Review of "All aboard! Earth system investigations with the CH2O-CHOO TRAIN v1.0"

by

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Summary and general comments:

Kukla and colleagues present the new computationally very efficient Earth system model framework, CH2O-CHOO TRAIN, that combines three existing modules: i) a zonal mean Moist Energy Balance Model (MEBM; after Roe et al., 2015), ii) a continental weathering module (after Maher and Chamberlain, 2014), and iii) a simple box model for the long-term carbon cycle (after Caves Rugenstein et al., 2019). The MEBM can be configured with different geographies to investigate its effect on temperature and runoff distributions for global weathering and carbon cycle dynamics. Especially due to the simple carbon cycle representation, the model simulates about 1 million model years in thirty minutes on a standard laptop. As such, it fills a gap between highly parameterized conceptual box models and Earth system Models of Intermediate Complexity (EMICs); thus, it represents a valuable new model for understanding interrelated Earth system dynamics.

The low computational demand of CH2O-CHOO TRAIN makes it very useful for large-ensemble experiments that are needed for uncertainty quantification. Another advantage the authors mention is that their model is "highly customizable", i.e., "making it easy to directly modify processes in the climate system". Unfortunately, both model strengths are not very well exploited in the manuscript. The model behavior is not compared for the different continental configurations, and only a few parameters are changed to lower and higher values. Why did the authors not put more work into investigating how the TRAIN really behaves, e.g., under different perturbation scenarios and/or model configurations (i.e., investigating structural uncertainties)? Many processes are not explicitly represented in the model and are thus highly parameterized and a large source of uncertainty. Therefore, a comprehensive sensitivity analysis is needed to quantify this uncertainty, identify the most sensitive parameters and adequately understand how the model works (see e.g., Pianosi et al., 2016, 2015, for some methods and ideas). Because this is the first CH2O-CHOO TRAIN model development paper and the model runs so fast, a comprehensive sensitivity study is needed and feasible.

Some parts of the manuscript are not well explained (motivation of the experiments) or information is missing (e.g., a comprehensive table stating model parameter names, values units, references; organic carbon burial & weathering; isotopic balance of the system) or confusing (e.g., is S and P calculated by the weathering module: if yes, how and why?).

Overall, I think the model can be a valuable tool to understanding Earth system dynamics and past climate variations which crucially depends on the combined use of different numerical representations of the Earth system. However, the manuscript would benefit from some more work to help the model uncertainty better and to showcase applications of the CH2O-CHOO TRAIN.

Specific comments:

Abstract: Please shorten some parts of the background and include a few main model results presented in the ms.

It could be made more clear what the main improvements of the model are compared to previous approaches, like COPSE or GEOCARB: I suppose it is the 1D atmospheric energy balance model and the improved water cycle? And also the possibility to represent a continental configuration for the MEBM model?

Related to this: be more specific how the climate processes in the model can be modified. This is mentioned e.g. in the abstract, introduction (~line 45) and the start of Section 3 (line 369). The authors are the most specific when they mention "The model is designed to be highly customizable, making it easy to directly modify processes in the climate system such as ..." (line 44-45) and that the processes are either highly parameterized in simpler models or emerging properties in more complex models. I understand that this is a major strength of the model therefore it would be good to discuss this in more detail, give examples what specifically can be changed and how (I suppose the parameters changed in your experiments are not all possible parameters). A table summarizing what parameters can be changed to affect the different processes in what direction might be helpful.

In the very beginning I thought the continental configuration would also impact the Long-term C-cycle but it actually does not. That should be made more clear in the text and in Fig 2.

Figure 1:
It was not obvious to me how some components shown are necessary to initialize the model. E.g., it is unclear how knowledge about lithology, soil age, soil pCO2 influences the weathering model (I am not able to judge the MEBM part – this is not my expertise). I did not see parameters for them in the main manuscript. E.g. soil age (T_S) is given in Table S2 but I can't see an equation where it is used – or it is t_{wz} in equation (12).

Model
The main manuscript does not include a table stating the main model parameters, their values, units and references. This makes assessing the model construction difficult. Some are given in the SI – this could go into the main manuscript. But do the Tables S1 – 3 include all important model parameters? Please make sure the units for all model outputs are stated, e.g. no units are given for q_{land} and $F_{w,sil,carb}$ after equations 8 + 18 or what is meant by [C] (+ units) in line 195 is not 100% clear.

Also, I suppose various model parameters are very uncertain. Therefore, a sensitivity study which assess the importance of these parameters for different model outputs and calculates quantitative sensitive indices would be very informative in order to understand how the model behaves and its results. In line367 – 368 you say: "These experiments are not meant to be an exhaustive sensitivity analysis of the model." But this is the first version of the model, therefore, in my opinion, a more complete sensitivity analysis is necessary. In contrast, the often long and sometimes vague discussion of model limitations (Section 2.5 & 5.1) could be shortened.

