TP) detected by the RQA. CENOGRID benthic  $\delta^{18}\text{O}$  data are from (22)

Fig. 2. **Variation through time of three main climate factors and comparison with the identified abrupt transitions (TP) in the CENOGRID benthic  $\delta^{18}\text{O}$ .** A) Global Mean Sea Level in meters from (54). Identification of particular warm and of glaciation events. The Laurentide, GIW-WAIS and Ice free lines are from (54); B) Carbonate Compensation Depth (CCD) in meters from (60). The purple circles identify the TPs on this record; C) Estimate of the  $\text{CO}_2$  concentration in parts per million volume (ppmv) from (61). The Antarctica glaciation threshold at 750 ppmv and the NH glaciation threshold at 280 ppmv lines respectively are from (62).

Fig. 3. **Probability density of the climate system in the projected CENOGRID benthic  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  space.** Panel a) Chronologically ordered  $\text{TP}_{\text{OS}}$  (diamonds) selected according to the KS methodology for  $\delta^{18}\text{O}$  with time window 1-4 My are shown. The two extra  $\text{TP}_{\text{OS}}$  found via RP are indicated with a \*. Panel b) Chronologically ordered fast  $\text{TP}_{\text{OS}}$  ( $\text{FTP}_{\text{OS}}$ , diamonds) selected according to the KS methodology for  $\delta^{18}\text{O}$  with time window 0.25-1 Myr are shown. Panel c) Same as a), but for the  $\delta^{13}\text{C}$  record. The approximate timing of the TPs is indicated (rounded to .01 My). The 5 Ky-long portions of trajectories before and after each TP are also plotted.

Fig. 4. **RQA of U1308 benthic  $\delta^{18}\text{O}$ .** A) Time series in Ma; B) RP; and C) RR. Crosses similar than Fig. S1.  $\text{TP}_{\text{O}9-10}$  and  $\text{RTP}_{\text{O}1-4}$  abrupt transitions identified in the RR. U1308 benthic  $\delta^{18}\text{O}$  data are from (23)

Fig. 5. **Evolution of the Earth Climate history among 2 different tipping landscapes and proposal for a potential third one.** The first landscape in light red, corresponds to the Hot-Warm House time interval. The second landscape in light blue corresponds to the Cold-Ice house time interval. The third landscape, in light green, corresponds to the potential new one represented

12 by the Anthropocene time interval. The different abrupt transitions identified in  
13 the present study are reported as TPo or RTPo to differentiate the major tipping  
14 points from the critical transitions characterizing transitions of lighter  
15 significance in the climate history. Various plate tectonic and ice sheet events  
16 are indicated and supported by maps of plate movements and North and South  
17 Hemisphere ice sheets. The Antarctica maps are from (86), Northern  
18 Hemisphere ice sheet maps are from (87). The paleogeographic maps have  
19 been generated using the Ocean Drilling Stratigraphic Network (ODSN) plate  
20 tectonic reconstruction service:  
21 <<https://www.odsn.de/odsn/services/paleomap/paleomap.html>>. The red  
22 arrows on the tectonic maps indicate the key events at the identified abrupt  
23 transition.

## 24 **SUPPLEMENTARY MATERIALS**

25 Please use the *Science Advances* [template](#) to format your Supplementary Materials.  
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**Supplementary Text****Comparison between GMSL, CCD and CO<sub>2</sub> concentration from CENOGRID (past 66 Myr)**

