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Earth System Dynamics Discussions

Interactive comment on "Climate change in a conceptual atmosphere–plankton model" *by* György Károlyi et al.

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Reply to reviewer 1

We thank the reviewer for a thorough reading of our paper and for the useful suggestions. Below we reply them and indicate the changes made to the manuscript.

This work presents an analysis of the feedbacks between atmosphere and ocean life with simplified mathematical models and detailed mathematical analysis. The questions and science considered in the paper are of broad relevance to researchers across many slices of the life sciences. Overall, the study is very good and offers broadly applicable insights relevant to the Earth Sciences. However, the paper does not sufficiently put the Earth Science relevant findings and broader implications front and center for

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ESD and its audience. The findings are there, but the paper (and especially the introduction and conclusion) would benefit from expansion in this direction. Overall, I suggest re-arranging the material to highlight broader relevance.

We thank the reviewer for considering the study “very good” which “offers broadly applicable insights relevant to the Earth Sciences”. We are grateful for his/her suggestions (below) that gives us the opportunity to highlight the broader relevance of our findings, as detailed below.

Major Comments:

1. As mentioned, a greater focus on the broader Earth science issues and relevance is needed for an ESD paper. This can likely be accomplished through changes to the introduction and discussion/conclusions. Questions I wish the paper had addressed are along the lines of: what do these findings mean for more complex, process-based Earth System Models? I wanted more than Lines 355-356, and I think more could be said.

In the revised form of the Introduction, we express our view that the understanding of the interplay between biogeochemistry and climate is still limited, and the situation of this problem is similar to the state climate science faced decades ago. This requires the use of a hierarchy of conceptual models increasing in details to shed light on the importance of various processes. Our simple conceptual model is an attempt to make the first step in this direction by coupling biogeochemistry and climate to identify the relative importance of some basic feedback mechanisms. In the Conclusions we also added that this model can be developed into a sequence of gradually more complex ones.

We added the following new text into the Introduction:

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In spite of the current trend to include biogeochemistry in
climate models (see e.g.  Schlunegger et al, 2019), a basic
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understanding of such processes is still limited. It is still under debate whether net primary production is increasing or decreasing in coupled carbon-climate models as a consequence of warming induces production increase and stronger nutrient limitations induced by increased stratification (Laufkötter et al, 2015). The situation appears to be similar to the understanding of thermal or fluid dynamical concepts decades ago. The study of e.g. the energy balance Ghil (1976) or of the thermohalin ciculation Stommel (1961) started with elementary conceptual models which later evolved into more complex ones, and are by now decisive components of cutting-edge climate models. We therefore propose here to study a conceptual atmosphere-plankton model where emphasis is on a proper choice of couplings (feedbacks).

We added the following new text into Conclusions:

As far as we know, our work is the first step in the direction of studying the feedbacks between the atmosphere and the biosphere by a simple conceptual model. As such, both the biological and climate models are highly simplified. However, one can consider it as a starting modul of an extendable model system. On the one hand, trophical levels and inorganic resources can be easily added to the biological side of our model, on the other hand, simple ocean circulation models can extend the climate side of our model in order to make a first step to build more complex coupled models (Daron and Stainforth, 2013). We think that mutual interactions and iterations between conceptual models and detailed Earth System Models (ESM) help to reveal the distinction between relevant and less relevant mechanisms and feedbacks behind climate change. We expect deeper insight into these feedbacks by studying conceptual and ESMs parallelly in the future.

1a. Section 3 is a good example of how the paper is heavily focused on the details of the math. There's good scientific insight there: Lines 179-181 "The relation indicates that in the case of a positive enrichment parameter the phytoplankton dynamics weakens the climate change, weakens the trend from D_0 to D in the temperature contrast, as expected. Quite surprisingly, however, the effect is rather weak since $\alpha\beta$ is quadratically small." Is there a way to make that point up front in this section, with fewer references to equations, and to move even more of the equations to the SI? Adjustments along these lines throughout would be beneficial to appeal to a broader audience of researchers.

We relegated the derivation of our formulae into the SI, and only kept those mathematical results in the main text that are explicitly used to reach the conclusions. We added a short paragraph about what a naive expectation suggests without any mathematical treatment, then reach the conclusion by analysing the results of the detailed calculation (obtained in the SI).

