Earth System Dynamics Discussions Article

Earth system modelling with complex dynamic human societies: the copan:CORE World-Earth modeling framework

Final authors' response

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(Reviewers' comments cited in italics)

Response to Brian J. Dermody (reviewer 1)

The authors present a modelling framework for a new generation of Earth System Models that they term World Earth Models (WEM). The paper presents their theoretical framework for capturing environmental, cultural and what they term, social metabolism processes in a linked model. They then provide details of the software package copan:CORE, which builds on their theoretical framework and is implemented in Python language.

It is this reviewers opinion a new generation of Earth System Models is urgently needed to capture complex dynamics between humans and the environment and this paper is an important first step in attempting to implement a modelling framework for a WEM.

We are happy that you share our opinion on the need for a new generation of models and thank you for your overall assessment of our attempt.

However, I would like to see more argumentation for the development of the theoretical framework they set out as well as clearer description of the model implementation, with consistency between the description of the theoretical framework and the model implementation framework. In addition, I suggest some structural changes to the paper.

We will attempt to improve the MS in this respect by considering your specific suggestions below. Regarding the consistency between the description of the theoretical framework and the implementation framework, we are not completely sure where you find them inconsistent, so we will check carefully during the revision process that these two levels of description are more easily matched by the reader. We would welcome any further comments on where there might be inconsistencies.

Paper Structure

I think the paper could benefit from a slight restructuring for sections 1–3. The introduction introduces many terms without explanation or explanation comes in section 2 and 3. One important example of this is the term social-metabolism. This is later defined along with the other theoretical framings of the Earth System: environment and culture. You should introduce this framing earlier.

We realize we might have misjudged the commonality of terms such as "social metabolism", which might, though well-established in some research communities, be unfamiliar to part of ESD's readership. We will make sure to identify such terms by having the MS read again by a more traditional Earth System scientist and will accordingly give their definitions earlier.

So, I would recommend starting with a shorter introduction with section 1.1 outlining the current state of modelling earth system processes, the shortcomings of these approaches and the motivation for a new framework.

Then section 1.2 outline briefly, and in a language that users can follow (so if you introduce a new term such as social-metabolism, explain it), your theoretical framework, what problems it addresses and how it is implemented.

We agree that such a summary will allow the reader to get a faster general understanding of what will follow, so we are happy to add it as a new section 1.2.

If we understand the following part of your comments correctly, you suggest to either remove the current section 2, which describes the guiding principles we suggest for World-Earth Models, or to include it in much shorter form in 1.1., or to merge it with the description of the theoretical modeling framework (which is currently section 3). Since you comment on parts of this current section 2 below, we assume you would agree that they should not be deleted completely. Because these principles constitute part of the motivation for particular choices we made in designing our framework, we believe that they need to stay included in some way, but may be shortened considerably. To keep the logic of the MS consistent, we believe these principles need to be given before summarizing the framework as you suggested in a new section 1.2. The most natural place for them therefore seems to be the beginning of that new section. So, we will restructure the first sections as follows:

1 Introduction
    1.1 Motivation (content as you suggested)
    1.2 Towards blueprinting World-Earth models (shortened version of current section 2 followed by summary of framework as you suggested)
2 The copan:CORE World-Earth modelling framework (currently section 3)

Then in section 2 outline the theoretical framework in more detail. Crucial here is to motivate your reasoning behind the choices you make. This is not always clear in the discussion manuscript (Theoretical reasoning behind framework).

