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Holocene stability: climate attractor, or lucky break?

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Abstract. Palaeorecords indicate that the average global temperature been relatively stable for the past ~10,000 years of the Holocene epoch, in contrast to cooling trends during previous interglacials and abrupt shifts during past Glacials. Hypotheses for this stability range from early anthropogenic emissions to orbital factors or the timing of carbon cycle feedbacks. An alternative suggestion grounded in dynamical systems theory is that Holocene stability reflects the Earth system residing near a climate 'attractor', with strong negative feedbacks acting to stabilise the climate's state, and Glacial/Interglacial cycling representing either a limit cycle or tipping between Interglacial and Glacial basins of attraction. This in turn has led to the more recent hypothesis that human actions are eroding the resilience of the Earth system's current state, and at some level could be sufficient to tip the whole Earth system towards a much warmer "Hothouse Earth" attractor. However, despite multiple hypotheses for Holocene stability, that the Earth system is close to the edge of a dynamical basin of attraction is often assumed rather than demonstrated. Here, I assess the basis for this hypothesis in the literature, finding that there is currently insufficient evidence to support this hypothesis over the alternatives of pseudo-stability from stable orbital forcing, lagged feedbacks, or more complex nonlinear dynamics. As such, more evidence is required to test these hypotheses, and in the meantime the presence of Holocene or Hothouse attractors should not be taken as a given. Given this, I outline some alternative frameworks for climate states and Earth system resilience that may be appropriate without strong attractors, centring adaptive capacity and stability through change.

1. Introduction

The combination of human-driven greenhouse gas emissions and biosphere degradation is dramatically transforming the Earth system (IPBES, 2019; IPCC, 2021). The magnitude of this transformation has led to (recently rebuffed) calls for the designation of a new 'Anthropocene' epoch starting at the latest in 1952 CE (Lewis and Maslin, 2015; Malhi, 2017; Steffen et al., 2015b, 2016). This would mark the end of the circa 12,000 years of the Holocene, the geological epoch stretching from the last cold 'Glacial' and the start of the current warmer 'Interglacial' period (Emiliani, 1994; Kaufman and Broadman, 2023). Before that, reconstructions based on various palaeotemperature proxies indicate that global mean surface temperature (hereafter global temperature) rose by 6-7°C over ~7 Ky between the peak of the Last Glacial Maximum and the Holocene (Osman et al., 2021; Tierney et al., 2020). This shift represents the latest in a series of Glacial/Interglacial cycles, with the last 800 Ky of the Pleistocene marked by around 11 such oscillations between Glacial and Interglacial climates, paced by orbital cycles and amplified by Earth system feedbacks (Barker et al., 2025; Imbrie and Imbrie, 1980; Kukla and Kukla, 1972; Pages, 2016; Ruddiman, 2003a) (Figure 1).

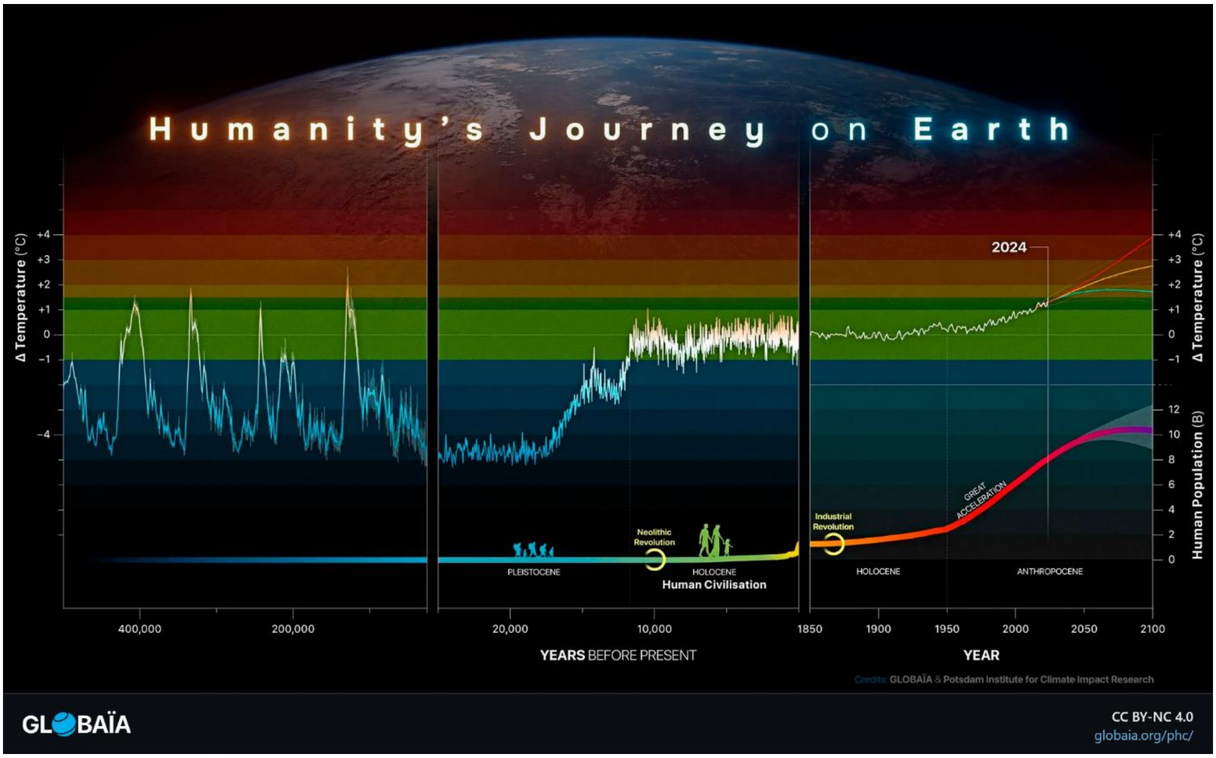

Figure 1: **A commonly used infographic for illustrating Holocene climate stability, showing global temperature changes over the past 500ky along with future projections (top) relative to colour graded safety levels (from blue for glacial, to green for "safe operating space", to orange to red for unsafe). Also depicted is human population with some key milestones(bottom), used to contextualise the above within an Anthropocene and Great Acceleration framing. Figure reproduced from GLOBAÏA (2026) (https://globaia.org/phc/, CC BY-NC 4.0), which used temperature reconstructions from (Jouzel et al., 2007; Morice et al., 2021).**

