Response Letter (EGUSPHERE-2025-2163)

Setting up the physical principles of resilience in a model of the Earth System

Authors: Orfeu Bertolami and Magnus Nyström

To Editor,

We very much appreciate the effort made by the reviewer to help us improve our manuscript.

We hope we've been able to clarify and shed light on the concerns raised by the reviewer.

Please find below our response to the reviewer's comments. Changes have for ease been inserted in red color to highlight where and how our responses are made. We also clarify our responses in our response letter below.

Sincerely,

Orfeu Bertolami and Magnus Nyström

(11/11/2025)

Reviewer's comments are in **bold**.

General comments:

The authors have made several changes to the manuscript, which has helped clarify a number of issues raised in the last review. However, there are still some issues which I don't think have been sufficiently dealt with.

While there has been some useful reorganisation, with moving more technical elements from the Introduction to the 2nd section helping the text flow, parts of the text could still be clarified to make the argument and methodology clearer. Additionally, while some additional caveats have been included on this, the text as it stands still implies that a Holocene equilibrium state (i.e. climate attractor) with a planetary-scale tipping point to a Hothouse state is a likely / default scenario given sufficient warming, with this model replicating those dynamics, rather than a hypothetical proposal which this model is exploring. This is not to say that the latter is not a worthwhile endeavour, but it is necessary context. Despite this, the updated Figure 2 actually now seems to imply relatively little resilience against a Holocene-to-Hothouse drift unless one reaches the alternative metastable state, which I think needs more discussion, along with reflecting how it affects the message of the paper – is it that if the real-world ES has similar resilience landscape then a hothouse runaway is unlikely, or is it that we'd need to push to reach that metastable state now in Figure 2? Finally, a number of specific comments

from last time marked as implemented do not appear to have been substantially addressed – further edits should be clearly flagged, or a case made for where changes aren't made.

Response: We have made several changes so to clarify the importance of putative metastable states to prevent the inevitable Holocene-to-Hothouse drift. Paving the way for a metastable state could be one way to buy more time to change ES dynamics in such a way that a Holocene-to-Hothouse drift is avoided.

Overall, I believe a clearer "articulation of the theoretical frameworks from which the Holocene-to-Hothouse-attractors hypothesis has emerged, with this study situated as extending previous work to explore how this scenario can be represented in a thermodynamical model", would help clarify and strengthen the argument, as would some further reorganisation and clarifications. –

Response: We think this articulation is better understood once it is realized the potentiality of the thermodynamic model to address the issue of overall resilience of the ES.

Specific comments (by line no.):

Abstract L5-7: Extra justification on practical relevance is provided here, which is welcome, but I'm not sure how useful such a simplified model is for real-world practice (e.g. specifically where or what actions are useful) beyond suggesting a general need for them. I think a clearer motivation would be in demonstrating how Earth system resilience (and in particular the conceptualisation of this resilience as a property of Earth system attractors) can be formalised & represented in a model, and then the degree to which non-climate mitigation is relevant for preventing a Hothouse trajectory in such a model (which is not unpacked so much in the current draft beyond a couple of statements).

Response: We acknowledge that other actions than climate mitigation can play important roles. L.110-114 we have added: "Way to do so include, mitigation strategies, such as halting deforestation and changing agricultural practices that contribute to CO2 emission; transformation strategies, such as shifting from fossil fuel-based economies to ones based or renewable energy, and; restoration strategies, such as restoration of degraded ecosystems and CO2 capture technologies."

Abstract L11: I still think that temperature/climate can't be said to be a direct "net result" of PB interactions in real ES, given PBs are constructs/proxies mapped on to fundamental variables (but are but not fundamental in themselves). Adding "variables" after PBs would provide some clarification here, or specifying it as the result in-model.

Response: Done.

Abstract L13-14: Runaway has been usefully clarified, but overall this sentence is still a bit confusing – it is not totally clear how the second part is dependent on the first part.

Response: To clarify, it now reads: "Our model shows that this runaway can be prevented

by the presence of metastable states and dynamic friction built out of the interaction among the PB variables once suitable conditions are satisfied."

Abstract L19: This of course assumes that such a hotter equilibrium state actually exists in real ES, and not just in model – adding "potential" would help hedge this.

Response : "potential" has been added.

