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Denis-Didier Rousseau, Witold Bagniewski, Valerio Lucarini. A Punctuated Equilibrium Analysis of the Climate Evolution of Cenozoic: Hierarchy of Abrupt Transitions. 2022. hal-03713538v3

HAL Id: hal-03713538

<https://hal.science/hal-03713538v3>

Preprint submitted on 7 Nov 2022 (v3), last revised 8 Jan 2024 (v4)

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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 CO₂ concentration, average
86 global sea level, and depth of the carbonate compensation.

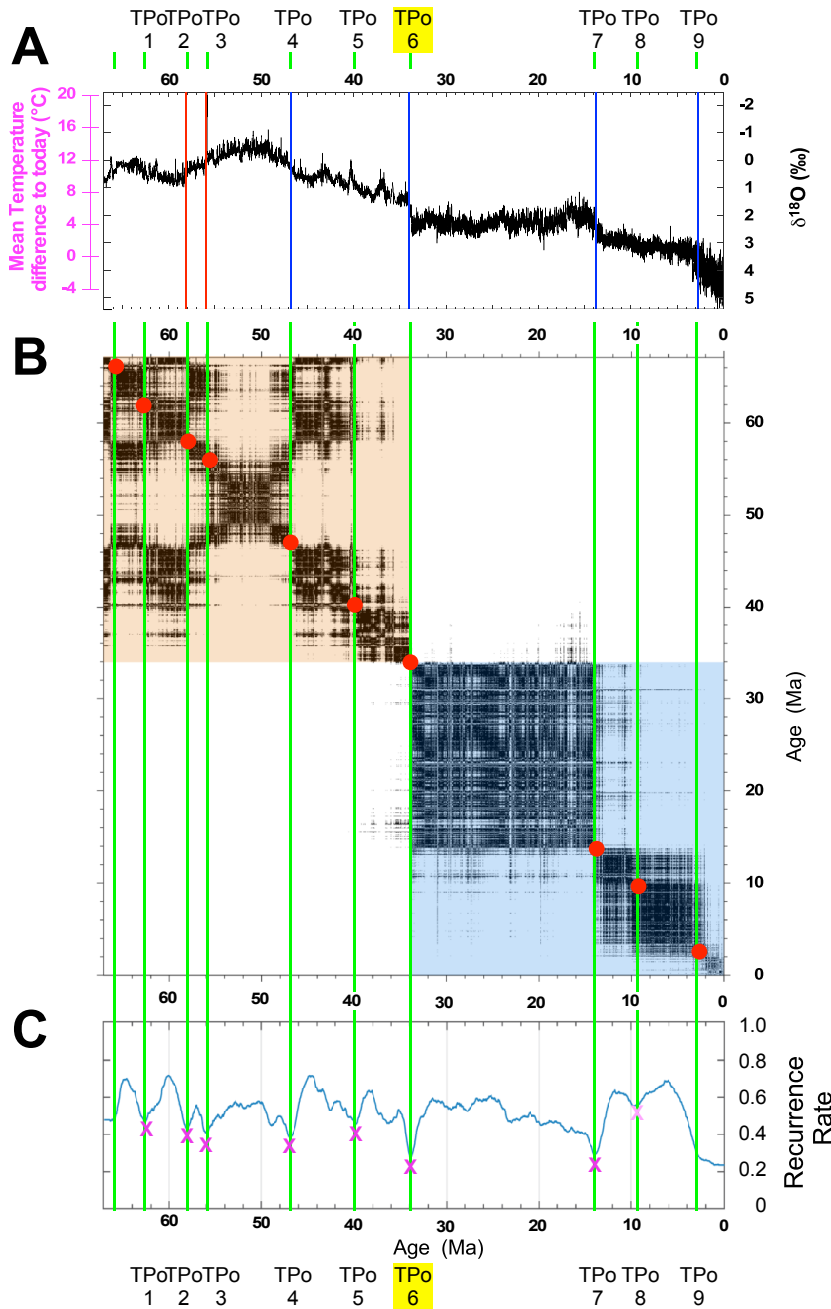
87 The existence of TPs is intimately related to the multistability properties of the climate
88 system, which have long been recognised in different contexts; see e.g. (25–28) and
89 discussion in (29) and (30). The multistability of the climate system is associated with
90 the presence of more than 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 TP₀1 to TP₀9, where the lower index refers to the used
 21 proxy data. As shown in Fig 1B, TP₀5 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 (TP₀) detected by the RQA. CENOGRID benthic $\delta^{18}\text{O}$ data are from (22)

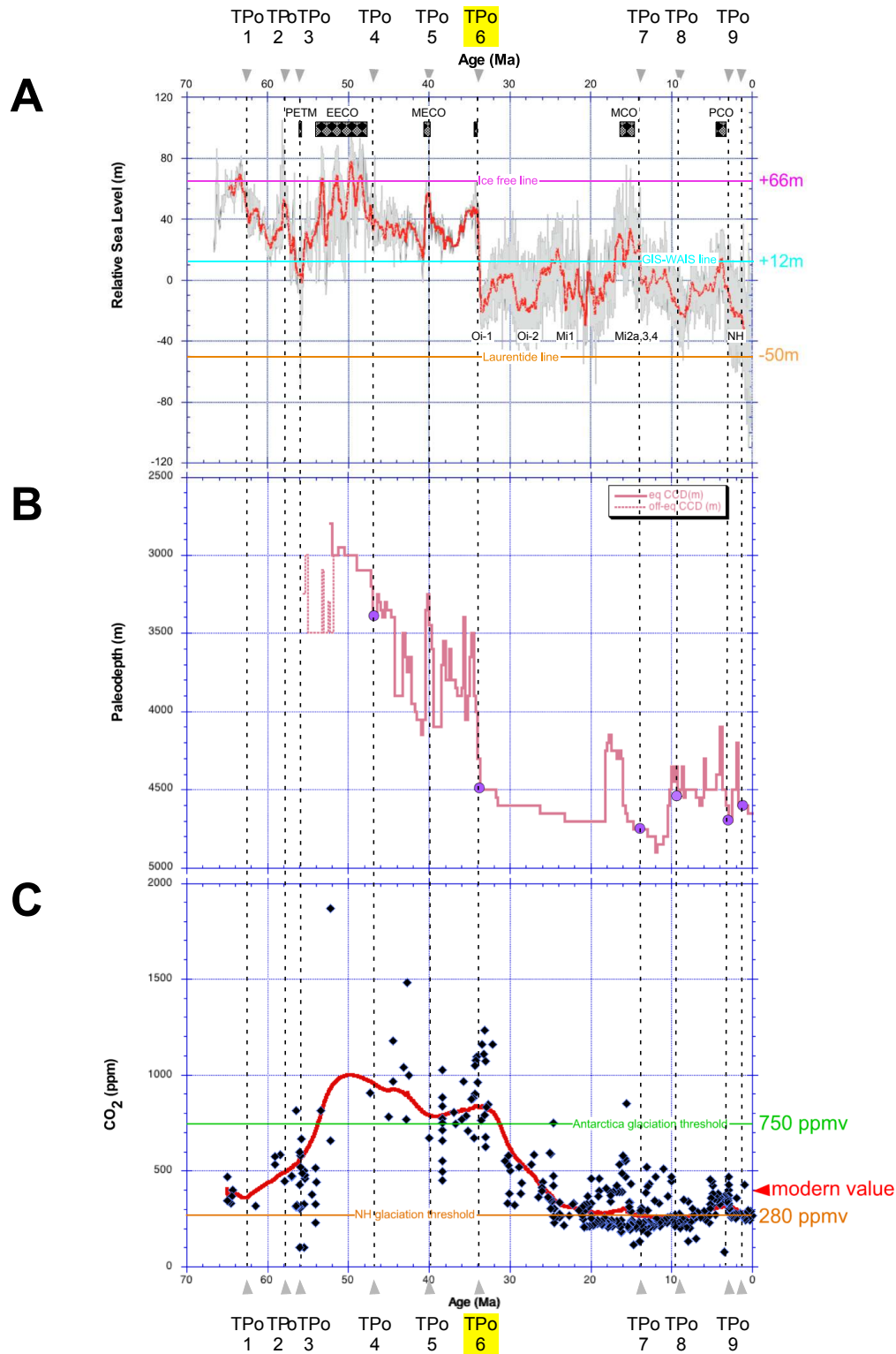
32
33 The older macrocluster shows a disrupted variability, according to Marvan et al.'s
34 nomenclature (49). One finds very large negative values of the benthic $\delta^{18}\text{O}$, which
35 correspond to the very warm climate conditions. The average global temperature was
36 estimated to be between 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_{O2})
39 and 56 Ma (TP_{O3}). 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_{O3}) 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_{O4}) inaugurates the period of continuous cooling due to decrease of
45 CO₂ concentration that eventually leads to the TP_{O6} event (57), which leads to the build-
46 up of the Antarctica ice sheets. TP_{O5} 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_{O6}, the climate featured mostly stationary conditions with a slight
50 warming until the Middle Miocene Climate Transition (TP_{O7}) that occurred around 14
51 Ma (58, 59). The last major transition (TP_{O9}) 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_C 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_O 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 CO₂ 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 CO₂
80 concentration. One clearly observes the signature of the TP_O6 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_O6 signals the start of the progressive decrease of the
83 CO₂ 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 CO₂ 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-TP₀₁ and TP₀₃- TP₀₅)
 93 and "Hothouse" (TP₀₁-TP₀₃) climates in the earlier, warmer period, followed by the
 94 "Coolhouse" (TP₀₅-TP₀₆) and "Icehouse" climates (TP₀₆ to present); see Fig. 1.