https://doi.org/10.5194/egusphere-2026-3886
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During the Holocene itself, reconstructions suggest that global temperature gradually increased post-deglaciation, peaking c. 0.5ºC above pre-industrial levels (1850-1900) during the Holocene Thermal Maximum around 6-7 Kya, before gradually declining by around 0.1°C per Ky, and culminating in the so-called 'Little Ice Age' just prior to modern warming (Fox-Kemper et al., 2021; Kaufman et al., 2020; Kaufman and Broadman, 2023; Marcott et al., 2013; Osman et al., 2021). In contrast, during most previous interglacials global temperature rapidly peaked in an interglacial 'optimum' before more gradually declining in to the next glacial, forming a distinctive 'sawtooth' pattern across the glacial/interglacial cycles (Lisiecki and Raymo, 2005; Pages, 2016). These records also reveal multiple abrupt climate shifts during past Glacials and deglaciations, including the Dansgaard/Oeschger cycles, Heinrich events, and Bond events, likely involving ice sheet instabilities disrupting ocean circulation (Boers et al., 2022; Bond et al., 1997; Broecker, 1987; Dansgaard et al., 1969, 1993; Oeschger et al., 1984).

The relatively limited global temperature variability of the Holocene stands out compared to this past variability, prompting many attempts at explanation. One explanation for the lack of declining temperatures and greenhouse gases during the Holocene versus prior interglacials is that early human emissions countered this natural fall – the so-called 'Early Anthropogenic Hypothesis' (Ruddiman, 2003b; Ruddiman et al., 2016, 2020). Another possibility is that the variable timing of different forcings and feedbacks naturally leads to different GHG and climate trajectories in each deglaciation (Ganopolski and Brovkin, 2017; Menviel and Joos, 2012). The relative orbital quietude of the Holocene may also be key, with the current low amplitude of obliquity cycle lowering the CO2 threshold for glacial inception to well- below pre-industrial levels (Berger and Loutre, 2002; Ganopolski et al., 2016; Tzedakis et al., 2012).

The apparent stability of the Holocene has also been interpreted as evidence for the Earth system having been in a self-stabilising state near an 'attractor', in which predominantly negative feedbacks kept the Earth system within a narrow climate range that was conducive to the emergence of human civilisation (Ripple et al., 2026; Steffen et al., 2018). The contrast of the recent 'Great Acceleration' in various human impacts (Steffen et al., 2015b), and global temperature projected to reach levels likely not seen for millions of years (Willeit et al., 2019), with the seeming stability of the Holocene is a key argument made for the Anthropocene, and is interpreted as evidence for the Earth system entering a new functional state and therefore justifying a new epoch (Zalasiewicz et al., 2024, 2025). In this framing, Glacial/Interglacial cycling represents either a limit cycle or tipping between Glacial and Interglacial basins of attraction, and the Anthropocene represents a 'trajectory' out of this self-stabilising Holocene state (Steffen et al., 2018). Furthermore, it has been hypothesised that once the edge of this attractor basin is reached, the Earth system will be inevitably pulled towards either a much warmer "Hothouse Earth" attractor (Ripple et al., 2026; Rockström et al., 2021; Steffen et al., 2018).

This idea of the Holocene representing the Earth system in a stable and resilient state which is now being eroded, threatening a global tipping point towards an alternative hotter attractor, has become increasingly embedded as a possible or even confirmed theory within wider scholarly literature (e.g. Chavez et al., 2024; Hardt, 2021; Kim, 2022; Kotzé, 2020; Ripple et al., 2020, 2025, 2026; Rockström et al., 2021, 2024; Rockström, 2024) and public discourse (e.g. Breaking Boundaries, 2021; Climate Extremes, 2024; Climate Crisis Advisory Group, 2021; Global Challenges Foundations, 2026; McGuire, 2022; Spratt, 2025; Spratt and Dunlop, 2022; TED, 2024; Rockström and Gupta, 2023; Trust, et al., 2026). However despite being so widely discussed and adopted, there has been little research to directly empirically test it since being proposed explicitly as such a hypothesis by Steffen et al. (2018). In addition, many other potential explanations for the apparent stability of the Holocene relative to previous interglacials (and thus the nature of the Holocene and the Earth system's potential resilience) remain in contention.

In this perspective, I assess the current extent of evidence for the hypothesis of the Holocene climate being in a stable basin of attraction, into which it tipped from a colder Glacial attractor basin 12000 Kya, and is now approaching a global tipping point to a much hotter attractor basin (hereafter the 'Heterostatic Holocene' hypothesis, with 'heterostasis' (c.f. Günther et al., 2003; Selye, 1973) referring to the Holocene as one of multiple highly self-stabilising equilibria, rather than just one such homeostatic point) versus alternative hypotheses in the literature. Finally, based on this I consider how Earth system states and resilience can be alternatively conceptualised.

2. Attractive climates

In the Heterostatic Holocene hypothesis, Holocene climate stability is a function of the climate system residing in a dynamical basin of attraction, in which stabilising negative feedbacks act to counter any perturbation away from the attractor. Conversely, crossing the edge of the attractor basin through warming would result in the climate being drawn towards an alternative hotter attractor by amplifying positive feedbacks (e.g. by orbital forcing initiating reglaciation).

If the climate system had been near a strong attractor, this would have potentially serious implications for modern climate change. The attractor view forms part of the basis for the 'Planetary Boundaries framework', which defines the limits within which 9 representative Earth system metrics remain within Holocene-like state (Rockström et al., 2009b, a; Steffen et al., 2015a; Rockström et al., 2023; Richardson et al., 2023; Sakschewski et al., 2025). Within this "safe operating space", the Earth is assumed as a self-regulating system to remain stable, resilient, and capable of providing planetary life-support functions, but pushing the Earth system beyond these boundaries erodes its resilience and risks nonlinear transitions such as tipping points (Rockström et al., 2024b, a; Rockström and Gupta, 2023; Sakschewski et al., 2025). More seriously, if the climate system were to be pushed to the edge of its basin of attraction by anthropogenic warming, there could come a point where net-cooling feedbacks transition to net-warming as it enters a warmer attractor basin. The key driver of this is posited to be the impact of climate tipping points, which are framed as regulating and stabilising the planet's climate state by generally acting as a negative feedback on warming (e.g. Climate Extremes, 2024; Nogués-Bravo and Pinto, 2025; Rockström et al., 2021; Rockström and Gupta, 2023; Sakschewski et al., 2025), but if transgressed would lock in further emission and warming, particularly if a 'tipping cascade' of one tipping point leading to another is triggered (Ripple et al., 2026; Rockström, 2024; Wunderling et al., 2021). This is posited to pull the planet inexorably towards a much hotter attractor, termed a "Hothouse Earth" state by Steffen et al. (2018).