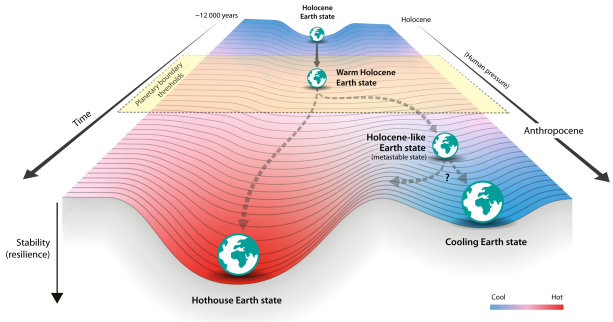
L52-54: The interlinkages between resilience, PBs, and TPs still hasn't really been fully explained – it'd be clearer to mention in previous paragraph introducing PBs that some of them have been set at an assumed precautionary distance away from potential TPs, as well as unpacking the fundamental linkage between TP & resilience theory, given that the former is to some extent an outgrowth of latter (as tipping can be framed as what occurs once a system's resilience is exceeded). Also, I still think it'd be useful to present a separate conceptual diagram of the proposed Earth system dynamics here (e.g. something similar to Steffen et al. (2018)'s energy landscapes, showing resilience as the landscape, TPs as the basin boundaries, PBs as the variables), to which your results in Figure 2 can be compared to show you've achieved something similar in the model.

Response: An important point made by the reviewer.

To clarify relationship between PBs and TPs we have added the following text (L49-56):
"Importantly, while the PB framework highlights the presence of tipping points in biophysical processes, it does not specify their exact thresholds. Instead, it delineates two risk zones: a zone of increasing risk and a high-risk zone. In the former, the further boundary limits are exceeded, the greater the likelihood of causing significant harm – destabilizing critical Earth system processes and disrupting essential life-support functions. In the latter, or high-risk zone, there is a substantial risk of severe and potentially irreversible damage to key planetary functions. In essence, these zones are defined at a precautionary distance from the estimated locations of potential tipping points."

To clarify relationship between TPs and resilience we have added the following text (L62-78):
"Multiple states (regimes), tipping-points and self-reinforcing feedback mechanisms (hysteresis) are a central feature of resilience (Holling 2001). For example, in cases where resilience is high, a powerful shock – such as, storms, large wildfires, pest outbreaks in ecosystems, or armed conflicts, trade wars, supply chain disruptions in social systems – is required to push the system beyond a tipping-point and into another state. However, gradual change – such as, loss biodiversity, habitat fragmentation and pesticide resistance in ecosystems, or growing inequality, changing social norms in society – erodes resilience in the current state, which makes the system vulnerable even to smaller perturbations. Once the system finds itself in this new state it can be difficult, or even impossible to reverse due to self-reinforcing feedback mechanisms (Scheffer et al. 2001, Scheffer 2009, Nyström et al. 2019). Within the context of PB variables, species extinction (i.e. biodiversity loss PB) represents an irreversible process."

Moreover, we have also added a new conceptual Figure 1. [Previous Figure 1 has been deleted].



The associated figure legend reads as:
"*FIG. 1. A schematic illustration of the evolution of the Earth System with a start from the Neolithic revolution (~12.000 years ago). Leading up to its current state (i.e. 'warm Holocene Earth state') 7 of 9 planetary boundaries have been transgressed. A continuation on this pathway suggests that the Earth system may end up in a Hothouse Earth state (Steffen et al. 2018) (left pathway). However, explicit dissipation of energy, and policies and actions geared at building resilience of a metastable 'Holocene-like Earth state' (see also Fig. 2) could provide an opportunity to build a trajectory toward a future 'cooling Earth state' (right pathway).*"

With these changes, we hope that the interlinkages now come out in a better and stronger way.

L60-65: A useful clarifier, but it could do with a citation where this argument is made in full (e.g. Steffen et al. 2018, or the PB papers themselves, which explicitly rely on this assumption).

Response: Steffen et al. 2018 has been added.