We believe that by “theoretical framework” you refer to the software-independent level of description of our framework that currently forms section 3.1, “Abstract structure”. We agree that its details might need a better motivation in terms of the reasoning presented in the earlier part of the MS. At the same time, we must make sure that this part can still serve as a concise reference to the main concepts used in our framework that is not cluttered by too much background information and motivation. We will therefore solve this by adding to the end of each subsections of this section a paragraph labelled “Rationale”, giving the reasoning you rightly request. So, the beginning of the new section 2 will look like this:

2 The copan:CORE World-Earth modelling framework
    2.1 Abstract structure
        2.1.1 Entities, processes, attributes
            …
            Rationale: …
        2.1.2 Entity-types, process taxa, process-types
            …
            Rationale: …
        …

The software design section (currently 3.4) will thus become 2.4

Then section 3 outline how the model is implemented. It should be very clear how the theoretical framework links with the implementation framework. This is not currently clear to me yet. Figure 2 is helpful, but I would like to see then how that relates to model framework structure: i.e. a figure like figure 4 but then capturing what is shown in figure 2. Importantly, if you keep more consistency between the theoretical framework structure and the implementation structure, then readers and users will be more easily able to follow what you have done.

We agree that the current description of our reference implementation of the framework in the Python language (currently 3.5) is less complete than the theoretical description of the modeling framework's concepts (currently 3.1–3.3) and the language-independent description of the software design (currently 3.4), and hence the link between the theoretical concepts and the individual Python features we mention may not be sufficiently clear.

Still, we feel that we should not add much more detail to this lowest-level description of the software for several reasons. On the one hand, the current implementation in Python is mainly meant as a first reference implementation which readers may use to try out the framework but whose details might undergo significant changes and improvements in future releases and will probably be accompanied by more high-performance-oriented alternative implementations of the same framework in other languages, in particular C++ and potentially Julia, so that a detailed description as part of the MS will soon be outdated. On the other hand, more importantly, ESD is not a software journal and we believe that software implementation details are not important for the scientific understanding of the framework, its design and possible merit for scientific research.

In view of this situation and the length of the MS we therefore plan to restructure the MS regarding the implementation description as follows. The current subsection 3.5, "Reference implementation in Python" will become subsection 2.5 but only its current first paragraph and the first code example (Fig. 5) will stay in the main text, extended by a sentence saying that the most recent API documentation can be found online. The rest of the current 3.5 will be moved into the SI, including the current Fig. 4 which we will rework to be more easily accessible and visually more appealing.

To visualize the different elements of the software more clearly, we use the freed space to improve Fig. 3 and add a new Fig. 4 as follows. Fig. 3, currently showing a class diagram only for entity-types, will be completed to show all classes that correspond to the abstract concepts shown in Fig. 2, in an arrangement corresponding to Fig. 2. i.e., we will add the classes "Culture", "Metabolism", and "Environment" to its left and the classes "Step", "Explicit", "ODE", "Implicit", "Event" etc. to its right. The new Fig. 4 will show in a simple way how several model components contribute mixin-classes to the entity type implementation classes of a composed model.

Theoretical reasoning behind framework

Page 4 Line 10: The planetary boundaries concept has come in for some criticism lately (Montoya et al. 2018). A model framework such as this can potentially explain how planetary boundaries emerge through cross-scale human-environment interactions. It would be good to explain shortly how such a model framework could illuminate how we can understand how global planetary boundaries link across scales, keeping in mind the criticisms of the concept.

We thank the referee for this helpful comment. We will add a more detailed discussion of how World-Earth modeling can help to understand the properties of planetary boundaries as emergent

properties of complex social-ecological systems on the global scale, reflecting also on different perspectives on the planetary boundaries concept.

Page 4 Line 25 "environmental and societal processes should be described on similar levels of complexity" – sounds good but why? And what does that mean in reality? A tree and a person is equivalent? A country and an ecosystem equivalent? If so, what is the theoretical grounds for that?

We aim to state here that in our opinion World-Earth models should contain balanced representations of social and biophysical components of the Earth system. They should neither be too biased towards very detailed biophysical processes (as current Earth system model already cover this terrain) or towards very detailed socio-economic processes (as current Integrated Assessment Models [IAMs] cover part of this terrain already). Still, concrete model design needs to follow the requirements of the research questions at hand. In the revised manuscript, we will provide a more differentiated reasoning behind this guideline for WEMs.