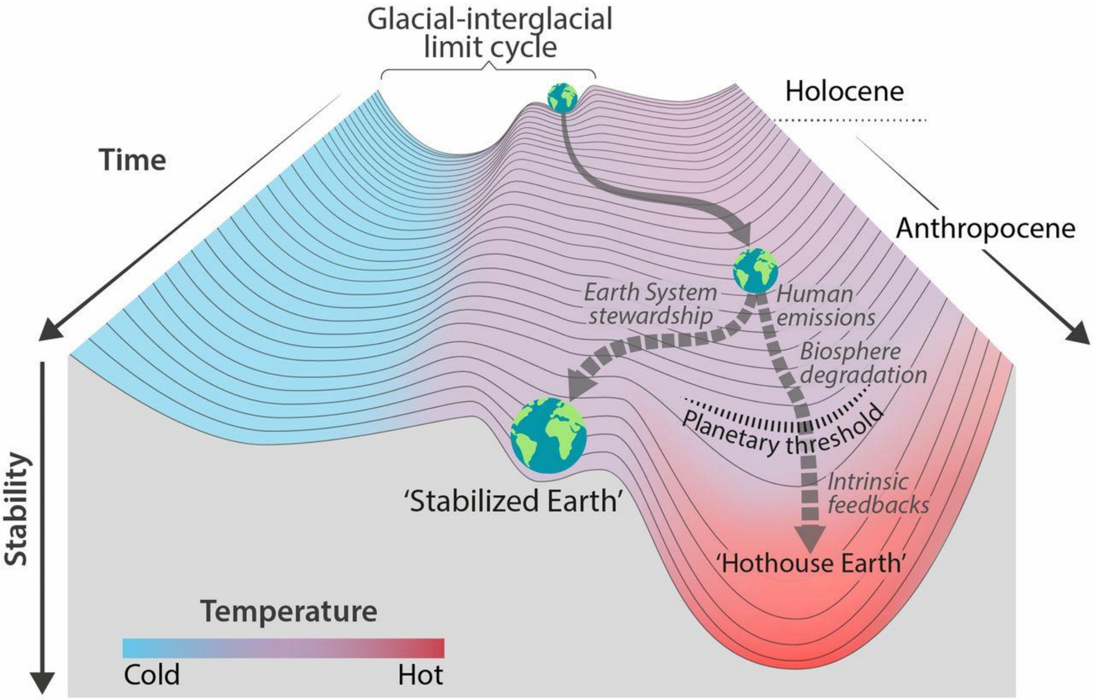

Figure 2: **The illustrative time-dependent stability landscape of Steffen et al. (2018) showing Glacial and Interglacial basins of attraction on the left (shown as valleys with their most stable point at their lowest point, with a**

deeper and more resilient Glacial and a shallower and less resilient Interglacial, between which the Earth system either tips or is in a limit cycle), and a potential Hothouse attractor on the right that the Holocene Earth system could tip towards. Also illustrated is a deepening of this Hothouse attractor with biosphere degradation, and an alternative Interglacial-like 'Stabilised Earth' attractor that human actions are speculated to be able to create instead. Reproduced from Proceedings of the National Academies of Sciences (CC BY-NC-ND 4.0).

The possibility of the climate system shifting between different basins of attraction finds some support in the palaeorecord and in models. While clearly paced by the Milankovitch cycles in orbital forcing, the exact mechanism linking this to Glacial/Interglacial cycling remains debated (Barker et al., 2025; Imbrie and Imbrie, 1980; Kukla and Kukla, 1972; Pages, 2016; Ruddiman, 2003a). One suggestion is that G-IG cycles represent nonlinear behaviour of the Earth as a complex dynamical system switching between cooler and warmer states as a result of orbital forcing, either as a free oscillation, excitation, or limit cycle through an unstable excited Interglacial state from the original stable Glacial state (Crucifix, 2012; Gildor and Tziperman, 2000; Le Treut and Ghil, 1983; Pierini, 2023; Riechers et al., 2022), or by crossing a global threshold between stable Glacial and Interglacial attractor basins (with e.g. stochastic resonance of weak noise triggering tipping) (Benzi et al., 1982; Ferreira et al., 2018; Gammaitoni et al., 1998; Nicolis, 1982; Nicolis and Nicolis, 1981; Paillard, 1998; Sutera, 1981). Steffen et al. (2018) present their hypothesis via both of these possibilities (with limit cycles between Glacial and Interglacial states as well as a speculative Hothouse limit cycle in their Figure 1, and multiple stable attractors in Figure 2), but the latter framing is dominant in subsequent interpretations (e.g. Rockström et al., 2021, 2024; Rockström and Gupta, 2023; Sakschewski et al., 2025) and is the focus of this assessment.