95 The first two states alternated in a warm-hot-warm sequence under extremely high CO₂
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 CO₂ concentration whose average values are: +38 ±
00 15 m, 4600 ± 150 m, and 630 ± 300 ppmv respectively (Suppl. Tab. 2). Note that the
01 CO₂ 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 CO₂ 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, CO₂ 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 CO₂ reconstructions show key transitions that fit with the
11 CENOGRID thresholds deduced from the KS and RR analysis of the benthic δ¹⁸O 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 CO₂. The variations observed in CO₂, CCD and GMSL at
15 the 9 identified TPs from the benthic δ¹⁸O 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_{O6}, 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 CO₂ 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 CO₂ (8). CO₂ concentration continued raising until about 500 ppmv with the
26 North Atlantic Igneous province very active at about 58 Ma – 56 Ma (TP_{O2} and TP_{O3})
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

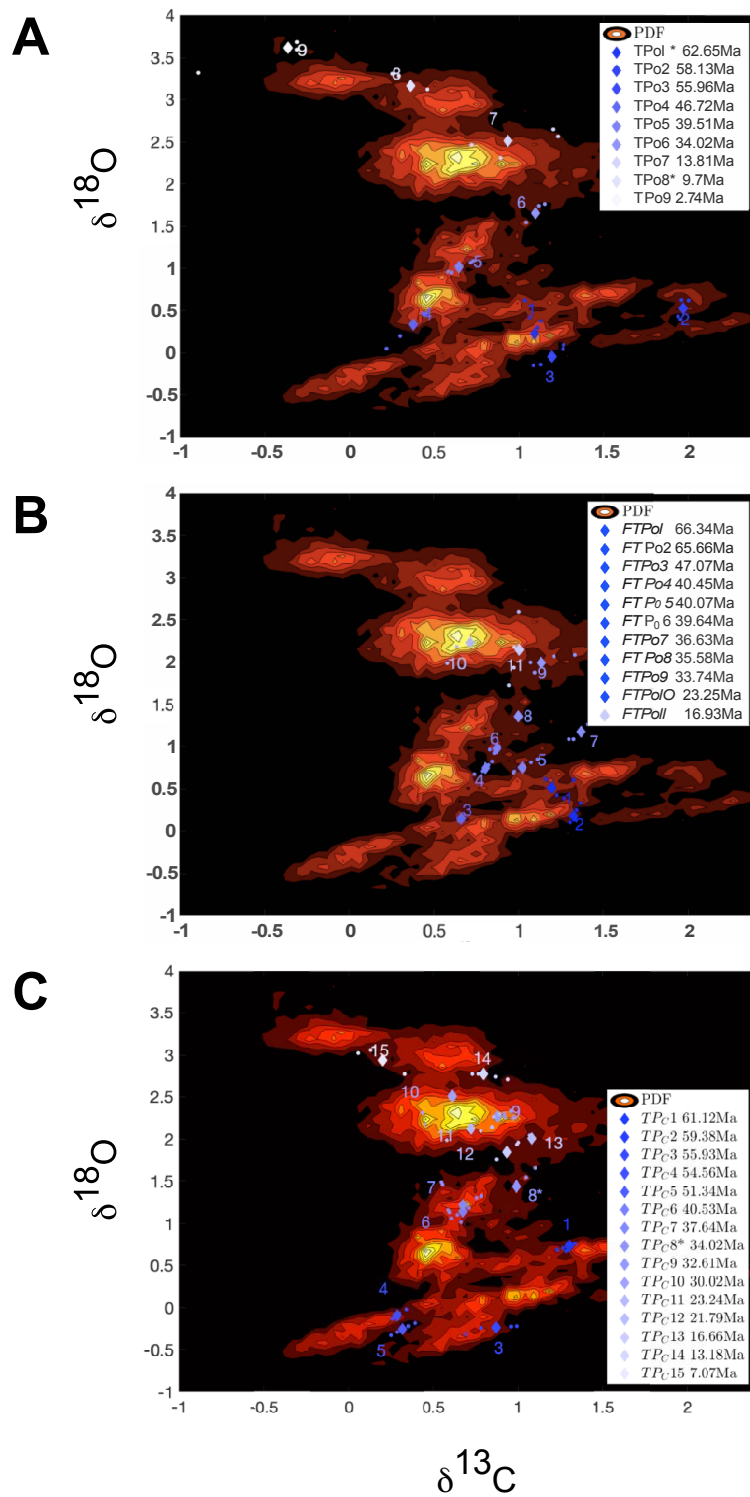
31 depth (CCD) reached a minimum value a bit later at about 54 Ma when CO₂
32 concentration reached its maximum of the whole Cenozoic above 1,100 ppmv (61). The
33 lowering of the GMSL and of the CCD at TP_O4 (about 40 Myr) has been interpreted as
34 the start of the icing of Antarctica through mountain 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_O4 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_O6) 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 CO₂, 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 CO₂ 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_O 6 and TP_O 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 CO₂ concentration (Fig. 2). Such high CO₂ concentrations may have
60 been fueled by the Columbia River major volcanism, which ended by TP_O 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_O8 at

67 about 9 Ma sees a strong lowering of the GMSL and of the CO₂ concentrations (Fig. 2).
68 TP_O9 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 CO₂ 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_O 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_Os 1, 2, 4, 5, 6, 8, 9, whereas no agreement is found for TP_Os 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_O6, 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_Os (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_Os found via RP
 07 are indicated with a *. Panel b) Chronologically ordered fast TP_Os (FTP_Os, 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_{OS} (FTP_{OS}) 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_{CS}. Figure 3C shows clearly that the TP_{CS} correspond for the most to saddles that had not been flagged by the TP_{OS}. 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_C s 4 & 5; TP_{CS} 6 & 7; TP_{CS} 12 & 13), which supports the dynamical interpretation discussed here. Comparing Figs 3A and 3C, one discovers that the same saddle is responsible for TP_O8 and for TP_C15 even if the dating is different. Similarly, the same saddle is responsible for TP_O5 and TP_{CS} 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_O6 and TP_C8.