Page 4 line 30–33, page 5 line 0–5 This seems all reasonable but why? And what is your grounding for these statements? In addition, there is a large body of work on applying agent-based models in the socio-cultural domain, which seems to have been ignored here. If you want to capture that, then you should demonstrate that you are aware of this literature and have considered it, including the many pitfalls of applying agent-based models to social systems. Also relates to the statement on Page 6, Line 13–15. There has been extensive work on formal modelling of socio-cultural processes. See Netlogo References for example: https://ccl.northwestern.edu/netlogo/references.shtml

We will add an explicit explanation of why we think that agent-based (ABM) and network modelling approaches are a valuable addition to Earth system modelling and should, hence, be implementable in World-Earth models. We will emphasize the point that while there is a rich literature on ABMs and formal modelling of socio-cultural processes, it has so far been weakly integrated with other Earth system processes in Earth system modelling. World-Earth models are intended to be designed as tools to enable this integration and coupling that is missing so far.

Page 5 line 9–10 Outline why it is important to capture tipping points. This should also be covered in the intro when discussing shortcomings of existing models.

We thank the referee for pointing out yet another missing explicit explanation for one of our suggested guidelines. We will revise the text accordingly, highlighting that a major shortcoming of existing models in the Earth system domain (particularly IAMs) is their inability to represent social-economic or social-ecological or social tipping points.

Coupling or not?

It is not clear to me whether the copan:CORE framework is designed to couple to other models such as LPJ-Guess and IAMs that you mention or if it is a standalone model with different modules or both? I.e. can external models can be modules within the copan:CORE framework? I would encourage you to outline this in more detail and with more prominence in the paper as a lot of the community are interested in a framework for coupling existing models that can incorporate the kind of dynamics you set out to include.

This is a really important remark which also very much resonates with Mr. Lemmen's comments. We admit we should have discussed the coupling issue in much more detail and will do so in a new subsection 2.1.6, "Interoperability with other model software". To answer your question already here, at the moment it is essentially possible to include external model software by writing a short

“wrapper component” that handles the exchange of state data, including any necessary regridding, and calls the external model’s time-stepping function as long as the external model provides some interface that allows this (e.g. by implementing a BMI, see Mr. Lemmen’s comments below). For IAMs that run in intertemporal optimization mode rather than time-forward simulation mode (via stepping or integration) this will probably not be possible since copan:CORE currently only supports time-forward simulation mode.

Model description

Generally, I find the model description too vague to know what can and can’t be done with it. For instance, it is mentioned you can model resources flows and migration with it. How would this be implemented? Perhaps a few simple examples of specific model frameworks would help the reader understand what copan:CORE can and cant do. E.g. explain how would you use the framework to capture the relation between migration and drought or how tragedy of the commons scenarios emerges within a river catchment?

We were hoping the exemplary model described in the current Sec. 4 would suffice to answer this question. As described in the SI, it implements some resource flows via ODEs in its carbon cycle and economic production components, and has other ODEs implementing migration in its “wellbeing-driven migration” component. The bottom lines of Fig. 10 show a code example, how ODEs are specified in the Python reference implementation. Regarding the modeling of a possible relationship between migration and drought, a model component developer has many possibilities: she could “micro”-model individual migration decisions by giving her “Individual” entity-type mixin class a process of type “Event” that makes the individual move to a different “SocialSystem” at some regular or random time-points with some probability depending on some attribute of its current “Cell” of residence that represents the occurrence of a drought. Or she might choose a “macro”-modeling approach by giving the “Cell” mixin class a process of type “Explicit” that specifies an explicit equation which computes at each time point the emigration flow from this place as a function of some drought-related cell attributes. For tragedy-of-the-commons scenarios the model component developer might chose a game-theoretic modeling approach and give each “Cell” representing a catchment a process of type “Step” that represents discrete time-points at which all “Individual”s residing in the cell make water extraction decisions; the outcome of these decisions might by implemented by giving each “Cell” another process of type “Implicit” that encodes a system of implicit equations which represent the Nash equilibrium between these individual decisions. Implicit equations can also be used to model price equlibria. We have chosen the code examples in Figs. 9 and 10 to show all available formal process types.