The interval between 66 Ma and 63 Ma (TP<sub>0</sub>1) shows a relative stable GMSL above +60m. It is followed by a lowering corresponding to a decreasing trend of about 70m in several steps between TP<sub>0</sub>1 at 63 Ma and TP<sub>0</sub>3 at 56 Ma, punctuated by an abrupt increase of 52m, at TP<sub>0</sub>2 around 58 Ma, and another of 28m corresponding to the short but intense Paleocene-Eocene Thermal Maximum (PETM – Fig. 3a) warming. GMSL raises between TP<sub>0</sub>2 at 58 Ma and 55 Ma by about +40m. The interval between 55 Ma and 48 Ma, the Early Eocene climatic optimum (EEOC – Fig. 2A), indicates a relatively high GMSL of about 66 m above the present mean sea level, which is associated with the occurrence of hyperthermal conditions at 58 Ma, 57 Ma, 53 Ma. Between 52 Ma and TP<sub>0</sub>4 at about 47 Ma, CCD reaches the shallowest depth of the record, about 3000m, (60) associated with the highest CO<sub>2</sub> concentrations estimated above 1100 ppmv by Ref (61) – Fig. 2B,C). A strong decrease in GMSL of about 30m occurs between 48 Ma and 46 Ma while it remains relatively stable at about +42m between 46 Ma and TP<sub>0</sub>5, at 40 Ma. It is however punctuated by two short events, first a lowering of about 25m between 42 Ma and 40.5 Ma, and strong increase of about 40m between 40.5 Ma and 40 Ma (TP<sub>0</sub>5) corresponding to the Middle Eocene Climatic optimum (MECO – Fig. 3A). A two-step lowering of about 35m of the GMSL occurs between 40 Ma (TP<sub>0</sub>5) and 36 Ma, followed by a gradual increase of about 25m between 36 Ma and 34.5 Ma just before the Eocene-Oligocene Transition (EOT – Fig. 3A). Between 46 Ma and 34 Ma (TP<sub>0</sub>6), the CCD is strongly oscillating with numerous deepening events of 500 to 1000 m magnitude and shoaling ones, corresponding to carbonate accumulation episodes. These oscillations in the CCD occurred during an interval indicating still high CO<sub>2</sub> concentrations, roughly above the 750 ppmv considered as an Antarctic glaciation threshold (62), and marked by a relative minimum at about TP<sub>0</sub>5 at 40 Ma (Fig. 3B,C). This first interval of the GMSL, ending by the strong deepening of about 1000m associated with a strong decrease in CO<sub>2</sub> concentration, determines variations of a rather completely ice free Earth, at least with no major ice sheet either in southern and northern hemisphere. This is deduced first from the high GMSL, mainly above 12m (Fig. 2A), which would correspond to the mutual contribution of the Greenland and the West Antarctic ice sheets, and second from high

64 CO<sub>2</sub> concentrations estimates in agreement with a CCD generally lower than 4000  
65 m (Fig 2B,C).

66 The second main interval shows a completely different scenario with the GMSL  
67 varying between +30m and -80m without considering the late Quaternary interval,  
68 and much lower CCD and CO<sub>2</sub> concentration (Fig. 2B,C). First the strong decrease  
69 in the GMSL at EOT reaches negative values of about -25m at about 33.5Ma. It is  
70 interpreted as the evidence of the first continental scale Antarctic ice sheet (first  
71 Oligocene isotope maximum - Oi1 – Fig. 2A) (96). After a return to values similar to  
72 present mean sea level, about +2m, between 32 Ma and 30 Ma, a new decreases of  
73 about 25m in GMSL is occurring between 29.5 Ma and 27 Ma corresponding to  
74 another continental scale Antarctic ice sheet extent labeled Oi2 (Fig. 2A). After a  
75 two-step increase in GMSL of about 40m between 27 Ma and 24 Ma, a new sharp  
76 decrease of about 40m is noticed at about 23 Ma. It corresponds to the Middle  
77 Oligocene Maximum (Mi1 – Fig. 2A), another Antarctic ice sheet wide expansion  
78 (96, 97). From TP<sub>06</sub>, at 34 Ma, and 23 Ma, the CO<sub>2</sub> concentration decreases  
79 associated with a deepening trend in the CCD down to about -4600m. From 23 Ma  
80 until about 19 Ma, GMSL shows oscillations but with lower values than present  
81 day at about -20m, whereas from 19 Ma until 17 Ma, GMSL increases by about  
82 50m to indicate high values around +30 m above present day value (Fig. 2A). The  
83 CCD indicates about 600 m shoaling which lasted around 2.5 Myr linked to some  
84 high estimates of CO<sub>2</sub> concentration (from paleosols, stomata) (61) (Fig. 2B,C). This  
85 strong increase corresponds to the Miocene Climatic optimum (MCO – Fig. 2A),  
86 between 17 Ma and TP<sub>07</sub> at 13.9 Ma, which is the last interval during which  
87 GMSL reaches such high values (higher than +20m) above the present day ones (Fig.  
88 2). The interval between TP<sub>07</sub> at 13.9 Ma and 13 Ma corresponds to the Middle  
89 Miocene transition during which GMSL decreases once more significantly by about  
90 35m. Such lowering is associated with the growth of the East Antarctic ice sheet to  
91 near its present state, remaining a perennial ice body that is thereafter impacting the  
92 Earth climate (86, 98). Although GMSL remains relatively stable between 13 Ma and  
93 12 Ma, another strong decrease, again of about 30m, occurs between TP<sub>08</sub> at about  
94 9 Ma and 8.5 Ma, associated with the strongest deepening recorded by the CCD,  
95 around 4800m. GMSL increases again by about 20m until 7.5 Ma to remain  
96 relatively stable until 5.5 Ma when GMSL increases by about 20m between 5.5 Ma  
97 and 3.5 Ma, corresponding to the Pliocene Climatic Optimum (PCO – Fig. 2A).