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_{O9} 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_{O8}) and are
58 followed by four more recent TPs associated with the benthic $\delta^{18}\text{O}$ record (RTP_{O8}).
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.

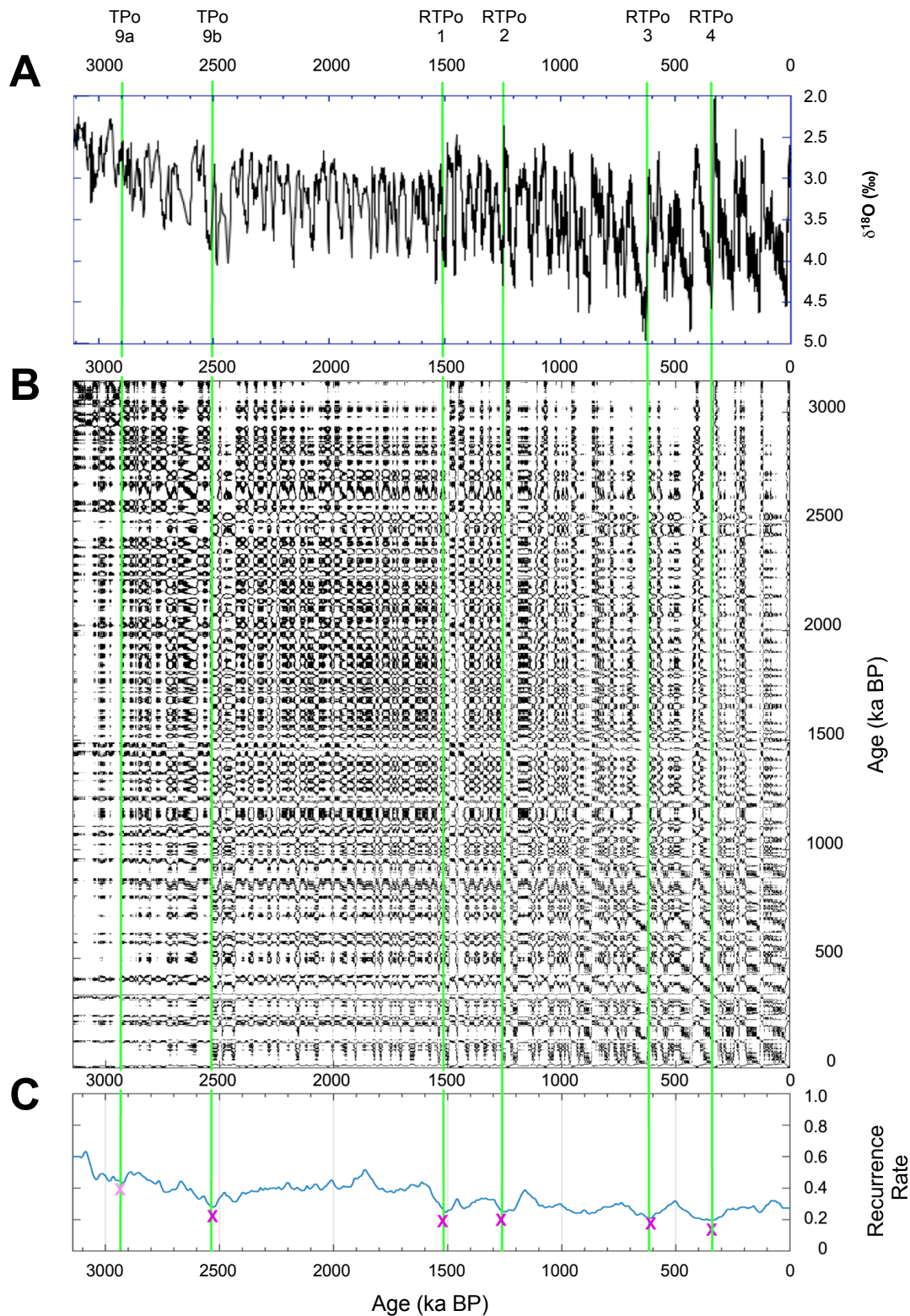


Fig. 4. **RQA of U1308 benthic $\delta^{18}\text{O}$.** A) Time series in Ma; B) RP; and C) RR. Crosses similar than Fig. S1. TP_O9 and RTP_O1-4 abrupt transitions identified in the RR. U1308 benthic $\delta^{18}\text{O}$ data are from (23)

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 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 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 TP_{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.

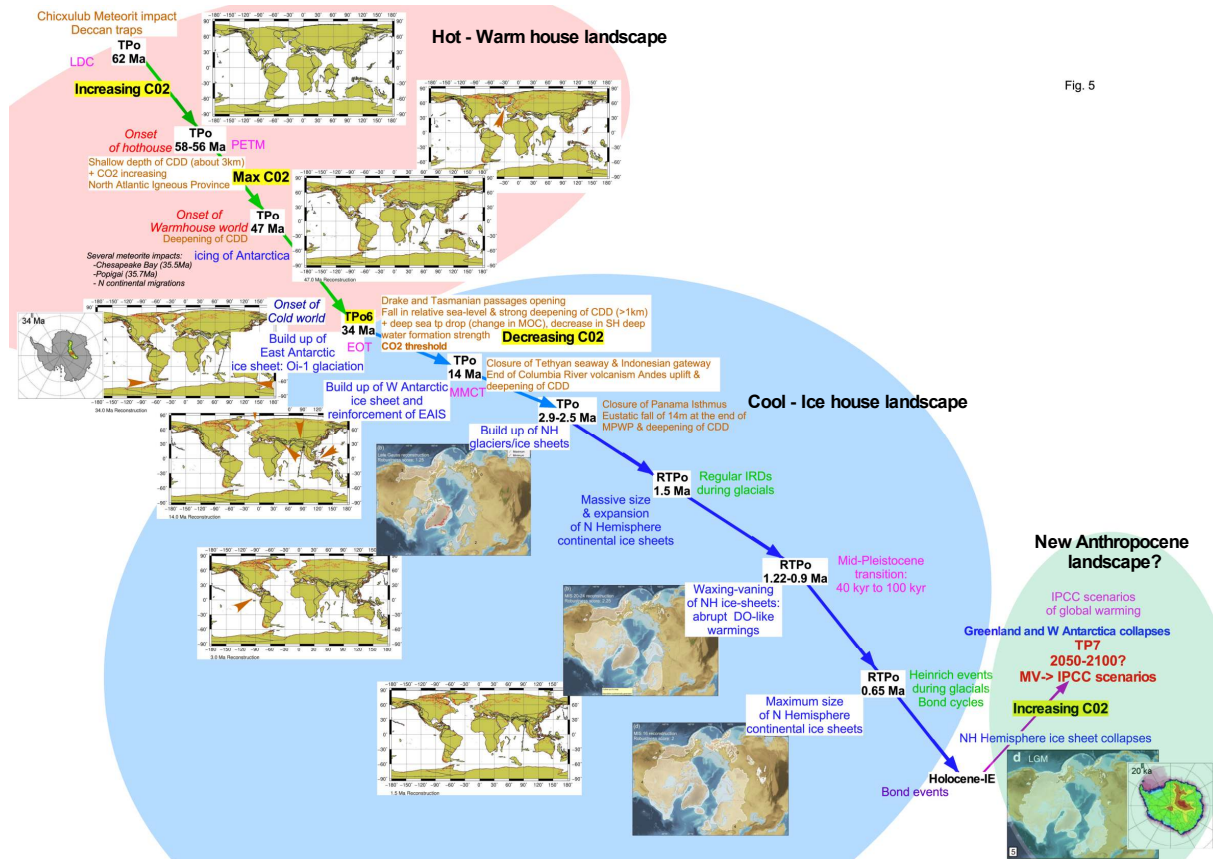


Fig. 5

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.