Evidence for potential climate attractors can also be identified in the geological record. Analysis of benthic isotope data and reconstructions of global temperature and sea level have suggested distinct icehouse, coldhouse, warmhouse, and hothouse climate regimes in the Cenozoic (<66 Ma) (Foster and Rohling, 2013; Westerhold et al., 2020) as well as the broader Phanerozoic (<485 Ma) (Judd et al., 2024). Quasi-potential and recurrence analyses of collated Cenozoic palaeorecords further suggest that several critical transitions can be detected coinciding with the shifts between some of these regimes, such as from warmhouse to hothouse at the Palaeocene-Eocene Thermal Maximum (PETM) (~56 Ma) or from warmhouse to coolhouse at the Eocene-Oligocene Transition (EOT) (~34 Ma) (Boettner et al., 2021; Rousseau et al., 2023; Westerhold et al., 2020). However, it should be noted that while distinct climate states and abrupt shifts between them can be detected in the palaeorecord, these states are not necessarily equivalent to basins of attraction in a dynamical systems sense.

https://doi.org/10.5194/egusphere-2026-3886
Preprint. Discussion started: 10 July 2026

Before then, modelling suggests that the 'snowball Earth' events in the Proterozoic involved global tipping dynamics. There is some evidence for quasi-global glaciation during the Cryogenian (~760-635 Ma) and Ediacaran (~635-539 Ma) periods, with for example likely glacial deposits reaching the palæoequator (Hoffman and Schrag, 2002; Macdonald et al., 2010) and a global bacterial to algal marine production shift (Brocks, 2018), although not all agree that glaciation was fully global (Allen and Etienne, 2008; Eyles and Januszczak, 2004). Simple models suggest this was driven by a potential global tipping point, with ice sheets and sea ice reaching ~30° latitudes being sufficient for ice-albedo feedbacks to become self-sustaining and glaciation to reach the equator, and making deglaciation highly difficult (Budyko, 1969; Hyde et al., 2000; Lucarini et al., 2010). Escaping this state may have involved accumulating volcanic CO_2 (Kirschvink, 1992) as well as feedbacks associated with dust, melt-ponds, or methane hydrate feedbacks (Kennedy et al., 2008; de Vrese et al., 2021; Wu et al., 2021) which gradually drove warming until the hysteresis of the snowball attractor was overcome.

Other models also provide support for climate system attractors being feasible. Simple energy balance models have supported at least two stable climate regimes for current astronomical boundary conditions, including a snowball state and the current warm state (Budyko, 1969; Ghil, 1976; Sellers, 1969). These states have also been found in more complex climate models, including intermediate complexity models such as PLASIM (Lucarini and Bódai, 2017; Margazoglou et al., 2021; Voigt and Marotzke, 2010), as well as in higher complexity atmospheric models (Abbot et al., 2011). In MITgcm, a fully-coupled general circulation model, two alternative states have been found for current conditions (Ferreira et al., 2018), three that map on to Glacial, Interglacial, and a hotter state in a preliminary version also including additional vegetation and ice sheet representation (Brunetti and Moinat, 2026; Moinat et al., 2026), five for an 'aquaplanet' setup (Brunetti et al., 2019; Brunetti and Ragon, 2023; Ragon et al., 2022), and three for boundary conditions at the Permian-Triassic boundary (Ragon et al., 2024). Some models also feature intermediate or unstable edge states (Lucarini and Bódai, 2017). These models generally feature colder alternative states, but some also support hotter states, with for example vegetation collapse during the Permian-Triassic Mass Extinction maintaining hothouse conditions for millions of years (Xu et al., 2025), and a similar mechanism in a recent highly idealised energy balance model featuring present and hothouse states (Chavez et al., 2024).

Based on the above evidence one can construct an illustrative feedback diagram, denoting various possible states (Figure 3):