L89-100: This is a useful addition to provide more context for the paper's motivation. However, as in my previous comments, I think it's debatable that one can clearly infer from observations that the ES is likely moving from a stable Holocene equilibrium (in a dynamical systems sense) that could proximately tip wholesale to a Hothouse state. Only Steffen et al. (2018) is cited to support observations on this, but while they do present some evidence in support, they explicitly propose it via a perspective (rather than research article) as a suggestion of a potential risk that's deserving of further exploration and precautionary action in meantime, rather than as a proof (for example, from Steffen et al. (2018): "This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway" & "Our initial analysis here needs to be underpinned by more in depth, quantitative Earth System analysis and modeling"). Not all of their proposed evidence is clear-cut either, with continued debate in palaeo community on what drives glacial/interglacial cycling, and no clear emergent threshold in carbon cycle feedbacks or tipping points. As such, that a Holocene-to-Hothouse runaway remains a possibility but for now an uncertain hypothesis should be made clearer here, e.g. "it has been hypothesised that the ES is moving away from the Holocene equilibrium state to a new state...". Furthermore, I think it'd be better phrased that your results show that ES resilience *could* be associated with metastable states and that this can prevent

runaway specifically your model, thereby fitting with the Steffen et al. suggestion, so as not to imply this is already proven in reality.

Response: A very important point made by the reviewer! Indeed, the Hothouse earth trajectory is indeed a speculative outcome suggested in the original work by Steffen et al. We have rephrased to –" …it has been hypothesized that the ES is moving away from the Holocene equilibrium state to a new state, potentially a Hothouse Earth state (Steffen et al. 2018)."

L104: "shown to be non-vanishing" a bit technical on its own for an Introduction.

Response: It has been removed from the Introduction.

L118-123: It's stated in your response that my request here (to describe what you did in these previous papers in broad, non-technical terms) was implemented, but that's not been done. However, you have unpacked it a bit more in section 2, so you could add a cross-reference to that here noting details can be found there (and potentially unpack it a bit more there).

Response: We now referred to the discussion in section 2, where this point can be better appreciated.

L128-129: My request here was for "dynamic friction" to be explained, rather than justified – fine for this to be done in later sections though (perhaps including a cross-reference to that here).

Response: To clarify, the sentence now reads: "A further requirement is dynamic friction, that is friction introduced via a kinetic energy-type term, to restrict the change of state in the phase space."

L139-144: This is a good addition, but would be better higher up with PBs, resilience, & TPs when talking about the theoretical frameworks you're using (so that mentioning socio-ecological here is covered), rather than tacked on to paragraph setting out structure of the rest of the paper.

Response: The section has been moved and modified to better fit with the existing text in the Introduction (at L62-67). We think it works much better now (less ad hoc). It now reads: "This conception of resilience is based on the understanding that humans and nature are deeply interconnected through feedbacks between social and ecological components, which together influence overall behavior and dynamics (Biggs et al. 2012). This interdependence defines a social-ecological system (Berkes and Folke 1998) in which human well-being and prosperity rely on the stability and functioning of the ES (Folke et al. 2011)."

L148-149: Some useful extra description of past modelling added, but I think a bit more detail on your 2018 paper would be useful for readers here to have solid grounding in model meaning.

Response: Following text has been added: "Previously, we aimed to show the inevitability of the Hothouse Earth state given the disestablishing nature of the human activities and the interplay among the PBs. Here, we consider…"

L197-199: Would it be possible to explain how this is so in brief?

Response: Text has been added to better express the point: "… dynamical variables, that are not only passively changed due to human activities, but that can be actively altered so to boost the resilience features of the ES."

L190-193: Good clarification, but I think it's worth re-mentioning that ES having similar metastable states is hypothesised, not confirmed (e.g. along lines of "Metastable states correspond to potential intermediate states between the proposed Holocene and Hothouse Earth states").

Response: "potential" has been added to indicate the nature of the metastable states.

L202-205: This sentence was not further unpacked, despite being marked as such in the response. It's not critical, but at least briefly explaining what is meant by discrete logistic map in context of human activities here without referring to citation would be helpful to the reader.

Response: A footnote on p.11 has been added to specify the technicalities associated with the discrete logistic map. It reads:
"[2] This means that the evolution of the PB, h_i, (i = 1, 2, ..., 9) is considered to be discrete and obey the equation $h_{i(j+1)} = rh_{i(j)}(1 - \alpha h_{i(j)})$, where j denotes the number of "generations", r is the rate of growth and α a constant."