We added the following new text to Sec. 3:

Naively, one expects that an increased CO_2 level (smaller F in (1)) leads to a higher carrying capacity and concentration of the plankton, and a slower decrease of the temperature contrast, i.e., $S(D)$ should increase (decrease) with the enrichment parameter. However, only by calculating the precise dependence can reveal whether these trends are important or hardly discernible.

2. One easy change would be to include a table of variable and parameter notations, the quantities each notation represents, and any assumed values or boundaries im-

posed on the variables/parameters (such as alpha). This could be included in the SI, but is important to include, given the number of variables, parameters, and values being considered.

We thank the reviewer for the suggestion. The table has been added as Supplementary Material III.

3. Similarly, any kind of figure/model schematic illustrating the setup and feedbacks (and their notations where possible) would be beneficial in the main text Section 2.

A schematic drawing, illustrating the main feedbacks used in the paper, has been added to Section 2 as a new Fig. 1. We think that this drawing indeed helps the reader by making the set of feedbacks used in the paper easier to overview. We also attach this new figure to the reply.

Specific comments:

1. Lines 42-57: some of this text would be better suited in a methods section than the introduction.

The first part of the mentioned lines provides a general qualitative introduction to the ensemble method, heavily used in our approach. The next part, describing the concept of snapshot attractors, is indeed too strongly mathematics oriented, and we hence moved it to the beginning of Section 5.

The moved sentences:

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The mathematical concepts underlying the ensemble view are
snapshot (Romeiras et al, 1990) or pullback (Ghil et al,
2008) attractors.  One might consider the ensemble of all
permitted climate realizations over all times as the pullback
attractor of the problem, and the set of the permitted states
of the climate at a given time instant as the snapshot
attractor belonging to that time instant (their union over
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Discussion paper

all time instants is the pullback attractor). Both views express that the climate system possesses a plethora of possibilities. In the terminology of climate science, climate has a strong internal variability (e.g.Stocker et al (2013)). The concept of snapshot or pullback attractors is nothing but a reformulation of this fact in dynamical terms.

In numerical simulations, we consider the members of an ensemble simulation to describe parallel climate realizations only after the initial conditions are “forgotten”, transient dynamics disappears. Due to dissipation, this time is typically short compared to the time span of interest. Such an ensemble approach was shown to be the only method providing reliable statistical predictions in systems with underlying nonpredictable dynamics (since in this class the traditional approach based on single time series is known to provide seriously biased results). A number of papers illustrate these statements within the physics literature (see. e.g. (Romeiras et al, 1990; Lai , 1999; Serquina et al, 2008)), as well as in low order climate models (Chekroun et al, 2011; Bódai et al, 2011; Bódai and Tél, 2012; Bódai et al, 2013; Drótos et al, 2015), in general circulation models (Haszpra and Herein, 2019; Kaszás et al, 2019; Pierini et al, 2018, 2016; Drótos et al, 2017; Herein et al, 2017; Bódai et al, 2020; Haszpra et al, 2020; Haszpra and Herein and Bódai, 2020) and also in experimental situations (Vincze, 2016; Vincze et al, 2017).

2. Line 60: What is the relevance to this work that the ensemble approach has been used in other adjacent but distinct studies that presumably consider different models of different variables?

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The ensemble method turns out to be the only reliable method in processes taking part in the presence of climate change. The traditional approach based on a single time evolution is not representative, and might lead to biased conclusions. This we emphasize now in the Introduction.