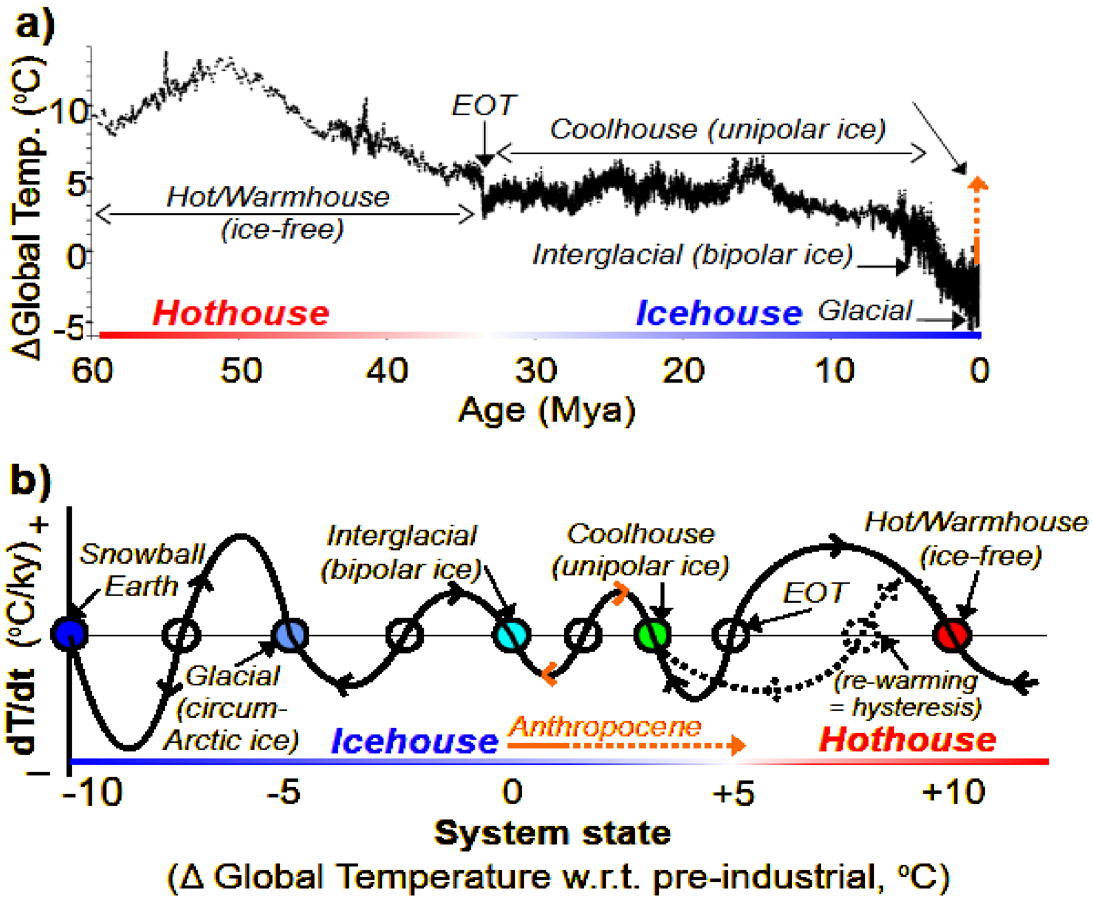

Figure 3: (a) Global temperature reconstruction (Zachos et al., 2008) illustrating how Earth's climate has shifted from a warm, ice-free 'Hothouse' state to a cold, bipolar ice sheet 'Icehouse' state over the Cenozoic era. (b) Illustrative diagram of feedback strength versus global temperature (following Tyrrell (2020)) based on Cenozoic palaeorecords and sources discussed in the text (e.g. Westerhold et al. (2020)), showing how various climates states the Earth system has passed through over time can be hypothesised as feedback-driven attractors, with feedbacks either stabilising towards stable attractors (filled circles) or amplifying away from unstable repellors (empty circles), which act as global tipping points between basins of attraction around each attractor. If this was the case, then the Anthropocene trajectory (orange arrow) may push the Earth system beyond the tipping point between an Interglacial and Coolhouse attractor basins.

3. Complex landscapes

Models across a range of complexity support the general possibility then of the Earth's climate system being multistable and featuring distinct attractors. Palaeorecord analysis also identify several potential candidate attractor states bounded by critical transitions (Figure 3). However, several major issues remain with this interpretation.

The key mechanisms proposed to potentially drive a Holocene/Hothouse tipping scenario are weakening negative feedbacks (e.g. carbon sink weakening, or reduced ocean heat uptake), strengthening positive feedbacks (e.g. permafrost thaw emissions), and climate tipping point cascades (Ripple et al., 2023, 2026; Steffen et al., 2018). Steffen et al. (2018) for example estimate that 2°C of warming could lead to another 0.47°C via feedbacks and tipping points, which they speculate could drive further feedbacks and a gradual drift towards 4°C (although many of these feedbacks are already included within current model projections). However, while some degree of warming amplification by natural feedbacks is expected, that they are sufficient to reach a point of self-sustained warming was not demonstrated. Specifically on tipping points, the assessments of Armstrong McKay et al. (2022) and Wang et al. (2023) show some but limited potential additional warming if all climate tipping points were triggered, with from 0.59°C to even a net cooling of 0.1°C (due to deep ocean convection collapse) on a 3°C baseline over centuries to millennia implied in the former, and ~0.24°C on a 3°C baseline by 2300 in the latter (with both sets of numbers – as with Steffen et al. (2018) – including feedbacks already partly included within current model projections, so are not necessarily additional). Beyond tipping points, there is some model evidence for a nonlinear increase in carbon cycle feedback with warming (Kaufhold et al., 2025). However, elevated feedbacks and climate sensitivity with warming does not specifically imply an attractor, with global carbon-cycle feedbacks still remaining net-negative in this analysis when including the ocean carbon sink. Similarly, while there is evidence for some carbon sinks weakening (Gatti et al., 2021; Hubau et al., 2020; Wang et al., 2020), in particular in 2023-24 for the land sink (Ke et al., 2025), at a global scale the fraction of carbon removed by all natural sinks has remained broadly constant as other sinks take up the slack (Friedlingstein et al., 2025; Pan et al., 2024), and ocean heat uptake is projected to continue in line with warming (Fox-Kemper et al., 2021).

While climate attractors have been detected in several models, this still represents a limited selection, and cannot be extrapolated across all Earth system models. For example, recent analysis of a simplified climate-vegetation model found that carbon-climate system instability only featured in plausible parameter space at low CO_2 levels corresponding to glacial conditions (Clarke et al., 2025). Additionally, even where found in relatively complex GCMs, these often still do not sufficiently resolve all key Earth system processes and feedbacks, and so cannot be directly extrapolated to the real Earth system (Canadell et al., 2021; Fox-Kemper et al., 2021). To improve

https://doi.org/10.5194/egusphere-2026-3886
Preprint. Discussion started: 10 July 2026

confidence, and similar to establishing support for major tipping points such as AMOC shutdown, global climate attractors need to be found across multiple differing high complexity models of the current Earth system, and mapped to equivalents in palaeorecords (e.g. Moinat et al., 2026). Similarly, while suggestive, climate states diagnosed in palaeorecords are not in themselves sufficient evidence for the climate system residing in an attractor at that time. Judd et al. (2024) and Westerhold et al. (2020) identify several climate states in Phanerozoic palaeorecords, but while there is some evidence for dynamical differences between these states (Boettner et al., 2021; Rousseau et al., 2023), the question remains whether these are states in a dynamical systems sense, or are periodising constructs on a longer term dynamic trend bounded by abrupt shifts. The latter view is reflected by longer term modelling by the SCION model that replicates the broad pattern of Phanerozoic Hothouse/Icehouse cycling from tectonics and dynamic vegetation without explicit dynamical attractors (Merdith et al., 2025), with tipping dynamics secondarily shaping abrupt shifts superimposed on this long-term trend (e.g. (Xu et al., 2025) with SCION and the end-Permian mass extinction; also suggested for the PETM (Armstrong McKay and Lenton, 2018; Dickens, 2011; Littler et al., 2014; Lunt et al., 2011; Setty et al., 2023), the EOT (Armstrong McKay et al., 2016; DeConto et al., 2008; DeConto and Pollard, 2003; Hutchinson et al., 2021), etc.).

Despite subsequent referencing focusing on the bistable attractors interpretation, Steffen et al. (2018) also alternatively proposed Glacial/Interglacial cycling – as well as the hypothesised Hothouse trajectory – as potential limit cycles, implying an alternative nonlinear route to a Hothouse state even if there is no equivalent attractor (despite this being implied by the shallow valley in Figure 2). However, palaeoclimate evidence does not support such a Hothouse limit cycle, with Miocene and Pliocene climate states (and similar states in prior cycles (Judd et al., 2024)) not simply being transient states on a continuous Hothouse Eocene to Icehouse Pleistocene trajectory, but long-lasting and quasi-stable conditions in themselves (Foster and Rohling, 2013; Westerhold et al., 2020; Zachos et al., 2001, 2008). On a shorter term, such a Hothouse limit cycle more closely resembles proposed rate-dependent ocean carbon system excitations during prior extinction events (Rothman, 2017, 2019), but this relies on a highly simplified model. If we instead assume that the climate states inferred from palaeorecords represent extant attractor basins (and have not been rendered obsolete by shifting astrogeophysical boundary conditions), we would instead expect a shift from an Icehouse to a Coolhouse rather than straight to a Hothouse state, with the latter resembling the Pliocene conditions that current policies could anyway lock in by the end of the century (Climate Action Tracker, 2025). These palaeorecord analyses also do not support Glacial/Interglacial transitions as tipping points between attractor basins within the Icehouse state, instead marking out some points such as the Mid-Pleistocene Transition as an abrupt shift within climate system dynamics, in this case shifting from ~40ky to

https://doi.org/10.5194/egusphere-2026-3886
Preprint. Discussion started: 10 July 2026

~100 Ky cycles but not substantially changing the nature of Glacials and Interglacial states themselves (Boettner et al., 2021; Rousseau et al., 2023; Westerhold et al., 2020).