22 REFERENCES

- 24 1. W. Dansgaard, S. J. Johnsen, J. Moller, C. C. Langway, One thousand centuries of
25 climatic record from Camp Century on the Greenland ice sheet. *Science*. **166**, 377–381
26 (1969).
- 27 2. W. Dansgaard, H. B. Clausen, N. Gundestrup, C. U. J. Hammer, S. F. Johnsen, P. M.
28 Kristinsdottir, N. Reeh, A new Greenland deep ice core. *Science*. **218**, 1273–1277
29 (1982).
- 30 3. W. Broecker, Climatic Change - Are we on the brink of a pronounced global warming.
31 *Science*. **189**, 460–463 (1975).
- 32 4. W. S. Broecker, M. Andree, G. Bonani, W. Wolfi, H. Oeschger, M. Klas, Can the
33 Greenland climatic jumps be identified in records from ocean and land? *Quat. Res.* **30**,
34 1–6 (1988).
- 35 5. W. S. Broecker, G. Denton, The role of ocean-atmosphere reorganizations in glacial
36 cycles. *Geochim Cosmochim Acta*. **53**, 2465–2501 (1989).
- 37 6. S. O. Rasmussen, M. Bigler, S. P. Blockley, T. Blunier, S. L. Bucharadt, H. B. Clausen, I.
38 Cvijanovic, D. Dahl-Jensen, S. J. Johnsen, H. Fischer, V. Gkinis, M. Guillevic, W. Z.
39 Hoek, J. J. Lowe, J. B. Pedro, T. Popp, I. K. Seierstad, J. P. Steffensen, A. M. Svensson,
40 P. Vallengona, B. M. Vinther, M. J. C. Walker, J. J. Wheatley, M. Winstrup, A
41 stratigraphic framework for abrupt climatic changes during the Last Glacial period based
42 on three synchronized Greenland ice-core records: refining and extending the
43 INTIMATE event stratigraphy. *Quat. Sci. Rev.* **106**, 14–28 (2014).
- 44 7. P. F. Hoffman, D. S. Abbot, Y. Ashkenazy, D. I. Benn, J. J. Brocks, P. A. Cohen, G. M.
45 Cox, J. R. Creveling, Y. Donnadieu, D. H. Erwin, I. J. Fairchild, D. Ferreira, J. C.
46 Goodman, G. P. Halverson, M. F. Jansen, G. Le Hir, G. D. Love, F. A. Macdonald, A.
47 C. Maloof, C. A. Partin, G. Ramstein, B. E. J. Rose, C. V. Rose, P. M. Sadler, E.
48 Tziperman, A. Voigt, S. G. Warren, Snowball Earth climate dynamics and Cryogenian
49 geology-geobiology. *Sci. Adv.* **3** (2017), doi:10.1126/sciadv.1600983.
- 50 8. C. R. Scotese, H. Song, B. J. W. Mills, D. G. van der Meer, Phanerozoic
51 paleotemperatures: The earth's changing climate during the last 540 million years.
52 *Earth-Sci. Rev.* **215** (2021), doi:10.1016/j.earscirev.2021.103503.
- 53 9. M. Grodzins, Metropolitan segregation. *Sci. Am.* **197**, 33- (1957).
- 54 10. M. Gladwell, *The Tipping Point: How Little Things Can Make a Big Difference* (Back
55 Bay Books, Boston, New York, London, 2002).
- 56 11. T. Lenton, H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf, H. Schellnhuber,
57 Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. U. S. A.* **105**,
58 1786–1793 (2008).
- 59 12. T. Lenton, "Environmental Tipping Points" in *Annual review of Environment and*
60 *Resources*, A. Gadgil, D. Liverman, Eds. (2013), vol. 38, pp. 1–29.
- 61 13. T. Lenton, J. Rockstrom, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, H.
62 Schellnhuber, Climate tipping points - too risky to bet against. *Nature*. **575**, 592–595
63 (2019).

- 64 14. V. Brovkin, E. Brook, J. Williams, S. Bathiany, T. Lenton, M. Barton, R. DeConto, J.
65 Donges, A. Ganopolski, J. McManus, S. Praetorius, A. de Vernal, A. Abe-Ouchi, H.
66 Cheng, M. Claussen, M. Crucifix, G. Gallopin, V. Iglesias, D. Kaufman, T. Kleinen, F.
67 Lambert, S. van der Leeuw, H. Liddy, M. Loutre, D. McGee, K. Rehfeld, R. Rhodes, A.
68 Seddon, M. Trauth, L. Vanderveken, Z. Yu, Past abrupt changes, tipping points and
69 cascading impacts in the Earth system. *Nat. Geosci.* **14**, 550–558 (2021).
- 70 15. T. Lenton, H. Williams, On the origin of planetary-scale tipping points. *Trends Ecol.*
71 *Evol.* **28**, 380–382 (2013).
- 72 16. W. Steffen, J. Rockstrom, K. Richardson, T. Lenton, C. Folke, D. Liverman, C.
73 Summerhayes, A. Barnosky, S. Cornell, M. Crucifix, J. Donges, I. Fetzer, S. Lade, M.
74 Scheffer, R. Winkelmann, H. Schellnhuber, Trajectories of the Earth System in the
75 Anthropocene. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 8252–8259 (2018).
- 76 17. E. Kriegler, J. Hall, H. Held, R. Dawson, H. Schellnhuber, Imprecise probability
77 assessment of tipping points in the climate system. *Proc. Natl. Acad. Sci. U. S. A.* **106**,
78 5041–5046 (2009).
- 79 18. N. Wunderling, J. Donges, J. Kurths, R. Winkelmann, Interacting tipping elements
80 increase risk of climate domino effects under global warming. *Earth Syst. Dyn.* **12**, 601–
81 619 (2021).
- 82 19. N. Boers, Observation-based early-warning signals for a collapse of the Atlantic
83 Meridional Overturning Circulation (vol 11, pg 680, 2021). *Nat. Clim. Change.* **11**,
84 1001–1001 (2021).
- 85 20. I. Otto, J. Donges, R. Cremades, A. Bhowmik, R. Hewitte, W. Lucht, J. Rockstrom, F.
86 Allerberger, M. McCaffrey, S. Doe, A. Lenferna, N. Moran, D. van Vuuren, H.
87 Schellnhuber, Social tipping dynamics for stabilizing Earth’s climate by 2050. *Proc.*
88 *Natl. Acad. Sci. U. S. A.* **117**, 2354–2365 (2020).
- 89 21. T. Lenton, S. Benson, T. Smith, T. Ewer, V. Lanel, E. Petykowski, T. Powell, J.
90 Abrams, F. Blomsma, S. Sharpe, Operationalising positive tipping points towards global
91 sustainability. *Glob. Sustain.* **5** (2022), doi:10.1017/sus.2021.30.
- 92 22. T. Westerhold, N. Marwan, A. J. Drury, D. Liebrand, C. Agnini, E. Anagnostou, J. S. K.
93 Barnet, S. M. Bohaty, D. De Vleeschouwer, F. Florindo, T. Frederichs, D. A. Hodell, A.
94 E. Holbourn, D. Kroon, V. Laurentano, K. Littler, L. J. Lourens, M. Lyle, H. Palike, U.
95 Rohl, J. Tian, R. H. Wilkens, P. A. Wilson, J. C. Zachos, An astronomically dated
96 record of Earth’s climate and its predictability over the last 66 million years. *Science.*
97 **369**, 1383–+ (2020).
- 98 23. D. A. Hodell, J. E. T. Channell, Mode transitions in Northern Hemisphere glaciation:
99 co-evolution of millennial and orbital variability in Quaternary climate. *Clim. Past.* **12**,
00 1805–1828 (2016).
- 01 24. W. Bagniewski, M. Ghil, D. D. Rousseau, Automatic detection of abrupt transitions in
02 paleoclimate records. *Chaos.* **31** (2021), doi:10.1063/5.0062543.
- 03 25. H. Stommel, Thermohaline convection with 2 stable regimes of flow. *Tellus.* **13**, 224–
04 230 (1961).
- 05 26. W. D. Sellers, A Global Climatic Model Based on the Energy Balance of the Earth-
06 Atmosphere System. *J. Appl. Meteorol. Climatol.* **8**, 392–400 (1969).
- 07 27. M. Budyko, Effect of solar radiation variations on climate of earth. *Tellus.* **21**, 611-
08 (1969).
- 09 28. M. Ghil, Climate stability for a Sellers-type model. *J. Atmospheric Sci.* **33**, 3–20 (1976).
- 10 29. M. Ghil, A Century of Nonlinearity in the Geosciences. *Earth Space Sci.* **6**, 1007–1042
11 (2019).
- 12 30. M. Ghil, V. Lucarini, The physics of climate variability and climate change. *Rev. Mod.*
13 *Phys.* **92** (2020), doi:10.1103/RevModPhys.92.035002.
- 14 31. V. Lucarini, T. Bodai, Edge states in the climate system: exploring global instabilities
15 and critical transitions. *Nonlinearity.* **30**, R32–R66 (2017).
- 16 32. J. Lewis, A. Weaver, M. Eby, Snowball versus slushball Earth: Dynamic versus
17 nondynamic sea ice? *J. Geophys. Res.-Oceans.* **112** (2007), doi:10.1029/2006JC004037.

