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Geoscientific
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Discussions

Interactive comment on "GEOCLIM *reloaded* (v 1.0): a new coupled earth system model for past climate change" *by* S. Arndt et al.

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We would like to thank both reviewers for their thoughtful and helpful comments. Please find our response to their comments below.

Reviewer ♯ 1:

General comment:
One disadvantage of the present paper is that it forces the general reader who truly wants to understand this new model and its validity to go back through the earlier version of GEOCLIM and the FOAM 3-D GCM, something most readers will not have the time or patience to do.

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Interactive Discussion

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We added a link to the FOAM website that provides a comprehensive overview of FOAM and its performance. In addition, the section 2.1 provides a short, general description of FOAM 3D, relevant references, as well as a description of the offline coupling between GEOCLIM *reloaded* and FOAM 3D results within the GEOCLIM *reloaded* framework. The paper thus contains all information necessary to assess GEOCLIM *reloaded* and its validity. The main aim of the paper is to introduce and test the new ocean and sediment modules, as well as the modifications of the continental weathering module. Therefore, a more detailed description of FOAM would go beyond the scope of this paper. Yet, the manuscript includes a detailed and comprehensive description of the continental, oceanic and sedimentary modules included in GEOCLIM *reloaded*. This description, also explicitly includes all processes that were directly adapted from the earlier version of GEOCLIM (e.g. continental weathering processes). Therefore, the reader does not necessarily have to go back through the earlier version of GEOCLIM to understand the new model.

If I understand correctly, as alluded to in the Introduction, it is ultimately the goal of the authors to use the GEOCLIM reloaded model to interpret Earth system environmental and climatic change of the geologic past. Indeed the authors spend most of the Introduction talking about the geologic past and modeling the carbon cycle and atmospheric CO2 changes through geologic time. After reading the paper, I realized that this is not the focus of the present paper; thus, it is not clear to me how the authors will go about modeling past environmental change with the present model, which describes mainly the modern day biogeochemical cycles of carbon, nitrogen, phosphorus, and oxygen and testing the model output against present-day vertical and spatial distributions of these elements in the ocean.

GEOCLIM *reloaded* is designed to investigate environmental and climatic change of the geological past. Therefore, the model integrates a mechanistic description of the major biogeochemical cycles and simulations are realised with a generic set of model parameters. The model is thus fully generic and flexible. It is designed to resolve the biogeochemical cycling under changing and extreme environmental conditions such ocean anoxia, euxinia or methane release events. The aim of the presented manuscript is to provide a comprehensive model description, as well as an evaluation of the model performance. The model performance is tested for the present-day ocean, since comprehensive, global benthic and pelagic data sets that allow for a careful and comprehensive model-data comparison are only available for the modern-day ocean. We clarified this point in the introduction and emphasised that both GEOCLIM and GEOCLIM *reloaded* are designed to explore past climate change.

GEOCLIM reloaded as presented here does not appear to deal with such geologic factors as sea level rise and fall on various time scales, changing continental positions, changing composition of the weathering regolith through geologic time, appearance of land plants,...

GEOCLIM *reloaded* is designed to explore past climate change. Therefore, as mentioned throughout the manuscript, GEOCLIM *reloaded* is fully capable of dealing with different kinds of geological factors. Changes in sea level are taken into account by a changing surface area of the coastal ocean. In addition, both GEOCLIM and GEOCLIM *reloaded* calculate spatially-resolved continental weathering fluxes on a 7.5^o long 4.5^o lat grid within the given paleogeographic setting and, thus, accounts for the impact of the continental setting on global biogeochemical cycles (see p.6, line 20 and section 2.2). GEOCLIM can also account for changes in the composition of the weathering regolith through the discrimination of basaltic, granitic, and carbonate rock weathering (see Donnadieu et al., 2006). The current version of GEOCLIM *reloaded* does not directly account for the impact of land plants on weathering. Nevertheless, weathering laws could be easily extended by the introduction of an "ad hoc" parameter similar to the approach adopted in GEOCARB. Note also that the original version of GEOCLIM has been recently coupled to a dynamic global vegetation model and thus

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accounts for the influence of terrestrial vegetation on continental weathering fluxes through its effect on global average temperature and runoff by promoting transpiration, reducing the surface albedo, and increasing the soil roughness.