There remain several feasible alternatives to Holocene stability representing being in a distinct basin of attraction or metastable state (Riechers et al., 2022). The Heterostatic Holocene view implies that the Holocene as well as prior Interglacials represent stable states, but as discussed earlier Glacial/Interglacial cycling can also emerge in models from a monostable glacial state via a limit cycle, free oscillations, or temporary excitations (Crucifix, 2012; Pierini, 2023; Riechers et al., 2022; Saltzman et al., 1984). This framework has the advantage of better capturing the sawtooth nature of Glacial/Interglacial cycling, with Interglacials generally gradually cooling into Glacials, whereas a bistable Glacial/Interglacial model tend to feature sharp transitions at both the start and end of Interglacials (Pierini, 2023). It also reflects the possibility that the Glacial state may not be so stable, with one model showing higher climate instability at low CO_2 (Clarke et al., 2025), and the current Northern Hemisphere ice sheet configuration arguably more resistant to warming than a Glacial state, with Greenland Ice Sheet collapse likely not triggering the same degree of biome change or ocean circulation change as Laurentide Ice Sheet collapse (Boers et al., 2022; Bond et al., 1997).

A limit cycle or excitation framework does not in itself explain the relatively stability of the Holocene though, as a decay back towards the monostable Glacial state would still be expected. In contrast, in a bistable model current orbital quietude would correctly suggest no tipping back to a Glacial state, but this would in turn not explain prior Interglacial decays. This conflict could be explained through other unique circumstances of the Holocene, such as the timing of post-Younger Dryas feedbacks (Ganopolski and Brovkin, 2017) which along with orbital quietude could delay glacial re-inception, while previous Interglacials did decay due to differing feedbacks and orbital forcing. Alternatively, the Holocene could represent a so-called ‘ghost state’ (Börner et al., 2026) or a ‘long transient’ (Morozov et al., 2023, 2024), in which a system can remain in a long-lived and seemingly quasi-stable state where there used to be an attractor or similar, which can be mistaken for a stable state despite actually being unstable. In this case, in the absence of an orbital nudge back towards the Glacial attractor, a Holocene ghost Interglacial state could last thousands of years and would appear-quasi-stable in itself, despite there being no underlying attractor. If this were the case, Earth system resilience from this state would not be linked to an attractor, and warming may lead to a more chaotic response and not necessarily a simple scenario of tipping towards a hotter attractor.

In summary, despite some model and palaeorecord evidence in support of a potential Holocene attractor amongst others, there currently remains insufficient evidence to rule out the other explanations discussed in this section.

https://doi.org/10.5194/egusphere-2026-3886
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4. Implications for Earth system resilience

Recent discussions of 'Earth (system) resilience' (e.g. Bertolami and Nyström, 2026; Global Challenges Foundations, 2026; Ripple et al., 2026; Rockström, 2024; Rockström et al., 2021, 2024) commonly define it with respect to the Heterostatic Holocene framework. In this definition, Earth system resilience is as a measure of the strength of stabilising net-negative feedbacks which keep the Earth system within the initial basin of attraction, but may transition to net-positive feedbacks at the basin's border, pulling the Earth system towards an alternative attractor. If Holocene quasi-stability cannot be assumed to necessarily support this framework though, then it raises the question of how else we might understand Earth system resilience if different frameworks apply.

Before we explore different frameworks for Earth system states and their resilience, and following the question of "resilience of what, to what?"(Carpenter et al., 2001), we must clarify the nature of the Earth system's stability landscape. In

Figure 4, the multidimensional Earth system is collapsed to a state space with just two dimensions representing the climate and the biosphere. These two dimensions are themselves simplified constructs representing multidimensional entities, and can be thought of as resulting from dimension reduction (with climate say correlating with temperature and aridity, and biosphere more complex but likely correlating with primary productivity or biodiversity, depending on palaeogeography). In this landscape, low points are more stable, and particular climate states can be defined either as qualitative regions the Earth system tends to vary within or as distinct basins. In either case this landscape is not fixed, being dynamic through time as the astrogeophysical boundary conditions of the Earth system change (and is equivalent to the 2D landscape moving through higher-order dimensions).