Simulating modern conditions:

It would be very informative to provide a more in depth evaluation of the model results with modern boundary conditions – which, I think, should be the main reference simulation to establish that the model works well. E.g., you could compare your model output with other estimates and/or observations (e.g., plot this in Fig. 4 A – C and also the simulated E minus P). Do I understand it correctly that the output of the C-cycle model is prescribed for the steady-state condition, i.e. all the initial fluxes in Table S3?

2.1 Moist Energy Balance Model – I don't have the expertise to review this in detail.
But where does the temperature threshold of -5°C for the appearance of ice come from? And should this not be very different for ice sheets (on land) and the formation of sea ice? Please give a reference and justify.

How is temperature calculated in the MEBM?

What happens to terrestrial runoff over the ice sheets? Should this not be significantly reduced because the precipitation is snow and becomes part of the ice sheet? This might not be important for the default setup of the model because it does not affect weathering but for your experiments "effect of ice cover on weathering" I suppose it is.

2.2 Weathering:
lines 239 ff. "We parameterize maximum carbonate weathering reaction rates as being 1000 times faster than silicate weathering… " Is this a reasonable assumption? I would assume these parameters have large uncertainties and a large effect on the model output. I would suggest include these (and similar parameters) in a sensitivity study.

Please provide information for how organic carbon weathering is calculated? Is it constant?

In the text (line 101) and in Fig. 1 the authors mention that the weathering module calculates fluxes of P & S, but this is not discussed/introduced in the model description. Why is this even in the model? If I understand it correctly, your ocean PP is not simulated (Corg burial is only scaled to CaCO3 burial) – hence P is not needed. And I don't understand why a S-cycle would be needed ? There is no information in the manuscript!

This section should also include details for the isotopic signals of the weathered Corg and carbonates – some of it is given in Table S3 but it would be good to include it in the main manuscript.

Table S3 does not state the initial silicate weathering rate. I suppose it is equal F_{volc}?

2.3 Carbon cycle:
Please state how organic carbon burial is scaled to CaCO3 burial? Is it done as by Kump & Archer (1999) to isotopically balance the system?

Steady-state of the model:
Related to the last comment: To achieve steady-state is it also necessary that organic carbon burial equals organic carbon weathering – or is this always the case in the model? Or do not have the option to restore some of the buried Corg via volcanic outgassing (see e.g., Lenton et al., 2018, Table 2)?

Please give information how the system is isotopically balanced! This is not discussed.

2.4 Coupled climate-carbon cycle model initialization and integration

Line 299: what does ‘the carbonate speciation described above’ mean? I suppose, you recalculate it every timestep, right – and also $W_{carb,sil}$? Is pH also updated? How?

Line 300: What is meant by “temperature guesses”? Why do you need to guess? Also the rest of the paragraph is unclear to me – why does the model result in a snowball? Does that mean the temperature is everywhere below the threshold of -5°C? And what does “In this case,” (line 301) refer to?

2.5 Model assumptions and limitations

This part, for the most part, speaks about model limitations. And could therefore be removed from Section “2 Model Formulation” and go to the end of the manuscript and combined with “5.1 Model applications and limitations”

3 Model Experiments

The different experiments are not very well motivated or explained. This could be expanded and subsections could be used as in Section 4. A table summarizing the setup of the different experiments would be very helpful.

Please state clearly what the background climate & C-cycle state is for set of experiments? For Fig. 6 – 8 only the normalized values are given – without information how they are normalized.

Would it not be informative to do the same perturbation experiment with every continental configuration to evaluate the effect of geography?

Especially, the description of the second series of experiments using the “Northland” geography is unclear. What parameter are the authors changing? And what is the effect: How much weathering happens under an ice-sheet? Or also the amount of runoff? This is not clear from Section 3. Maybe that is why I struggle to understand the model results (see comments on Section 4.3).

Subtropical continents:
I am not entirely sure how the last set of experiments links to the hypotheses of the breakdown of the silicate weathering feedback. You arbitrarily change the runoff in an experiment that is at steady-state which then causes the feedbacks to respond. And yes, you get a runaway greenhouse for a small continent where the runoff is very sensitive to changes in *w* and the stabilizing strength of the silicate weathering is weak. Would it not be better to to setup different steady-state experiments with the three configurations (and different values of *w*) and then perturb the system (i.e., by injection of CO2) and see how the responses are different?

4 Results

4.1 Reference Simulation

Here you talk again about the temperature guess. This is unclear to me.

Line 424-426: “If both temperature guesses are the same, the first pole to glaciate in the meridionally symmetric case will depend on the tuning of the numerical solver.”
Can the authors please give more details here. Maybe this is related to my question how temperature is calculated in the MEBM?

4.2 Response to abrupt pCO2 increase with modern geography
What is the isotopic signal of the carbon injection?

The motivation given for this experiment is (line 376): “This simulation is used as a verification of the coupled model’s performance in comparison with other, similar simulations across the model hierarchy.” This is not done at all.

There could be more content in this section. The model runs so fast. Why do the authors not put more work into investigating how it behaves under different perturbation scenarios or model configurations or for different parameter settings. I feel like this is a missed opportunity to understand their model better.