99 Between 3.5 Ma until TP<sub>0</sub>9 at about 2.7 Ma GMSL shows a sharp decreasing  
100 trend of about 35m (Mi2a, 3, 4 – Fig. 2A) with the initiation of the development of  
101 the large northern ice sheets between 2.9 Ma (TP<sub>0</sub>9a) and 2.5 Ma (TP<sub>0</sub>9b – Fig. 2),  
102 especially the Laurentide ice sheet corresponding to about 50m decrease of GMSL  
103 with regards to the present day value (Fig. 2A). From TP<sub>0</sub>8 at about 9 onward, CCD  
104 shows fluctuations although remaining at around 4500m with two strong deepening at  
105 about TP<sub>0</sub>9a 2.9 Ma and TP<sub>0</sub>9b (Fig. 2) at 2.5 Ma.

106  
107 In another global sea level reconstruction, (99) individualized several major  
108 thresholds that agree with Miller et al (2020) reconstruction and our present  
109 analysis. Indeed they estimate the EOT global sea level drop at 34 Ma (TP<sub>0</sub>6) as  
110 being of about between 30m, while previously reconstructed of 70m-80m by (100),  
111 and by (54). They also estimate this drop in global sea level being associated to a  
112 2.5°C cooling interpreted previously as above the onset of the Antarctic ice sheet  
113 glaciation. (99) also identify 14 Ma (TP<sub>0</sub>7) threshold as the end of the last  
114 intermittently ice free period of the Earth history of the last 40 Ma with only  
115 southern hemisphere ice sheets impacting the Earth climate. Ref. (54) indicates a 35m  
116 lowering at that particular transition. Indeed Ref. (99) indicate a slight sea level  
117 negative shift at about 10 Ma (TP<sub>0</sub>8), of about 10m for (54), as the onset of partial  
118 or ephemeral northern Hemisphere ice bodies with 2 other sea level threshold at  
119 about 3 (about TP<sub>0</sub>9a) and 2.75 (TP<sub>0</sub>9b), also observed in Miller et al. (54). These  
120 two key dates correspond to respectively the first major iceberg calving in the  
121 Nordic Seas (101) and from the Laurentide ice sheet (102) although this  
122 interpretation was rejected by (103) reviewing N Atlantic ice rafted records, and  
123 rather attributing the IRD signature to Greenland and Fennoscandian glaciers. (23)  
124 identified the first occurrence of iceberg calving in North Atlantic at about 2.75  
125 from the analysis of the  $\delta^{18}\text{O}$  of benthic bulk carbonate in core U1308 (Supp. Fig.  
126 3), a date identified as an abrupt transition in the RR analysis of both  $\delta^{18}\text{O}$  of  
127 benthic foram and bulk carbonate (79). All along the past 66 Ma, GMSL has been  
128 varying between average values of  $+38. \text{ m} \pm 15 \text{ m}$  above the present day value  
129 during the hot world interval prior TP<sub>0</sub>6 at 34 Ma, and of  $-3.5\text{m} \pm 13 \text{ m}$  after 34 Ma  
130 until present day during the cold world interval (Tab. 2).