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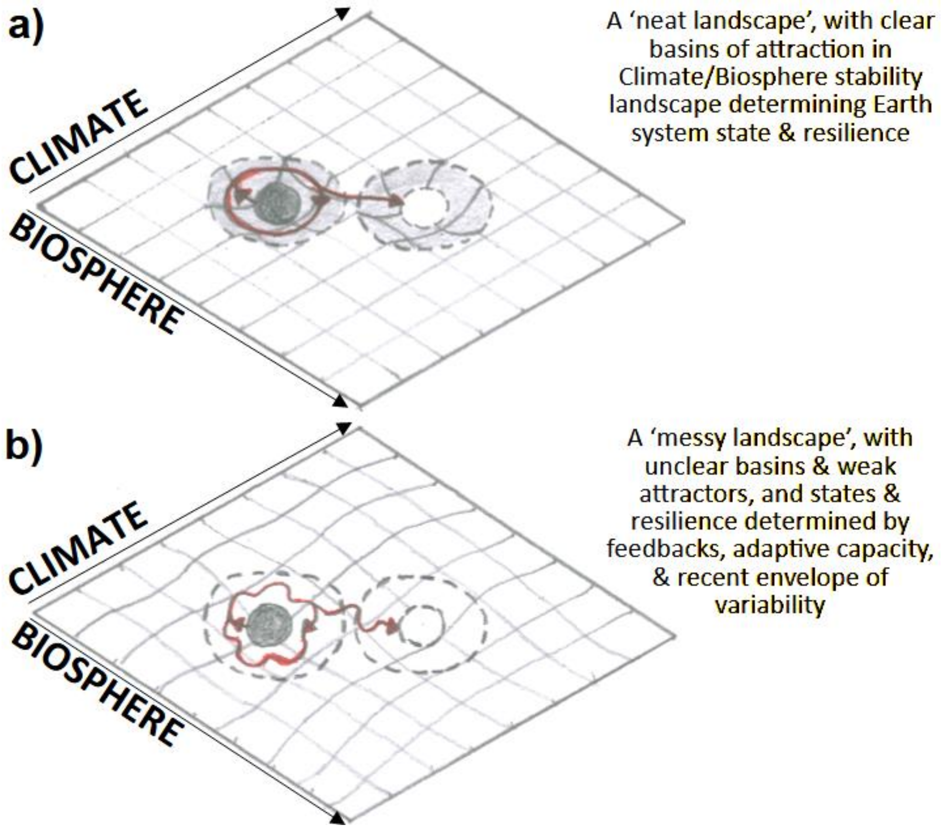
Preprint. Discussion started: 10 July 2026



A 'neat landscape', with clear basins of attraction in Climate/Biosphere stability landscape determining Earth system state & resilience

A 'messy landscape', with unclear basins & weak attractors, and states & resilience determined by feedbacks, adaptive capacity, & recent envelope of variability

Figure 4: Visualisations of two different Earth system resilience frameworks via illustrative stability landscapes. a) The heterostatic framework, in which there are distinct basins of attraction in climate/biosphere state space, with resilience corresponding with net-negative feedbacks as the Earth system is perturbed by endogenous forces towards the edge of the basin, risking crossing the threshold between the basins and being pulled towards the alternative attractor. b) An alternative 'messy landscape' framework, in which there are weak attractors in a dynamic and complex stability landscape, with resilience also corresponding with the Earth system's adaptive capacity, and climate states also determinable by recent envelope of variability. [N.B. this figure is currently in draft, and will be improved in revision.]

In the Heterostatic Holocene framework, the basin slopes correspond to resilience (with steep slopes to deep attractors corresponding to high buffering against astrogeophysical forcing and perturbations, as well as natural variability), while hillcrests correspond to global tipping points between attractor basins, before which resilience declines as the slope levels off. If the landscape is flatter or a 'messy landscape' with weak attractors though, then climate change would have no clear global tipping point to different basins, and Earth system resilience may not decline prior to such a basin threshold. However, Earth system resilience can still be relevant, as resilience is not necessarily tied to multistability. Instead, if Earth system resilience reflects its adaptive capacity, then the Earth system may buffer itself against perturbations from any initial state as long as the rate of forcing stays within this capacity. Conversely, the magnitude or rate of forcing may eventually overwhelm its adaptive capacity, leading to reduced buffering. In this view, Earth system states diagnosed from palaeorecords correspond with recent envelope of variability within a portion of the wider landscape, which is partly but not wholly determined by the underlying landscape (which may feature only a weak attractor, or the Earth system state may not be near the attractor's minima). If applied today, this model of Earth system resilience would still motivate rapid emission cuts and ecosystem restoration in order to keep the rate and magnitude of change within this capacity.

A related approach is to reframe Earth system resilience more in terms of 'ecological resilience' rather than 'engineering resilience'. In Holling's (1996) definition (and building on prior definitions of resilience and stability respectively (Holling, 1973)), engineering resilience measures the system's resistance to disturbance and the time taken for to bounce back, which can be related to the overall strength of net-negative feedbacks and would be expected to decline prior to tipping to a different attractor basin (Dakos, 2008; Dakos et al., 2024; Scheffer et al., 2001, 2009). This approach is often favoured when estimating climate or Earth system resilience, as it is more easily quantified via for example measures of critical slowing down (e.g. Armstrong McKay and Lenton, 2018; Setty et al., 2023) (although others have recently proposed a trajectory-based approach (Anderies et al., 2026; Harteg et al., 2026)). In contrast, ecological resilience reflects a wider but harder to measure view of the ability of a system to persist by absorbing disturbance and reorganising to maintain overall function and identity, rather than returning to exactly the same state (Folke et al., 2010; Walker et al., 2004). This reflects the dynamic turn in ecology away from expecting ecosystems to be near to and return rapidly to a stable equilibrium, and towards expecting disturbance and dynamic states far from equilibrium (Holling, 1996; Pickett et al., 1992; Pickett, 2013), as well as resilience thinking and adaptive cycles, in which adaptation, collapse, and transformation across scales are an essential part of system dynamics (Carpenter et al., 2001; Folke et al., 2010; Gunderson and Holling, 2002; Holling, 1985).

Holling (1996) connects a multistability focus (versus assuming only one stable point) to ecological resilience, and elsewhere ecological resilience is equated to remaining broadly within the initial attractor (Carpenter et al., 2001; Walker et al., 2004). However, by assuming the Holocene represented a near-equilibrium Earth system state with strong stabilising feedbacks, emphasising the need to stay as close as possible to that assumed equilibrium, and generally equating net-negative feedback strength to Earth system resilience (e.g. Bertolami and Nyström, 2026;

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Global Challenges Foundations, 2026; Ripple et al., 2026; Rockström, 2024; Rockström et al., 2021, 2024), in practice the Heterostatic Holocene framing more closely maps to the engineering resilience view (albeit also emphasising alternative stable states). In contrast, the broader ecological resilience view can better account for the Earth system's continual reorganisation as a result of life's evolutionary innovations (such as photosynthesis (Lenton and Daines, 2017), calcifying plankton (Ridgwell, 2005), or C4 grasslands (Edwards et al., 2010)) and gradually shifting astrogeophysical boundary conditions (such as tectonics or solar luminosity), as well as the possibility that the Earth system may not be near-equilibrium in the recent past of the Holocene or far into the future. If there is no Holocene attractor, or it is relatively weak as part of a messy stability landscape, then ecological resilience's focus on adaptive capacity provides an alternative potential focus for Earth system resilience (Carpenter et al., 2001; Folke et al., 2010).