- 18 33. D. Abbot, A. Voigt, D. Koll, The Jormungand global climate state and implications for
19 Neoproterozoic glaciations. *J. Geophys. Res.-Atmospheres*. **116** (2011),
20 doi:10.1029/2011JD015927.
- 21 34. G. Margazoglou, T. Grafke, A. Laio, V. Lucarini, Dynamical landscape and
22 multistability of a climate model. *Proc. R. Soc. -Math. Phys. Eng. Sci.* **477** (2021),
23 doi:10.1098/rspa.2021.0019.
- 24 35. C. Ragon, V. Lembo, V. Lucarini, C. Verard, J. Kasparian, M. Brunetti, Robustness of
25 Competing Climatic States. *J. Clim.* **35**, 2769–2784 (2022).
- 26 36. V. Lucarini, T. Bodai, Transitions across Melancholia States in a Climate Model:
27 Reconciling the Deterministic and Stochastic Points of View. *Phys. Rev. Lett.* **122**
28 (2019), doi:10.1103/PhysRevLett.122.158701.
- 29 37. V. Lucarini, T. Bodai, Global stability properties of the climate: Melancholia states,
30 invariant measures, and phase transitions. *Nonlinearity*. **33**, R59–R92 (2020).
- 31 38. R. Graham, "Macroscopic potentials, bifurcations and noise in dissipative systems" in
32 *Fluctuations and stochastic phenomena in condensed matter* (Springer, 1987), pp. 1–34.
- 33 39. C. H. Waddington, Canalization of development and the inheritance of acquired
34 characters. *Nature*. **150**, 563–565 (1942).
- 35 40. C. H. Waddington, *The strategy of the genes* (Allen & Unwin, London, 1957).
- 36 41. A. D. Goldberg, C. D. Allis, E. Bernstein, Epigenetics: a landscape takes shape. *Cell*.
37 **128**, 635–638 (2007).
- 38 42. J. Baedke, The epigenetic landscape in the course of time: Conrad Hal Waddington's
39 methodological impact on the life sciences. *Stud. Hist. Philos. Sci. Part C Stud. Hist.*
40 *Philos. Biol. Biomed. Sci.* **44**, 756–773 (2013).
- 41 43. M. Allen, Compelled by the diagram: thinking through CH Waddington's epigenetic
42 landscape. *Contemporaneity*. **4**, 119 (2015).
- 43 44. N. Eldredge, S. J. Gould, "Punctuated Equilibria: An alternative to Phyletic Gradualism"
44 in *Models in Paleobiology*, T. J. M. Schopf, Ed. (Freeman Cooper, San Francisco,
45 1972), pp. 82–243.
- 46 45. S. J. Gould, N. Eldredge, Punctuated equilibria: the tempo and mode of evolution
47 reconsidered. *Paleobiology*. **3**, 115–151 (1977).
- 48 46. K. Christensen, S. de Collobiano, M. Hall, H. Jensen, Tangled nature: A model of
49 evolutionary ecology. *J. Theor. Biol.* **216**, 73–84 (2002).
- 50 47. H. J. Jensen, Tangled Nature: A model of emergent structure and temporal mode among
51 co-evolving agents. *Eur. J. Phys.* **40** (2019), doi:10.1088/1361-6404/aaee8f.
- 52 48. J. Zachos, M. Pagani, L. Sloan, E. Thomas, K. Billups, Trends, rhythms, and aberrations
53 in global climate 65 Ma to present. *Science*. **292**, 686–693 (2001).
- 54 49. N. Marwan, M. Carmen Romano, M. Thiel, J. Kurths, Recurrence plots for the analysis
55 of complex systems. *Phys. Rep.* **438**, 237–329 (2007).
- 56 50. J. Zachos, J. Breza, S. Wise, Early Oligocene ice-sheet expansion on Antractica - stable
57 isotope and sedimentological evidence from Kerguelen Plateau, Southern Indian-Ocean.
58 *Geology*. **20**, 569–573 (1992).
- 59 51. L. Ivany, W. Patterson, K. Lohmann, Cooler winters as a possible cause of mass
60 extinctions at the eocene/oligocene boundary. *Nature*. **407**, 887–890 (2000).
- 61 52. J. Sun, X. Ni, S. Bi, W. Wu, J. Ye, J. Meng, B. Windley, Synchronous turnover of flora,
62 fauna, and climate at the Eocene-Oligocene Boundary in Asia. *Sci. Rep.* **4** (2014),
63 doi:10.1038/srep07463.
- 64 53. E. Thomas, J. C. Zachos, T. J. Bralower, "Deep-sea environments on a warm earth:
65 latest Paleocene-early Eocene" in *Warm Climates in Earth History*, B. T. Huber, K. G.
66 Macleod, S. L. Wing, Eds. (Cambridge University Press, Cambridge, 1999;
67 [https://www.cambridge.org/core/books/warm-climates-in-earth-history/deepsea-
68 environments-on-a-warm-earth-latest-paleoceneearly-
69 eocene/5812213E2DDEB85D28B654244C4ECE86](https://www.cambridge.org/core/books/warm-climates-in-earth-history/deepsea-environments-on-a-warm-earth-latest-paleoceneearly-eocene/5812213E2DDEB85D28B654244C4ECE86)), pp. 132–160.
- 70 54. K. Miller, J. Browning, W. Schmelz, R. Kopp, G. Mountain, J. Wright, Cenozoic sea-
71 level and cryospheric evolution from deep-sea geochemical and continental margin

records. *Sci. Adv.* **6** (2020), doi:10.1126/sciadv.aaz1346.