Specific Comments

Page 1 line 1–3. This is quite a vague opening sentence. I would drop it. Start with: we introduce.… (the abstract is already quite long)

This first sentence of the abstract was intended to motivate the need for a new class of Earth system models. We will attempt to weave this motivation into the remainder of the abstract and generally shorten the abstract overall.

Page 1 line 5: Not clear what is meant by user roles. Can you be more explicit, especially since this is the abstract.

We will give examples which become clearer later: model end user, model composer, model component developer.

Page 1 Line 14: I wouldn't include social metabolism in the abstract. Not a widely know term.

We will add a brief explanation of the term or replace it by a more widely known term in the abstract.

Page 3 line 30–35 Is this an agent-based model? From the abstract and introduction, I thought it was more than that. However, this concluding paragraph makes the reader think that you are going to introduce an ABM. If you view it as an ABM, fine. But then state that clearly in the abstract.

World-Earth models in our understanding contain agent-based process representation along with other modules that may be, e.g. grid-based. We will clarify this at the indicated place in the text and where else appropriate.

Page 5 line 8 what is time forward integration?

We will define it like this: simulation of changes in system state over time consecutively in discrete time-steps (e.g. via difference equations or stochastic events) or at a continuum of time points (e.g. via ordinary differential equations), rather than solving equations that describe the whole time evolution at once as in intertemporal optimization.

Page 7 Figure 2. While I like this figure, it could be clearer. It's not clear to me how each of the elements relate. Is each level of the network equivalent to Cul, Met and Env and are they then equivalent to the network on the right? It could be simpler to just show the central image (entity types) in one figure in the new intro section 1.2, for example. I like the way you show the different modelling approaches but it isn't clear with the network image how they relate or how cul,met, env relate.

The current version of the Fig. is the result of a lot of discussions with colleagues. We found it important to make clear that there are these three different aspects of WEMs, process taxa, entity types, and modeling approaches, and that they are loosely related without having a simple one-to-one relationship. The thicker lines between "CUL" and "individuals", "MET" and "social systems", and "ENV" and "cells" indicate that we expect that most socio-cultural processes will be implemented at the level of individuals, most socio-metabolic processes at the level of social systems, and most environmental processes at the level of grid cells. The thinner lines however are meant to make clear that this is by no means necessary and that some socio-cultural processes (e.g. regular elections) might better be implemented at the level of social systems etc. The same holds for the relationship between entity types and modeling approaches. While agent-based model components will probably most often use the "individual" entity type, they might also use the "social system" entity type, e.g. for representing governments' decisions, etc.

Section 3.1 is very clear.

Page 10 line 4-5 delete "maybe changing numbers and"

Here we disagree since we believe it is a notable feature that during a simulation, the number of, say, individuals may change.

Page 10 line 12 instead of following entity types, write entity types outlined in Section 3.2

OK.

Page 10 line 20: Give an example, such as countries to clarify

OK.

Page 11 line 4: human-designed, human-reproduced

OK.

Page 12 Line 6–30 Introduce this earlier in the manuscript. See my comments on structure

We agree and will edit the introduction accordingly, see also our response on restructuring the sections above.

Page 16 Line 4: Examplary is not a word. It appears to be an obsolete form of exemplary which means "perfect".

We will correct this typo of "exemplary".

A couple of important references "in prep". Try to find pre-existing publications to support arguments in addition to these where possible.

The Donges et al., in prep., paper is now published as a discussion paper in Earth System Dynamics (currently in review). We will update the reference accordingly. Regarding the Otto et al., in prep., paper which is currently in review but not published online, we will support it by already published literature on the topic.

Page 22: Figure nested within references

We'll move these to the SI as stated above.