The adjusted text in the Introduction:

An appropriate treatment of even elementary models describing climate change is not obvious since basic parameters change with time and, therefore, traditional long-time averages cannot be used to define (in the sense of any statistical quantifiers) a state of the climate. An emerging new view, already embraced by Drótos et al (2015), follows a different route to obtain information on instantaneous statistical quantifiers (e.g. expected, average properties) of the climate. Since our information on the actual state of the climate is incomplete, one imagines an ensemble of parallel Earth systems carrying parallel climate realizations subjected to the same set of physical laws, boundary conditions and external forcing, but with different initial conditions. Then the chaotic or turbulence-like properties of the climate dynamics allows for distinct climate realizations (for a review see Tél et al, 2019). These realizations, however, cannot be arbitrary since only those are permitted that are compatible with physical laws and the given forcing. The ensemble of realizations defines a probability distribution of all the relevant variables at any instant of time from which one can obtain expected, ensemble average properties of the climate (for more details, and mathematical aspects, see Sec. 5). It is therefore natural to use the ensemble view in our conceptual biogeochemistry model,

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too. The ensemble approach in it corresponds to generating parallel atmosphere-phytoplankton realizations from different initial conditions.

3. Figure 8 : Could you add a colorbar rather than (or in addition to) writing it out in the caption?

We added the colorbar to Figure 8 (now Fig. 9, due to the addition of the new schematic drawing, Fig. 1, in Section 2).

4. Section 4: overall I like this section very much but please make explicit mention that angled brackets always correspond to ensemble average, for every variable, early in the section.

We have made this explicit at the beginning of Section 4.

The new text added to Section 4:

Here and in what follows angled brackets <> will always denote averages taken with respect to our ensemble at a given time instant, t.

5. Please consider making code and possibly some archive of the ensembles you run available to support open-access, reproducible science.

We upload the code as supplementary information upon acceptance of the paper.

We thank again the reviewer for the insightful comments, and we hope that with the indicated changes the paper can be accepted for publication in ESD.

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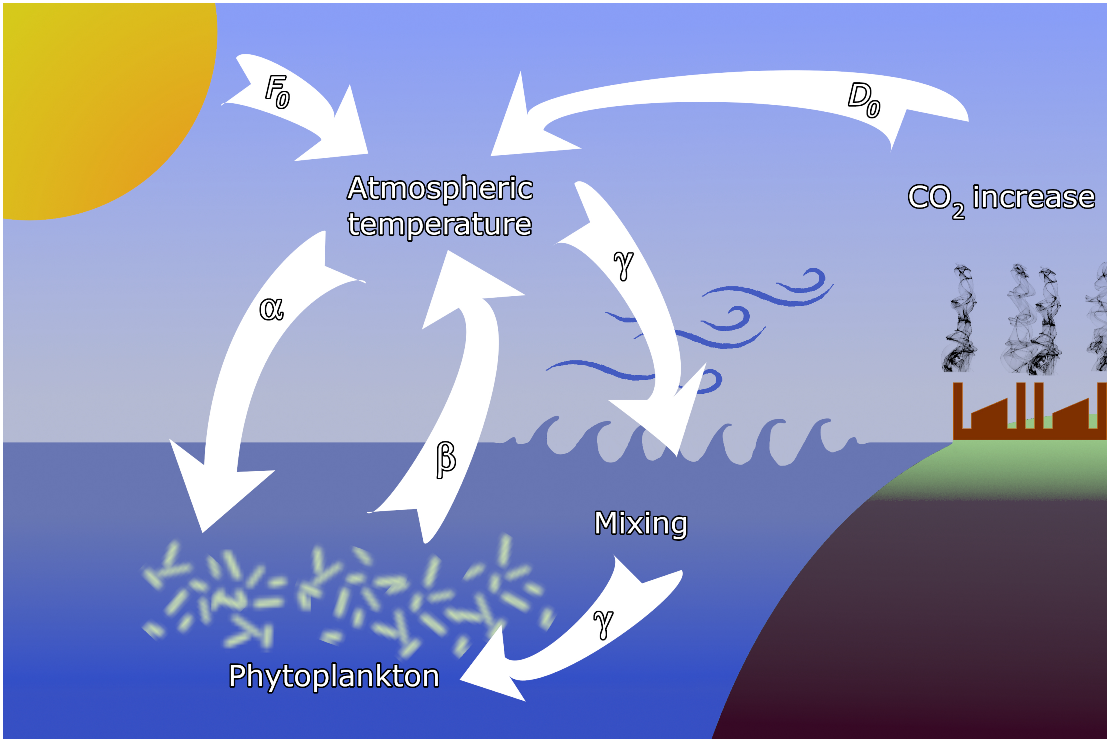

Fig. 1.

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