55. J. Kennett, L. Stott, Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*. **353**, 225–229 (1991).
56. G. R. Dickens, M. M. Castillo, J. C. Walker, A blast of gas in the latest Paleocene: simulating first-order effects of massive dissociation of oceanic methane hydrate. *Geology*. **25** **3**, 259–62 (1997).
57. V. Lauretano, A. Kennedy-Asser, V. Korasidis, M. Wallace, P. Valdes, D. Lunt, R. Pancost, B. Naafs, Eocene to Oligocene terrestrial Southern Hemisphere cooling caused by declining pCO₂. *Nat. Geosci.* **14**, 659–+ (2021).
58. J. Kennett, N. Shackleton, Oxigen isotopic evidence for development of psychrosphere 38 Myr ago. *Nature*. **260**, 513–515 (1976).
59. N. J. Shackleton, "Oceanic Carbon Isotope Constraints on Oxygen and Carbon Dioxide in the Cenozoic Atmosphere" in *The Carbon Cycle and Atmospheric CO₂: Natural Variations Archean to Present* (American Geophysical Union (AGU), 1985; <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GM032p0412>), pp. 412–417.
60. H. Palike, M. Lyle, H. Nishi, I. Raffi, A. Ridgwell, K. Gamage, A. Klaus, G. Acton, L. Anderson, J. Backman, J. Baldauf, C. Beltran, S. Bohaty, P. Bown, W. Busch, J. Channell, C. Chun, M. Delaney, P. Dewangan, T. Dunkley Jones, K. Edgar, H. Evans, P. Fitch, G. Foster, N. Gussone, H. Hasegawa, E. Hathorne, H. Hayashi, J. Herrle, A. Holbourn, S. Hovan, K. Hyeong, K. Iijima, T. Ito, S. Kamikuri, K. Kimoto, J. Kuroda, L. Leon-Rodriguez, A. Malinverno, T. Moore, B. Murphy, D. Murphy, H. Nakamura, K. Ogane, C. Ohneiser, C. Richter, R. Robinson, E. Rohling, O. Romero, K. Sawada, H. Scher, L. Schneider, A. Sluijs, H. Takata, J. Tian, A. Tsujimoto, B. Wade, T. Westerhold, R. Wilkens, T. Williams, P. Wilson, Y. Yamamoto, S. Yamamoto, T. Yamazaki, R. Zeebe, A Cenozoic record of the equatorial Pacific carbonate compensation depth. *Nature*. **488**, 609–+ (2012).
61. D. Beerling, D. Royer, Convergent Cenozoic CO₂ history. *Nat. Geosci.* **4**, 418–420 (2011).
62. R. DeConto, D. Pollard, P. Wilson, H. Palike, C. Lear, M. Pagani, Thresholds for Cenozoic bipolar glaciation. *Nature*. **455**, 652–U52 (2008).
63. IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021), vol. In Press.
64. J. D. O’Keefe, T. J. Ahrens, Impact production of CO₂ by the Cretaceous/Tertiary extinction bolide and the resultant heating of the Earth. *Nature*. **338**, 247–249 (1989).
65. B. Lomax, D. Beerling, G. Upchurch, B. Otto-Bliesner, Rapid (10-yr) recovery of terrestrial productivity in a simulation study of the terminal Cretaceous impact event. *Earth Planet. Sci. Lett.* **192**, 137–144 (2001).
66. D. W. Jolley, B. R. Bell, "The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic, and Magmatic Processes" in (Geological Society of London, 2002).
67. K. Birkenmajer, A. Gaździcki, K. P. Krajewski, A. Przybycin, A. Solecki, A. Tatur, H. I. Yoon, First Cenozoic glaciers in west Antarctica. *Pol. Polar Res.*, 3-12-3–12 (2005).
68. K. Rose, F. Ferraccioli, S. Jamieson, R. Bell, H. Corr, T. Creyts, D. Braaten, T. Jordan, P. Fretwell, D. Damaske, Early East Antarctic Ice Sheet growth recorded in the landscape of the Gamburtsev Subglacial Mountains. *Earth Planet. Sci. Lett.* **375**, 1–12 (2013).
69. C. Janis, Tertiary mammal evolution in the context of changing climates, vegetation, and tectonic events. *Annu. Rev. Ecol. Syst.* **24**, 467–500 (1993).
70. T. H. Torsvik, L. R. M. Cocks, *Earth history and palaeogeography* (Cambridge University Press, 2016).
71. Y. Lagabrielle, Y. Godderis, Y. Donnadieu, J. Malavieille, M. Suarez, The tectonic history of Drake Passage and its possible impacts on global climate. *Earth Planet. Sci. Lett.* **279**, 197–211 (2009).