### 31 The past 3.3 Myr.

32

33 We provide here a more detailed discussion of the past 3.3 Myr. The first date, TP<sub>0</sub>9b  
34 detected by RQA, is interpreted as corresponding to the earliest occurrence of IRD  
35 in the North Atlantic. This occurrence characterizes the presence of Northern  
36 Hemisphere coastal glaciers large enough to calve icebergs in the ocean, and the  
37 melting of these icebergs is likely to have impacted the oceanic circulation. (103),  
38 however, reported the occurrence of weak IRD events in the late Pliocene that they  
39 attributed mainly to Greenland and Fennoscandian glaciers. Such interpretation  
40 points to nevertheless smaller ice sheets over these regions than during the later  
41 Quaternary, when North American ice sheets were considerably larger. The interval  
42 TP<sub>0</sub>9a, at 2.8 Ma, to RTP<sub>0</sub>2, at 1.2 Ma, shows glacial–interglacial sea level  
43 variations of about 25–50 m below the present day. The CO<sub>2</sub> concentrations varied  
44 between 270 ppmv and 280 ppmv during interglacials and between 210 ppmv and  
45 240 ppmv during glacials, with a decreasing trend of about 23 ppmv over this 1.4-  
46 Myr–long interval (104).

47  
48 The second date, RTP<sub>0</sub>1, at 1.55 Ma, corresponds to increased amplitude in ice volume  
49 variations between glacial minima and interglacial optima. This second step shows  
50 the permanent occurrence of ice-rafted events during glacial intervals in the record  
51 (Suppl. Fig. 3), therefore an amplified relationship of climate variations with  
52 Northern Hemisphere ice sheets. The increase in IRD variability and magnitude since  
53 RTP<sub>0</sub>1, however, shows that distinct, faster processes have to be considered than  
54 those due to slow changes in Earth’s orbital parameters; see again Fig. 4.

55  
56 The third date, RTP<sub>0</sub>2, at 1.25 Ma, close to the MIS22–24  $\delta^{18}\text{O}$  optima, shows  
57 increased continental ice volume in the Northern Hemisphere (87), but also more  
58 stability in the East Antarctic ice sheet in Southern Hemisphere (105). In parallel,  
59 evidence of a major glacial pulse recorded in Italy’s Po Plain, as well as in <sup>10</sup>Be-  
60 dated boulders in Switzerland, is interpreted as marking the onset of the first major  
61 glaciation in the Alps (106, 107).

62 After RTP<sub>0</sub>2, at 1.25 Ma, the sea level changes decreased to about 70–120 m below  
63 the present day, while the CO<sub>2</sub> concentrations varied between 250 ppmv and 320  
64 ppmv during interglacials and between 170 ppmv and 210 ppmv during glacials  
65 (108). Similar variations were determined by (109), although pCO<sub>2</sub> changes that  
66 occurred before the time reached by ice core records are associated with high  
67 uncertainties in both dating and values. The sawtooth pattern of the interglacial–



68 glacial cycles (*110*) becomes noticeable at 0.9 Ma. At about the same time, the  
69 synthetic Greenland  $\delta^{18}\text{O}$  reconstruction indicates the occurrence of millennial  
70 variability expressed by DO-like events (*111*).

71 Finally RTP<sub>o3</sub>, at 0.65 Ma, marks the end of the transition from the Lower and  
72 Mid-Pleistocene interval —characterized by 41-Kyr–dominated cycles and smaller  
73 23-Kyr ones — to the Upper Pleistocene, with its 100-Kyr–dominated cycles; see  
74 Fig. 4. The sawtooth pattern of the interglacial–glacial cycles is well established  
75 during this final interval, in contradistinction with the previous, more smoothly shaped  
76 pattern that appears to follow the obliquity variations. The global ice volume is  
77 maximal, exceeding the values observed earlier in the record, especially due to the  
78 larger contribution of the Northern American ice sheets. The latter now have a  
79 bigger impact on Northern Hemisphere climate than the Eurasian ice sheets (*87*).  
80 The IRD event intensity and frequency of occurrence increase (*112*) as well (Suppl.  
81 Fig. 3), leading to the major iceberg discharges into the North Atlantic named  
82 Heinrich events (HEs); see (*113–116*),. The interval of 1 Ma – about 0.4 Ma  
83 (RTP<sub>o4</sub>) is also the interval during which Northern Hemisphere ice sheets reached  
84 their southernmost extent (*87*). Applying Mg/Ca transfer functions, (*77*) have  
85 estimated that the past 0.4 Myr water temperatures have been the highest the past  
86 1.2 Myr, supporting the local temperature variations deduced from the Antarctic ice  
87 cores (*117*)  
88