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Robustness and Uncertainties of Current Marine Carbon Cycle Models

Andreas Oschlies (Kiel)

Numerical biogeochemistry-circulation models are essential tools for exploring ideas, testing hypotheses, and making inferences about the possible past and future evolution of climate and the Earth system. Results of such models are used not only for academic purposes, but are also used to inform society and decision makers. It is therefore mandatory that we aim for a good understanding of the robustness and uncertainties of the results of such models. This is not an easy task as current state-of-the-art models are complex systems, composed of many different modules describing different components of the Earth system, with different modules often developed for different purposes, and each one having numerous input parameters that are difficult to constrain from observations. A complete sensitivity or uncertainty analysis of such complex models is not routinely done, and this study will describe first attempts to evaluate the robustness and uncertainty of marine carbon cycle components of current Earth system models.

We begin with the question of how we can assess whether a given model is any good. For different research questions "good" will have different meanings, and in the context of the large-scale and long-timescale carbon cycle, patterns of observed biogeochemical tracer distributions may serve as a reasonable reference that a "good" model should be able to reproduce. Observations are available mostly for the current state of the ocean, and one has to keep in mind that a reasonable simulation of the present state does not automatically imply that the same model will provide reasonable simulations of different climate states. A reasonable simulation of present-day biogeochemical tracer distributions may, however, be regarded as a necessary test that any high-quality model has to pass. To this extent we have developed a computationally efficient testbed for marine biogeochemical models that can, *via* the transport matrix method (Khatiwala 2007), be integrated for several thousand years per day (Kriest et al. 2010, 2012). In this scheme, a seasonally cycling steady-state circulation field is employed to transport passive tracers and to spin up the biogeochemical model for a range of different parameter combinations or initial conditions. One interesting preliminary result is that for typical models of one or two nutrients, dissolved organic matter, one phytoplankton and one zooplankton compartment, the model-derived steady state is independent of the chosen initial tracer distributions as long as total phosphorus is kept constant. This suggests some robustness of model results, although this finding has been difficult to generalize given the strong nonlinearities in biogeochemical model formulations and the associated potential for bifurcations and multiple steady states. The result is, however, good news for any paleo modelling studies that usually have to start from initial conditions about which we have very little prior knowledge (though even our prior knowledge about the ocean's phosphorus content at different times might be very limited, Wallmann 2012).

In general, the outcome of biogeochemical model integrations will depend on both ocean circulation and biogeochemical process descriptions. The attribution of any model-data misfits to either of these is therefore not straightforward. An encouraging finding is that initial model evaluations suggest that even different circulation fields result in very similar biological model parameters that yield smallest model-data misfits with respect to global distributions of nutrients and oxygen (Kriest and Oschlies 2013). Less encouraging is that a range of models, ranging from conceptually simple nutrient-restoring models to state-of-the-art multi-nutrient multi-plankton functional type models, seems to yield very similar root-mean-square misfits to observed global distributions of phosphate and oxygen (Kriest et al. 2012). If these results are confirmed for different circulation fields and fully optimized biogeochemical model parameters, the biogeochemical model development of the last decades appears to have had essentially no effect on the ability of the different models to reproduce observed distributions of these biogeochemical tracers. Overall, all models investigated can at least simulate global tracer distributions better than a random model, with most explanatory power being found for the distributions of nutrients and oxygen in the vertical. This vertical distribution is highly relevant for the ocean-atmosphere partitioning of carbon, which is of particular interest for research topics such as glacial cycles.

While an evaluation of models with respect to their ability to reproduce the current state of the ocean is, in principle, possible and straightforward, uncertainties in the simulated sensitivity of the different models with respect to environmental change are much more difficult to assess. Specifically tuned models that yield very similar fits to present-day tracer distributions can simulate changes in simulated primary production of even opposite sign in response to global warming (Taucher and Oschlies 2011). Changes in simulated export production and air-sea fluxes of CO_2 appear, however, more robust with respect to changes in biogeochemical parameters. Analysis of the way current biogeochemical models simulate the marine nitrogen cycle suggest far less robust results with respect to its sensitivity to changes in redox conditions or oceanic nutrient supply from land or from the atmosphere (Landolfi et al. 2013). It is shown that typical formulations used to describe marine nitrogen fixation and its response to nitrogen loss processes *via* denitrification and anammox can yield counterintuitive results of net losses of marine fixed nitrogen upon addition of new nitrogen to large parts of the tropical oceans. Changes in redox conditions associated with oxygen minimum zones can also affect the cycling of iron and phosphorus, with potentially large impacts on oceanic nutrient inventories and the global carbon cycle. Such processes are not generally represented in state-of-the-art models such as those used in the Coupled Model Intercomparison Project Phase 5 (CMIP5), which formed the basis of the model simulations used in the recent 5th IPCC Assessment Report. A neglect or misrepresentation of such processes that can change the marine nutrient inventory can introduce substantial uncertainty in model projections of past or future climates that is difficult to quantify. A better process understanding and case studies involving observed changes ranging from paleo events to interannual or seasonal variability appears promising for providing better constraints on models and estimated uncertainties.

While assessing models *via* metrics evaluating large-scale patterns of model-data misfits can provide reasonable information about the models' ability to simulate the current state of the ocean, the investigation of individual processes is advocated to gain more confidence into the models' applicability for extrapolations to past and future environmental conditions.

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Prof. Dr. Andreas Oschlies
GEOMAR Helmholtz Centre for Ocean Research Kiel
and University of Kiel
Düsternbrooker Weg 20
24105 Kiel
Germany
Phone: +49 431 6001936
Fax: +49 431 6004469
E-Mail: aoschlies@geomar.de