- 26 72. D. Rowley, B. Currie, Palaeo-altimetry of the late Eocene to Miocene Lunpola basin,
27 central Tibet. *Nature*. **439**, 677–681 (2006).
- 28 73. O. Bialik, M. Frank, C. Betzler, R. Zammit, N. Waldmann, Two-step closure of the
29 Miocene Indian Ocean Gateway to the Mediterranean. *Sci. Rep.* **9** (2019),
30 doi:10.1038/s41598-019-45308-7.
- 31 74. D. Lunt, P. Valdes, A. Haywood, I. Rutt, Closure of the Panama Seaway during the
32 Pliocene: implications for climate and Northern Hemisphere glaciation. *Clim. Dyn.* **30**,
33 1–18 (2008).
- 34 75. J. Chappell, N. J. Shackleton, Oxygen isotopes and sea-level. *Nature*. **324**, 137–140
35 (1986).
- 36 76. N. J. Shackleton, The 100,000-year ice-age cycle identified and found to lag
37 temperature, carbon dioxide, and orbital eccentricity. *Science*. **289**, 1897–1902 (2000).
- 38 77. H. Elderfield, P. Ferretti, M. Greaves, S. Crowhurst, I. N. McCave, D. Hodell, A. M.
39 Piotrowski, Evolution of Ocean Temperature and Ice Volume Through the Mid-
40 Pleistocene Climate Transition. *Science*. **337**, 704–709 (2012).
- 41 78. S. K. Turner, Pliocene switch in orbital-scale carbon cycle/climate dynamics.
42 *Paleoceanography*. **29**, 1256–1266 (2014).
- 43 79. D. Rousseau, W. Bagniewski, M. Ghil, Abrupt climate changes and the astronomical
44 theory: are they related? *Clim. Past*. **18**, 249–271 (2022).
- 45 80. N. J. Shackleton, N. D. Opdyke, Oxygen isotope and palaeomagnetic evidence for early
46 Northern Hemisphere glaciation. *Nature*. **270**, 216–223 (1977).
- 47 81. N. G. Pisias, T. C. Moore, The evolution of Pleistocene climate: A time-series approach.
48 *Earth Planet. Sci. Lett.* **52**, 450–458 (1981).
- 49 82. W. F. Ruddiman, M. Raymo, D. G. Martinson, B. M. Clement, J. Backman, Pleistocene
50 evolution: Northern Hemisphere ice sheets and North Atlantic Ocean.
51 *Paleoceanography*,. **4**, 353–412 (1989).
- 52 83. P. U. Clark, D. Pollard, Origin of the middle Pleistocene transition by ice sheet erosion
53 of regolith. *Paleoceanography*. **13**, 1–9 (1998).
- 54 84. P. U. Clark, D. Archer, D. Pollard, J. D. Blum, J. A. Rial, V. Brovkin, A. C. Mix, N. G.
55 Pisias, M. Roy, The middle Pleistocene transition: characteristics, mechanisms, and
56 implications for long-term changes in atmospheric PCO₂. *Quat. Sci. Rev.* **25**, 3150–
57 3184 (2006).
- 58 85. C. Boettner, G. Klinghammer, N. Boers, T. Westerhold, N. Marwan, Early-warning
59 signals for Cenozoic climate transitions. *Quat. Sci. Rev.* **270** (2021),
60 doi:10.1016/j.quascirev.2021.107177.
- 61 86. D. Pollard, R. DeConto, Continuous simulations over the last 40 million years with a
62 coupled Antarctic ice sheet-sediment model. *Palaeoclimatol. Palaeoecol. Palaeogeogr.*
63 **537** (2020), doi:10.1016/j.palaeo.2019.109374.
- 64 87. C. L. Batchelor, M. Margold, M. Krapp, D. Murton, A. S. Dalton, P. L. Gibbard, C. R.
65 Stokes, J. B. Murton, A. Manica, The configuration of Northern Hemisphere ice sheets
66 through the Quaternary. *Nat. Commun.* **10** (2019), doi:10.1038/s41467-019-11601-2.
- 67 88. W. Bagniewski, D.-D. Rousseau, Ghil, Michael, PaleoJump: A database for abrupt
68 transitions in past climates. *arXiv* (2022), p. doi:10.48550/arxiv.2206.06832D.
- 69 89. J. P. Eckmann, S. O. Kamphorst, D. Ruelle, Recurrence plots of dynamical systems.
70 *Europhys. Lett.* **4**, 973–977 (1987).
- 71 90. N. Marwan, S. Schinkel, J. Kurths, Recurrence plots 25 years later - Gaining confidence
72 in dynamical transitions. *EPL*. **101** (2013), doi:10.1209/0295-5075/101/20007.
- 73 91. B. Efron, nonparametric estimates of standard error - The Jackknife, the bootstrap and
74 other methods. *Biometrika*. **68**, 589–599 (1981).
- 75 92. B. Efron, R. Tibshirani, Bootstrap methods for standard errors, confidence intervals, and
76 other measures of statistical accuracy. *Stat. Sci.* **1**, 54–75 (1986).
- 77 93. A. Tantet, V. Lucarini, H. Dijkstra, Resonances in a Chaotic Attractor Crisis of the
78 Lorenz Flow. *J. Stat. Phys.* **170**, 584–616 (2018).
- 79 94. A. Tantet, V. Lucarini, F. Lunkeit, H. Dijkstra, Crisis of the chaotic attractor of a climate

80 model: a transfer operator approach. *Nonlinearity*. **31**, 2221–2251 (2018).

- 81 95. J. X. Zhou, M. D. S. Aliyu, E. Aurell, S. Huang, Quasi-potential landscape in complex
82 multi-stable systems. *J. R. Soc. Interface*. **9**, 3539–3553 (2012).
- 83 96. K. Miller, J. Wright, R. Fairbanks, Unlocking the ice-house Oligocene-Miocene oxygen
84 isotopes, eustasy, and margin erosion. *J. Geophys. Res.-Solid Earth Planets*. **96**, 6829–
85 6848 (1991).
- 86 97. S. Boulila, B. Galbrun, K. Miller, S. Pekar, J. Browning, J. Laskar, J. Wright, On the
87 origin of Cenozoic and Mesozoic “third-order” eustatic sequences. *Earth-Sci. Rev.* **109**,
88 94–112 (2011).
- 89 98. G. Paxman, S. Jamieson, K. Hochmuth, K. Gohl, M. Bentley, G. Leitchenkov, F.
90 Ferraccioli, Reconstructions of Antarctic topography since the Eocene-Oligocene
91 boundary. *Palaeoclimatol. Palaeoecol. Palaeogeogr.* **535** (2019),
92 doi:10.1016/j.palaeo.2019.109346.
- 93 99. E. Rohling, J. Yu, D. Heslop, G. Foster, B. Opdyke, A. Roberts, Sea level and deep-sea
94 temperature reconstructions suggest quasi-stable states and critical transitions over the
95 past 40 million years. *Sci. Adv.* **7** (2021), doi:10.1126/sciadv.abf5326.
- 96 100. A. Houben, C. van Mourik, A. Montanari, R. Coccioni, H. Brinkhuis, The Eocene-
97 Oligocene transition: Changes in sea level, temperature or both? *Palaeoclimatol.*
98 *Palaeoecol. Palaeogeogr.* **335**, 75–83 (2012).
- 99 101. Y. Smith, D. Hill, A. Dolan, A. Haywood, H. Dowsett, B. Risebrobakken, Icebergs in
00 the Nordic Seas Throughout the Late Pliocene. *Paleoceanogr. Paleoclimatology*. **33**,
01 318–335 (2018).
- 02 102. I. Bailey, G. Hole, G. Foster, P. Wilson, C. Storey, C. Trueman, M. Raymo, An
03 alternative suggestion for the Pliocene onset of major northern hemisphere glaciation
04 based on the geochemical provenance of North Atlantic Ocean ice-rafted debris. *Quat.*
05 *Sci. Rev.* **75**, 181–194 (2013).
- 06 103. B. D. A. Naafs, J. Hefter, R. Stein, Millennial-scale ice rafting events and Hudson Strait
07 Heinrich(-like) Events during the late Pliocene and Pleistocene: a review. *Quat. Sci.*
08 *Rev.* **80**, 1–28 (2013).
- 09 104. R. S. W. van de Wal, B. de Boer, L. J. Lourens, P. Koehler, R. Bintanja, Reconstruction
10 of a continuous high-resolution CO₂ record over the past 20 million years. *Clim. Past.* **7**,
11 1459–1469 (2011).
- 12 105. K. A. Jakob, P. A. Wilson, J. Pross, T. H. G. Ezard, J. Fiebig, J. Repschläger, O.
13 Friedrich, A new sea-level record for the Neogene/Quaternary boundary reveals
14 transition to a more stable East Antarctic Ice Sheet. *Proc. Natl. Acad. Sci. U. S. A.* **117**,
15 30980–30987 (2020).
- 16 106. G. Muttoni, C. Carcano, E. Garzanti, M. Ghielmi, A. Piccin, R. Pini, S. Rogledi, D.
17 Sciunnach, Onset of major Pleistocene glaciations in the Alps. *Geology*. **31**, 989–992
18 (2003).
- 19 107. M. F. Knudsen, J. Norgaard, R. Grischott, F. Kober, D. L. Egholm, T. M. Hansen, J. D.
20 Jansen, New cosmogenic nuclide burial-dating model indicates onset of major
21 glaciations in the Alps during Middle Pleistocene Transition. *Earth Planet. Sci. Lett.* **549**
22 (2020), doi:10.1016/j.epsl.2020.116491.
- 23 108. C. J. Berends, B. de Boer, R. S. W. van de Wal, Reconstructing the evolution of ice
24 sheets, sea level, and atmospheric CO₂ during the past 3.6 million years. *Clim. Past.* **17**,
25 361–377 (2021).
- 26 109. O. Seki, G. L. Foster, D. N. Schmidt, A. Mackensen, K. Kawamura, R. D. Pancost,
27 Alkenone and boron-based Pliocene pCO₂ records. *Earth Planet. Sci. Lett.* **292**, 201–
28 211 (2010).
- 29 110. W. S. Broecker, J. van Donk, Insolation changes, ice volumes, and 0-18 record in deep-
30 sea cores. *Rev. Geophys. Space Phys.* **8**, 169–198 (1970).
- 31 111. S. Barker, G. Knorr, R. L. Edwards, F. Parrenin, A. E. Putnam, L. C. Skinner, E. Wolff,
32 M. Ziegler, 800,000 Years of Abrupt Climate Variability. *Science*. **334**, 347–351 (2011).
- 33 112. J. F. McManus, D. W. Oppo, J. L. Cullen, A 0.5-million-year record of millennial-scale

climate variability in the North Atlantic. *Science*. **283**, 971–975 (1999).