...,but since this paper does not deal with the geologic past, why so much emphasis on it in the Introduction?. The authors might consider a rewrite of their Introduction with less emphasis on the geologic past.
GEOCLIM *reloaded* is designed to investigate the evolution of the biogeochemical cycling over geological timescales and especially in the distant past. We stressed this aspect in the introduction.

Specific Comments:

On p. 2111 the authors refer to the "Walker thermostat (Walker et al., 1981)". Although Walker has been given credit for this feedback mechanism, I believe it actually had its beginning in the works of Hoegbom (see Berner, Am. J. Sci., 1995).
We added a reference to Hoegbom's original work and the very interesting disquisition on his work by Berner, 1995.

On p. 2127 the authors state that " "shallow-water carbonate formation R2.1 depends on the saturation state of the epicontinental ocean with respect to aragonite, ΩAr, as well as on the total shelf area. . ." There is no mention of a temperature dependence, although we well know that temperature is an important variable in controlling marine carbonate phase mineralogy and chemical composition.
Except for the temperature dependence of the solubility product, GEOCLIM *reloaded* does not account for temperature effects on shallow-water carbonate formation. In

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general, reaction kinetics of carbonate minerals in the natural environment are poorly known. Multiple experiments on corals and coraline algae revealed a dependence of biogenic calcification on temperature (e.g. Leclerq et al., 2002; Mackenzie and Agegian, 1989, Marshall and Clode, 2004, Lough and Barnes, 2000). However, these relationships are species-dependent and often subject to uncertainties associated with experimental design. In GEOCLIM *reloaded*, shallow water carbonate precipitation integrates both abiotic and biotic carbonate precipitation. Because of the uncertainties associated to the temperature-dependency of shallow carbonate formation, the evolution of the coastal surface area, simulated shallow water temperatures and the generic nature of GEOCLIM *reloaded*, a simplifying description was adopted here. Although this formulation cannot resolve the carbonate phase mineralogy, it allows for a simple and scalable description of shallow water carbonate fluxes and their impact on global carbon cycling in the light of uncertainties associated with simulating past climate change.

On p. 3132 the authors state that "The formation of iron sulfides in the water column...is an important sulfur sink." I do not follow this. Iron sulfide is mainly a product of diagenesis in today's ocean and in the geologic past, it has taken exceptional environmental circumstances for it to form in the water column as an important phase. The formation of iron sulfide in the water column can be an important sulfur sink under euxinc conditions. GEOCLIM *reloaded* is designed to resolve the biogeochemical cycling in the geological past and under different environmental conditions (e.g. oceanic anoxic events) and, therefore, it includes this process. We have modified this sentence to stress that iron sulfide precipitation may be an important sulfur sink under extreme environmental conditions, but is negligible in a well-ventilated ocean.

On p. 2140 the authors state that "Precipitation of iron sulfides, R12, only occurs in the oxic and suboxic layer of the sediment." This appears to be a misstatement. Sulfate reduction occurs in the anoxic layer and with available reactive iron through a

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series of steps, iron sulfide is formed.
This statement may indeed be misleading. The precipitation of iron sulfide is limited to the oxic and suboxic layers of the sediment to account for the limited availability of reactive iron under anoxic conditions. Sulfides are produced in the anoxic sediment layers and diffuse upwards towards. A fraction of the diffusive sulfide flux precipitates as iron sulfide in the upper oxic/suboxic sediment. Due to computational constrains and the uncertainties associated with the iron cycle, GEOCLIM *reloaded* does not include an explicit description of iron. Therefore, we adopted this simplified treatment to account for the consumption of sulfide.