So far these frameworks assume that the Earth system's state will to a greater or lesser degree tend inevitably towards minima in this stability landscape. However, this is not necessarily the case either, as what appears to be a 'stable' state in a complex system can be far from equilibrium. Life itself can be characterised as far-from thermodynamic equilibrium dissipative systems (Schrödinger, 1944), a property that the Earth system also shares (Kleidon, 2023; Lovelock, 1965, 1979; Lovelock and Margulis, 1974; Rambler et al., 1989). The concept of Dynamic Kinetic Stability in chemistry generalises evolutionary idea of fitness to survival of stable self-replicating systems, applying them to explain how (bio)chemical systems can use energy to remain on otherwise unstable energetic slopes within a stability landscape (Pascal et al., 2013; Pross and Khodorkovsky, 2004; Yang et al., 2021). Similarly, the Red Queen hypothesis in evolutionary biology – metaphorically drawing from Lewis Carroll's Through the Looking Glass, in which the Red Queen tells Alice "it takes all the running you can do, to keep in the same place" (Carroll, 1873) – emphasises that species most constantly adapt and evolve to survive (Van Valen, 1973).

For the Earth system, a similar framework would imply that its state cannot simply be thought of as a marble deterministically rolling around a fixed stability landscape – it can *defy* the landscape too, with life capable of maintaining the Earth system far from attractors, as well as changing the landscape itself over time. Together with the messy landscape / weak attractor interpretation above, Earth's climate history could therefore be seen as an astrogeophysically-driven random walk though a dynamic biogeophysical stability landscape, with a far-from-equilibrium biosphere maintaining the Earth system in some degree of dynamical stability *despite* the landscape. In this view, Holocene quasi-stability may represent then the biosphere keeping the Earth system seemingly stable in an Interglacial state in the absence of substantial orbital forcing even if there was no Interglacial attractor, and human "rewiring" of the Earth system may be further changing the underlying stability landscape. Compared to a historical focus on 'planetary homeostasis' (and in this perspective the related concept of heterostasis) as a biological metaphor for a tendency towards strong negative feedbacks maintaining planetary equilibrium, this framing of stability through change might be better described by planetary *allostasis* (which instead emphasises flexibility in setpoint and the maintenance of functioning through change, comparing to e.g. a fever), planetary *homeorhesis* (which emphasises the tendency to return to a dynamic trajectory, e.g. Waddington's epigenetic landscape of morphological development, which the time-dependent stability landscape of Steffen et al. (2018) in Figure 2 bears a resemblance to) (Rambler et al., 1989; Waddington, 1957), or even planetary *antisyzgy* (in the sense of productive tension between opposing forces, noting that "disorderly order is order after all" (Smith, 1919)).

Finally, the extent to which the Earth's climate has been stable during the Holocene can also be interrogated. 'Stability' here is generally meant in terms of in relatively constant mean and limited variability (i.e. stationarity) in global temperature, but this global average masks larger regional changes, as well as hydroclimate variability. The Holocene witnessed several major regional hydroclimate perturbations, including the various 'Bond events' including the 8.2ka and 4.2ka events associated with Laurentide ice sheet collapse and AMOC disruption (Boers et al., 2022; Bond et al., 1997; Gerber et al., 2025; Martin-Puertas et al., 2023; Ning et al., 2019; Yan and Liu, 2019) (contrary to recent characterisation of the AMOC as a key climate stabiliser, e.g. Abram et al. (2025)). Some Bond events are also associated with the decline of the African Humid Period and Green Sahara, which broadly follows vegetation retreat in both the Sahara and boreal tundra after the mid-Holocene as a result of changing orbital forcing, which helped drive substantial regional and modest global cooling via the albedo feedback (Kaufman and Broadman, 2023; Pausata et al., 2020). The impact of these events was not substantial globally (at least relative to deglaciation), but illustrate the dynamism of the Holocene climate system, which is not clear when focusing only on global averaged temperature. While the term stability can be synonymous with stationarity, it can also imply properties of not being easily movable (which contradicts the key role of positive feedbacks in amplifying Holocene Thermal Maximum (Kaufman and Broadman, 2023)) or resisting force (but, as described in previous sections, low variability cannot be assumed to be due to dynamical stability). As such, the Holocene's apparent stability is conditional both on definition and scale, and can be easily misinterpreted.

5. Conclusion

While the limited variability in Holocene global temperature gives the impression of climate stability prior to the modern hyperthermal, the evidence presented in this perspective indicates it is not in itself sufficient evidence for the existence of a self-stabilising Holocene climate state. Similarly, declining carbon sinks or the occurrence of tipping points does not necessarily mean that Earth system resilience is declining due to the edge of a current basin of attraction being approached. Holocene quasi-stability can also be explained by a number of alternative hypotheses, including orbital quietude, post-glacial feedback interactions, or more complex nonlinear dynamics, and Earth system resilience can also for example be understood as the Earth system's adaptive capacity to buffer against change from any starting point. As such, the existence of a Holocene basin of attraction from which the Earth can tip towards a hotter attractor still remains one hypothesis amongst many. To progress, the field of Earth system resilience should seek out evidence that can discern between these hypotheses, as well as explore alternative conceptualisations of resilience. In the meantime, a Holocene attractor and an imminent tipping point to a Hothouse state should not be taken as a given, either within sustainability science or in public communication. Presenting a Holocene/Hothouse tipping point as confirmed theory could be argued to help motivate stronger action, but it also carries risks, such as inducing fatalism or encouraging emergency global climate interventions. It also forecloses other ways of exploring the Earth system's future trajectory, as well as the difference between the Holocene and prior Interglacials. Given this, as Earth system scientists we should be cognizant to how the way we frame Earth system resilience may affect research and the wider public discourse, and be open and transparent to the framings we use and the multiple possibilities that remain open to us.

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Code and data availability

No new code or data was used in this study.

Author contributions

Conceptualisation: DIAM; Investigation: DIAM; Visualisation: DIAM; Writing: (original draft preparation) DIAM; Writing (review and editing): DIAM

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