113. H. Heinrich, Origin and Consequences of Cyclic Ice Rafting in the Northeast Atlantic Ocean during the Past 130,000 years. *Quat. Res.* **29**, 142–152 (1988).
114. G. Bond, H. Heinrich, W. Broecker, L. Labeyrie, J. McManus, J. Andrews, S. Huon, R. Jantschik, S. Clasen, C. Simet, K. Tedesco, M. Klas, G. Bonani, S. Ivy, Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. *Nature*. **360**, 245–249 (1992).
115. G. Bond, W. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel, G. Bonani, Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature*. **365**, 143–147 (1993).
116. S. P. Obrochta, T. J. Crowley, J. E. T. Channell, D. A. Hodell, P. A. Baker, A. Seki, Y. Yokoyama, Climate variability and ice-sheet dynamics during the last three glaciations. *Earth Planet. Sci. Lett.* **406**, 198–212 (2014).
117. J. Jouzel, V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Minster, J. Nouet, J. Barnola, J. Chappellaz, H. Fischer, J. Gallet, S. Johnsen, M. Leuenberger, L. Loulergue, D. Luethi, H. Oerter, F. Parrenin, G. Raisbeck, D. Raynaud, A. Schilt, J. Schwander, E. Selmo, R. Souchez, R. Spahni, B. Stauffer, J. Steffensen, B. Stenni, T. Stocker, J. Tison, M. Werner, E. Wolff, Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science*. **317**, 793–796 (2007).

Acknowledgments

We would like to thank our colleagues from Horizon 2020 TiPES project (grant No. 820970) and especially Michael Ghil for useful discussions about this study. This is LDEO contribution and TiPES contribution XXX. VL acknowledges useful exchanges with T. Bodai, R. Boerner, R. Deeley, G. Margazoglou, C. Nesbitt, and L. Serdukova.

Funding:

This research has been supported by the European Commission, Horizon 2020 Framework Programme (TiPES, grant no. 820970), by the Marie Cure ITN Critical Earth (Grant No. 956170) and from the EPSRC Project No. EP/T018178/1

Author contributions: Conceptualization: DDR; Methodology, investigation and Visualization: DDR, VL, WB; Writing—original draft: DDR; Writing—review & editing: DDR, VL, WB

Competing interests: All authors declare they have no competing interests.

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 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 TP_{OS} (diamonds) selected according to the KS methodology for $\delta^{18}\text{O}$ with time window 1-4 My are shown. The two extra TP_{OS} found via RP are indicated with a *. Panel b) Chronologically ordered fast TP_{OS} (FTP_{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.
26
27
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30 **Supplementary Text**

31 Comparison between GMSL, CCD and CO₂ concentration from 32 CENOGRID (past 66 Myr)

33 The interval between 66 Ma and 63 Ma (TP₀1) shows a relative stable GMSL above
34 +60m. It is followed by a lowering corresponding to a decreasing trend of about
35 70m in several steps between TP₀1 at 63 Ma and TP₀3 at 56 Ma, punctuated by an
36 abrupt increase of 52m, at TP₀2 around 58 Ma, and another of 28m corresponding to
37 the short but intense Paleocene-Eocene Thermal Maximum (PETM – Fig. 3a)
38 warming. GMSL raises between TP₀2 at 58 Ma and 55 Ma by about +40m. The
39 interval between 55 Ma and 48 Ma, the Early Eocene climatic optimum (EEOC –
40 Fig. 2A), indicates a relatively high GMSL of about 66 m above the present mean
41 sea level, which is associated with the occurrence of hyperthermal conditions at 58
42 Ma, 57 Ma, 53 Ma. Between 52 Ma and TP₀4 at about 47 Ma, CCD reaches the
43 shallowest depth of the record, about 3000m, (60) associated with the highest CO₂
44 concentrations estimated above 1100 ppmv by Ref (61) – Fig. 2B,C). A strong
45 decrease in GMSL of about 30m occurs between 48 Ma and 46 Ma while it remains
46 relatively stable at about +42m between 46 Ma and TP₀5, at 40 Ma. It is however
47 punctuated by two short events, first a lowering of about 25m between 42 Ma and
48 40.5 Ma, and strong increase of about 40m between 40.5 Ma and 40 Ma (TP₀5)
49 corresponding to the Middle Eocene Climatic optimum (MECO – Fig. 3A). A two-
50 step lowering of about 35m of the GMSL occurs between 40 Ma (TP₀5) and 36 Ma,
51 followed by a gradual increase of about 25m between 36 Ma and 34.5 Ma just
52 before the Eocene-Oligocene Transition (EOT – Fig. 3A). Between 46 Ma and 34
53 Ma (TP₀6), the CCD is strongly oscillating with numerous deepening events of
54 500 to 1000 m magnitude and shoaling ones, corresponding to carbonate
55 accumulation episodes. These oscillations in the CCD occurred during an interval
56 indicating still high CO₂ concentrations, roughly above the 750 ppmv considered as
57 an Antarctic glaciation threshold (62), and marked by a relative minimum at about
58 TP₀5 at 40 Ma (Fig. 3B,C). This first interval of the GMSL, ending by the strong
59 deepening of about 1000m associated with a strong decrease in CO₂ concentration,
60 determines variations of a rather completely ice free Earth, at least with no major
61 ice sheet either in southern and northern hemisphere. This is deduced first from the
62 high GMSL, mainly above 12m (Fig. 2A), which would correspond to the mutual
63 contribution of the Greenland and the West Antarctic ice sheets, and second from high

64 CO₂ 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 CO₂ 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 TP₀₆, at 34 Ma, and 23 Ma, the CO₂ 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 CO₂ 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 TP₀₇ 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 TP₀₇ 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 TP₀₈ 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 TP₀9 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 (TP₀9a) and 2.5 Ma (TP₀9b – 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 TP₀8 at about 9 onward, CCD
104 shows fluctuations although remaining at around 4500m with two strong deepening at
105 about TP₀9a 2.9 Ma and TP₀9b (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 (TP₀6) 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 (TP₀7) 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 (TP₀8), 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 TP₀9a) and 2.75 (TP₀9b), 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 TP₀6 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, TP₀9b
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 TP₀9a, at 2.8 Ma, to RTP₀2, at 1.2 Ma, shows glacial–interglacial sea level
43 variations of about 25–50 m below the present day. The CO₂ 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, RTP₀1, 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 RTP₀1, 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, RTP₀2, 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 ¹⁰Be-
60 dated boulders in Switzerland, is interpreted as marking the onset of the first major
61 glaciation in the Alps (106, 107).

62 After RTP₀2, at 1.25 Ma, the sea level changes decreased to about 70–120 m below
63 the present day, while the CO₂ 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 pCO₂ 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_{o3}, 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_{o4}) 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