Evaluation of the organic matter mineralization flux in the model appears to be a problem, yet do not the calculated vertical concentration gradients of carbon, nitrogen, and phosphorus in the ocean fit reasonably well the WOCE, etc observations? Does this not constrain the mineralization flux?
Model results indeed suggest that the model provides a realistic estimate of pelagic and benthic organic matter mineralization rates. We added a sentence to section 5.2 to emphasise this point.

p. 2152 section 5.5: Is there still not debate about the statement that "the depth of the lysocline coincides with the saturation horizon." Certainly the late John Morse and Bob Berner (see e.g., Morse and Mackenzie, 1990) believe the lysocline is a kinetic horizon. The authors should at least qualify this statement and not simply accept unequivocally Sarmiento and Gruber's paper (2006) conclusion. Also, what about dissolution of calcium carbonate above the lysocline (e.g., Milliman, et al., Deep-Sea Res., 1999)? This paper is referenced in the References but it is not clear whether this process has been considered in the GEOCLIM reloaded model.
We added a paragraph in section 2.3 (calcite dissolution) to acknowledge the complex interplay that determines the the dynamic of calcium carbonate dissolution in the global ocean and the uncertainties associated with it. Due to the uncertainty associated to

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calcium carbonate dissolution above the lysocline, the model does not account for this process.

Before publication the authors should go though the manuscript carefully. There are quite a few typographical errors like p. 2115, line 3, should be describe; p. 2128, line 15, should read for the; p. 2132, line 4, the is repeated, line 5 availability of iron; p. 2145, line 10, not than but to; and so forth
We carefully checked the manuscript for typographical errors.

Reviewer ♯ 2:

(i) The authors point out on p.2116 that computational cost renders a direct coupling of the atmospheric module FOAM with GEOCLIM reloaded infeasible. On p.2115, the authors say that the atmospheric module FOAM is a parallelized version of CCM2. The authors should add a paragraph about model performance in terms of computational costs. How does the performance of this climate model compare with other comparable models? Can the entire model run on a single-CPU and/or in a parallelized version? I think the computational costs may be a critical point for other potential users and this journal is the right place to discuss and clarify that. The authors may include a table in the model section with some benchmark tests.
We agree. We added a paragraph to section 3, which addresses the computational performance of the model.

(ii) I would like to see the source code of the present model to be put on a open-access server to get even more transparency.
The source code of the ocean, sediment and continent modules is added as a supplementary material. Yet, the look-up tables required for the offline coupling between

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GEOCLIM *reloaded* to FOAM results require event-specific FOAM simulation results and can therefore not be provided.

(iii) I do not understand why the authors compare their model output with bottle data from WOCE Hydrographic Program. What is the advantage over using the gridded quality-controlled WOA01/05 or GLODAP?
The World Ocean Circulation Experiment WOCE provides global ocean observations of unprecedented extent and quality for the period between 1988 and 1998. Model performance is evaluated on the quality of the model fit to the main features of the global distribution of dissolved carbon and nutrients in the world ocean. The choice of the observational data set is thus not of critical importance for the main conclusions.

(iv) I have a question regarding the length of the simulation until steady-state is reached. How long does it take (in model years) to reach 'quasi' equilibrium for the atmospheric module as well as the coupled continent/ocean/sediment system in the performed present-day model simulations?
Assuming constant atmospheric CO_2 levels, the continent-ocean-sediment reaches a steady state after approximately 10 kyrs. The simulation time required to reach a 'quasi' equilibrium for the coupled model is much longer and takes a few 100 kyrs depending on the initial conditions.

(v) The authors point out that the model is mainly capable to deal with very long-term simulations for the past climate. However, all of their model-data comparison is focused on present-day observations. Please add why the focus is on the present-day, and/or change the introduction accordingly.
The main purpose of the presented manuscript is to provide a comprehensive and detailed description of the model, as well as a careful evaluation of its performance. The availability of comprehensive data sets which allow such an evaluation is limited to the modern-day ocean and the performance of GEOCLIM *reloaded* is therefore

evaluated under present-day conditions. However, GEOCLIM *reloaded* was designed to resolve the biogeochemical cycling under past extreme climate conditions. Its satisfactory performance for the present-day ocean without a parameter optimisation increases the confidence in the model's flexibility.

Technical points
We carefully checked the manuscript for typographical errors.

Interactive comment on Geosci. Model Dev. Discuss., 3, 2109, 2010.