L222-224: The conditions necessary to reach this metastable state and their physical correlates would be good to unpack here, and would connect to where in the abstract & elsewhere you are connecting this to real-world practical relevance (e.g. discuss how it differs from Hothouse state in lower H, i.e. within PBs, but similar high psi, implies lots of human activity but within the PBs).

Response: A phrase has been added about the origin of the cubic terms: "In concrete terms, cubic terms might arise from PB interactions that have a strong dependence on the temperature."

Figure 2: This updated figure is clearer (although my original comment here was to describe this figure more in text, which would still be useful, rather than changing figure itself). However, it now seems to imply there's now actually relatively little resilience on the direct Holocene-to-Hothouse path, with a fairly gentle slope (in contrast to the last draft, in which there was a basin boundary between them), which seems to go against the general argument of there being resilience against a Hothouse runaway from Holocene state. Does this imply that if this applied to the real ES, that to avoid a drift to Hothouse would require actively pushing ES to the metastable state instead? This also presumably shows that the results are quite sensitive to tweaking in order to make a new metastable state to appear, which in itself would be worthy of further discussion. How exactly did you alter the model in order to generate these new

results, and what are the implications?

Response:

With the new conceptual Figure 1. (and figure legend), this should now be clearer.

L226-228: I don't think this sentence was further explained, despite labelling as implemented. I presume you mean that for such a simplified. phenomenological model, it is preferable for higher-order terms to be minimised. (in general too, that this is a phenomenological model fits my wider points about being clear that this is a simplified model exploring hypothesised ES dynamics.)

Response: A clarification phrase has been added: "We consider the essential set of terms in order to carry out the minimisation procedure. Thus:…".

L246: Adding "energy dissipation" somewhat helps in more clearly explaining dynamic friction, but for clarity I think it could be explicitly linked to the equation terms you introduce.

Response: The meaning of dynamic friction has been clarified above in the text.

L249: With respect to my original comment here, I'm not convinced you've substantially expanded on currently limited generalisability of the model to real ES. As it stands, the conditions here endow the ES with resilience only within this model (& specifically in context of metastable states, and not other ways of formalising ES resilience), and further work would be required to show these also apply to real-world ES resilience (going beyond the proposal of Steffen et al. 2018 to test it more thoroughly). Adding "in this model" or similar to this sentence would make that clear.

Response: "…in this model" has been inserted.

L250-260: This still reads like something from the Conclusion that doesn't fit contents of the rest of this section (despite reply saying change to this has been implemented).

Response: We agree. It felt misplaced.
The following sentence was removed as it was redundant with what already in the Conclusion (L223-228): "Since the Holocene, the ES has been subjected to a great stress. From the Great Acceleration of the second half of the last century, which presumably sparked the Anthropocene, the hyper expansion of human activities resulted that the safe operating space has been crossed for 6 of the 9 PBs (Richardson et al. 2023) and created all sorts of tensions, whose ongoing climate change crisis is the most persistent consequence for the ES."

However, the number of PB transgressed has been changed from 6 to 7, and a new reference has been added (Kitzmann et al. 2025 for The Planetary Health Check Report).

The following sentences (L328-333) have been rewritten and moved to the end of the Conclusion. This makes more sense, and it now reads:

“Given that the tipping of some of the major ecosystems that compose the ES, such as the Amazon rainforest and the Pacific Coral reefs, are already visible, one faces the question of knowing if we have already inflicted an irreversible damage on ES, or are close to it. The answer comes only through the understanding of the mechanisms of resilience and how their boosting, through the PB interactions, can be effective. We hope that our work can provide a modest help in this respect.”

L267: The existence conditions are shown with respect to your model, but as a model is not the real world, and given the commonplace misinterpretations of this topic in wider discourse, I think it should be made clear that the former is meant here.

Response: A remark has been made on the matter: “For sure, further research is needed in order to establish which PBs are more suitable for setting up the conditions obtained above. This means that the PB properties concerning their dependence on the temperature and strength of their self-interaction and with other PBs must be further studied.”

L273-274: You haven't really unpacked here that these ES states remain hypothetical for now, and where you have added more on this (up in Intro) it's implied that it's fairly solid rather than a proposal worth exploring. I think it’s worth briefly highlighting that caveat both there and here.

Response: We have rewritten the conclusions and emphasized the importance the hypothetical metastable states potentially have for the ES and humanity.