Unclear how the last two sentences of the section fit in.

4.3 Varying the effect of ice cover on weathering
If I understand the experiment correctly two parameters are changed at the same time:
1. % of effective runoff
2. volcanic outgassing
I think this makes it difficult to disentangle what’s going on. Imagine, keeping volcanic outgassing unchanged and only changing the effective runoff: this should already result in a different equilibrium climate because some weathering is possible under the ice sheets. If I am correct, this should be evaluated first by the authors.

I find the text difficult to follow. In general, it might be good to start from your default setup: which is, as I understand it, is 0% effective runoff. And then describe what happens if effective runoff is increased.

Please plot the global area of ice-cover as it is talked about in the text, it’s a main part of the experiment and important to understand what’s going on. This might also solve my confusion with the statement in Fig. 5 “Ice sheet growth limits runoff”: Why would this be largest in the experiment with the warmest climate? Ice sheets should expand the least here.

Also what about the ice-albedo-temperature feedback? Does it not play a role for the results of Fig. 5? It is only mentioned at the end to explain the step-changes.

Why does the model calculate higher mean runoff in the 100% effective runoff setup which is the colder climate state. I had the impression runoff scales mainly with temperature (see, e.g. Fig. 4E, F).

4.4 Instantaneous change in moisture recycling efficiency
Why are all results now shown normalized and how is this done?

Fig. 6 D: Why is there first an increase in net C emissions? This is never discussed.

In my opinion, the last paragraph (lines 494 - 502) does not belong into the results section. If at all it could into the limitations section.

4.6 Subtropical continents
line 530: “Runoff tends to decrease with warming in the subtropics in the MEBM module” can you show model output for that? It is in contrast to the statement in lines 436 – 437: “runoff is generally insensitive to global climate between 30 and 50 degrees latitude”.

The description of Fig. 9 is very confusing as it jumps back and forth between increased runoff and decreased runoff experiments and explains how runoff changes through the transient experiments.

Isn’t the small continent of business belt world a big factor why it runs into a runaway greenhouse: i.e. the weathering feedback is weaker than in the other worlds and runoff is probably also more sensitive to changes in *w*.

5 Discussion
It is not really a Discussion paragraph. Maybe something like “Scope of applicability and limitations” would fit better.

The numbering is a bit odd. Why do you need 5.1 if there is not a 5.2?

Maybe move “2.5 Model assumptions and limitations” to the end of the manuscript and combine with information given in “5.1 Model applications and limitations”. Or it might be useful to have two different sections: 1) Model applications 2) Model limitations

Conclusions
The manuscript is missing a conclusion paragraph.

Technical corrections:

Line: 34: ‘the most physically realistic’ maybe better write ‘a more mechanistic’

line 43: add: and ‘a’ box model for …

line 65: Maybe ‘… account for more spatial dynamics than the 0-D representations ...’ because it is just 1D so does not account for all the spatial dynamics

line 68: “precipitation (assumed proportional to runoff)” The phrasing is a bit unclear to me.
Do you mean runoff is proportional to precipitation (because it sounds like the model calculates precip first)? And why is this needed here? Because you are eventually interested in runoff?

Line 73: maybe say ‘in a more mechanistic way’

line 97: delete the first occurrence of the word ‘box’

line 100: add ‘long-term carbon cycle **model**’ + singular for ‘outputs’

line 101:should read: These fluxes are used **to** calculate

Equation (7) *w* is not defined here. In Figure 6 you call it evapotranspiration. Which is confusing because ET was defined as evapotransipiration after Eq. (7).

Equations: be consistent with commata in subscripts, e.g., compare (19) vs (21)

line 195: It might be good to explicitly state here: "We calculate solute concentrations for inorganic carbon, [C], ... " To make clear that all forms are considered here.

line 281: please provide a reference for the 10° colder also in the text – not just in Table S3

line 363: small letter p in phosphorus

Missing references for PETM C injection: lines 375-376, 449-450

line 420: why geography? You are only looking at the cat-eye geography here!

Line 471-473: this is trivial

Fig. 6: And related text, define what net C emissions are.
The names of the geographies are different in Fig. 6.

line 636 + 637: Please be careful: GENIE (i.e., Holden et al., 2016; Ridgwell et al., 2007) does not include a representation for ice sheets but only a sea ice model.

Fig. S4: has the wrong exponents for the *D* values

References

Caves Rugenstein, J. K., Ibarra, D. E., and von Blanckenburg, F.: Neogene Cooling Driven by Land Surface Reactivity Rather than Increased Weathering Fluxes, Nature, 571, 99–102, https://doi.org/10.1038/s41586-019-1332-y, 2019.

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Pianosi, F., Sarrazin, F., and Wagener, T.: A Matlab toolbox for Global Sensitivity Analysis, Environ. Modell. Softw., 70, 80–85, https://doi.org/10.1016/j.envsoft.2015.04.009, 2015.

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