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Tipping point interactions may also generate weakening cascades

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Text

The paper written by D. I. A. McKay *et al.* represents an interesting milestone for understanding the Earth's climate (*1*), and has stimulated public interest in such global issues. However, as researchers engaged in climatology and biome responses, we have some concerns about its findings. In this response, we posit five technical and conceptual arguments that question the assumptions of this work. McKay *et al*.'s paper provides a detailed analysis of the possible tipping points (TPs, with their associated thresholds) that the Earth may experience. While not doubting the existence of such possible TPs *per se*, we question the methods used to study them. Crucially, we ask: how can TPs be studied without considering all their interactions and, in particular, possible mitigation processes? In a previous paper (*2*), we suggested labelling such attenuation events as "stabilizing points", possibly combining them into "weakening cascades".

Our first argument is that the conclusion of this letter is not the result of an *integrated model* of the Earth's climate, but rather a debatable combination of previously identified TPs. This raises several questions about consequences, as it does not highlight the dynamics of the whole Earth system. It assumes that TP causes are central to the Earth's climate and ignores any other causes and processes, whether reversible or not. More precisely, the simulations of McKay *et al.* take little account of the *interactions* at play in the Earth's system. To list the system's variables (the Earth's components and TP elements) and their influences is insufficient, considering their highly probable indirect interactions (*3*). For this purpose, we need dedicated models, among which some GCMs or even Earth System Models are more robust than others. An alternative is to develop possibilistic and discrete-event models designed to compute all potential dynamics of a system according to its assumed state variables, processes and chosen initial state (*4*). This has proved to be a relevant and rigorous (tractable) way of modeling complex systems (*5*), such as the Earth's system. Applied to the Earth's climate (*2*) it provides possibilistic spaces (known as state-transition spaces, Fig. 1) which are more reliable than a TP list or any *potential surface* or function. What might be true of a single TP is not necessarily valid for a complex system of interrelated TPs.

Our second argument advocates studying the single trajectory of the Earth combining successive events to suggest quantifying the *conditional* probabilities of such events, rather than cumulating their respective probabilities. Considering that the conditional probability of any combination of at least two TPs together is probably not equivalent to the sum of marginal probabilities of each TP (*6*). Considering that each TP belongs to a specific space and time, especially in nonlinear dynamical systems, this is very different from considering two TPs in the same space and time.

For a reasonable estimate of the joint probability of the co-occurrence of the dieback of the Amazon forest and the massive melting of Greenland, they should be evaluated in the same unique realization (run) of the climate system. Adding the marginal probabilities of each individual run may significantly overestimate the conditional probability of the joint events. This is also why it is crucial to consider any set of N (N>1) TPs with all their dynamical interactions. Any modelling strategy exploring extreme events should properly consider this premise.

Our third argument is that this approach does not consider the possible *mitigation processes* likely to occur once TPs are triggered. Taking into account only potentially negative behaviours (TPs) is a sibylline way to bias the dynamics toward specific consequences. By using a discrete-event model (*4*), we show that mitigation processes may play a critical role in TP cascades (*2*), which are thus hindered by TP elicitations and TP analyses (*7*). A more integrated approach would definitely reveal whether or not such stabilizing points may combine to create TPs. We find studying only one (detrimental) face of this coin to be a highly risky undertaking.

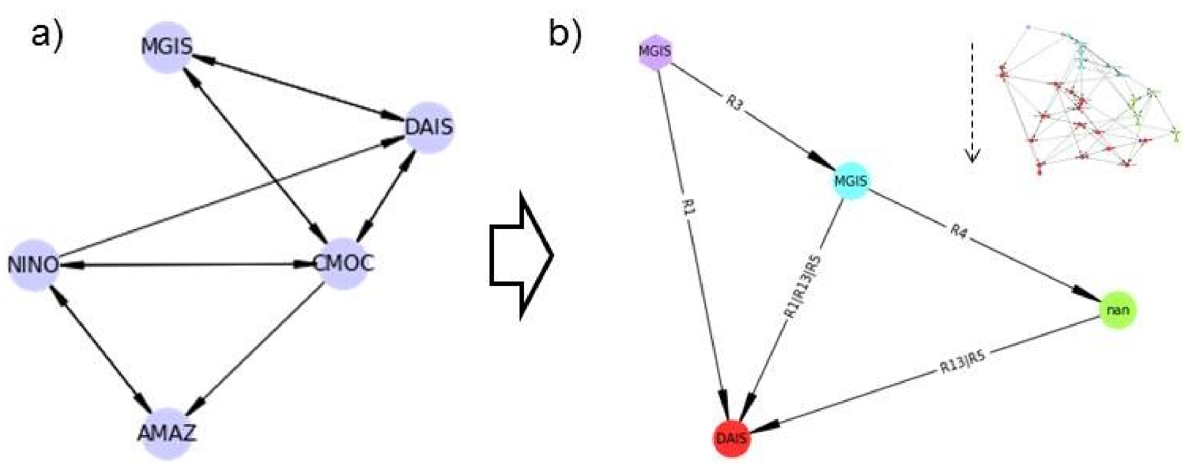

Figure 1. The interaction network (a) made up of the main TPs identified and discussed in (2, 7), with its computed state-transition space displayed in reduced/merged (b) and extended versions (insert). The interaction network displays state variables (a, nodes) and interacting processes (a, edges). The resulting state-transition space displays qualitative stabilities (b, nodes) with systematically present TPs (b, node labels) and event transitions (b, edges labeled Rx) connecting them (4). These possibilistic spaces highlight the potential tipping cascades, absent here (i.e. a single TP in each stabilities), yet still with highly incomplete Earth modeling.

Our fourth argument is that we form part of the scientific community that remains unconvinced by the relevance of a simplistic TP concept. Such a reductionist approach that only considers TPs may also be misleading. It may well be that the Earth does experience a TP one day. Yet, we are convinced that, as things stand, we do not yet have the appropriate concepts and tools for modeling and anticipating such behaviour. TPs have been theorized by physics; they assume that the local stability of the dynamics is guaranteed by a *potential function*, whose time derivative along the solutions of the system is negative, at least locally. When such potential is not strictly decreasing everywhere, then multiple steady states or periodic orbits occur (*8*). So far, we have not seen any evidence of such assumptions in environmental sciences, and more specifically, in the case of the Earth's climate. Such a potential function would have a significance largely different from the traditional gravity potential first used in physics to demonstrate its behavior. In a previous study, we proposed to use state-transition spaces to represent more reliably the dynamics of any complex system (*5*).

What is true of climate tipping points remains true of social (*9*), biome or ecological (*10, 11*) systems and their tipping points identified so far: they may not be identified and reliably used without robust approaches (*12*). Numerous studies argue the presence of TPs and TP cascades without using rigorous, process-based, tractable and validated models. Any similar conclusions about the Earth's future (whether global or local) should be based on integrated models that take most interactions of such complex systems into account. Finally, we would like to warn climatologists as well as ecologists and environmental science scholars that such a TP concept exported from physics is likely not the most appropriate way of interpreting environmental dynamics. We must continue looking for more relevant concepts and associated tools for understanding (and later on, recommending), the behaviors of such a complex system as that of the Earth.

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