

Interactive comment on “C-GEM (v 1.0): a new, cost-efficient biogeochemical model for estuaries and its application to a funnel-shaped system” by C. Volta et al.

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Response to Referee #1 (Dr. J. Lin)

Dear Dr. Lin,

We appreciate your positive feedback and we are grateful for the constructive comments that helped improve our manuscript. Please, find a detailed answer to your comments and questions below. For clarity, our reply is highlighted in blue, while quotes of updated manuscript sections are indicated in red.

C2996

General comments:

I normally work with three-dimensional water quality models that being used for management purposes. I see the strength of this model is its simplicity, yet still being able to represent the major hydrodynamic and biogeochemical characters of a system. The level of complexity of this model is perhaps equivalent to a one-dimensional longitudinal model, the difference is that this model assumes for an ideal type of geometry that both estuary width and depth can be represented with mathematical equations (as functions of distance for the estuarine mouth). However, there is trade off for taking this route. On the one hand, it makes easier to apply the model to different type of estuaries, and hence as a better tool to study geometric effects on biochemical characters of a system. On the other hand, the inaccuracy of morphology representation of a system may lead to errors of biochemical simulations when the model is calibrated or validated through field data. This contradiction will limit the model usage.

Although the use of idealized geometries is obviously a simplification, previous research (Savenije, 1992, 2005, 2012), as well as the presented model validation show that the proposed approach provides an accurate representation of the main hydrodynamic features and the estuarine transport processes (Figs. 6-8 in the manuscript). The quality of this representation is comparable to the one of a multi-dimensional model based on detailed bathymetric maps (e.g. compare with Arndt et al., 2007). We are thus confident that the idealized representation won't compromise the results of the biogeochemical simulation.

Instead of closely mimic the field data, the authors may consider to calibrate this model against several biochemical patterns and apply the model to different estuarine types. Figure 3 is currently presented as a concept, the model and the publication would be much strengthened if the model could realize the concept.

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Perhaps this manuscript is a first step on the road and for that reason I'd like to support its publication.

This is exactly the purpose of the new, idealized approach. As already stated in the introduction of the manuscript, C-GEM is not designed to replace complex, multi-dimensional, process-based models that are used to unravel biogeochemical dynamics in well-surveyed estuarine systems. Instead, C-GEM has been developed as a tool for the assessment of global estuarine biogeochemical dynamics for which multi-dimensional models are, due to their high data demands and computational costs, not suited. The C-GEM framework affords the treatment of a large number of estuaries, including those for which morphological, hydrodynamic and biogeochemical data are incomplete or absent. Yet, unlike simplified box model approaches, which are still widely used to assess global estuarine dynamics, C-GEM does not compromise on the representation of the physical environment, but provides an accurate representation of the estuarine hydrodynamics based on a data-efficient idealized approach. We added a few sentences to the introduction to emphasize these points. In addition, a discussion of the scope of applicability has been added to Section 5 "Current model Limitations", which is now called "Scope of Applicability and Model Limitations". This manuscript is indeed the first step towards a regional and global application of the model, which is currently underway. The purpose of this "GMDD Model Description Paper" is to provide:

- a) a comprehensive and technical description of the model approach and the numerical model to which future users will be able to refer to;
- b) a fully documented and complete version of the model source code and an example of a model set-up;
- c) a comprehensive assessment of the model's performance.

The Scheldt estuary has been chosen as a test case because of the availability of comprehensive, multi-annual observations, as well as simulation results from a multi-dimensional model for the Scheldt that provide a robust basis for a detailed

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assessment of C-GEM's performance.

PAGE 5649, line 12:

"The C-GEM modelling platform is thus compatible with hundreds to thousands of stationary or fully transient simulations (including daily to seasonal fluctuations) on a time span of years to decades, using geometric information readily available through maps or remote sensing images. Moreover, unlike simpler box model approaches, which are still widely used to assess global estuarine dynamics (e.g. Andersson et al., 2005; Slomp and Van Cappellen, 2007; Laruelle, 2009; Mackenzie et al., 2012), C-GEM resolves the most important temporal and spatial scales and provides an accurate description of the estuarine hydrodynamics and transport. It may thus represent a promising avenue towards the development of a generalized method for exploring and quantifying biogeochemical transformations and fluxes in alluvial estuaries at the regional and/or global scale.

In the first ..."

PAGE 5676, line 5:

"5 Scope of Applicability and Model Limitations"

PAGE 5676, line 10:

"... comparison. However, our ability to assess the role of the estuarine environment for global biogeochemical cycles and greenhouse gas budgets, as well as their response to ongoing global change requires tools that are computationally efficient and can extrapolate knowledge from well-studied to data-poor systems, while at the same time resolving the most important hydrodynamic and biogeochemical processes and scales. The new one-dimensional model C-GEM proposed here is such a computational tool. It represents a valid compromise between performance and computational efficiency and reduces data-requirements by using an idealized representation of the estuarine geometry. Its scope of applicability covers the entire

C2999

range of alluvial estuaries, from tidally-dominated systems with a large tidal range and low river discharge to fluvial-dominated systems characterized by significant freshwater input (Regnier et al., 2013b). It can be used to resolve the complex process interplay that drives the estuarine biogeochemical dynamic and to quantify estuarine carbon and nutrient budgets. In addition, the computational efficiency of C-GEM offers the possibility to simulate simultaneously the biogeochemical dynamics of a large number of estuaries and the contiguous coastal ocean. Although not considered so far, C-GEM could theoretically be applied to the tidally-influenced, inland sections of very large river systems (e.g. Amazon). The value of such application is however questionable because large rivers contribute disproportionately to the overall land to ocean carbon fluxes and might thus deserve a dedicated model. In addition, their tight estuarine-continental shelf coupling and the importance, as well as, the complex multi-dimensional dynamics of their coastal plumes requires a multi-dimensional model representation. Numerous models have already been developed for these systems (e.g. Gallo and Vinzon, 2005; Denamiel et al., 2013) and in the future, they could be explicitly represented in high-resolution Earth System Models (Bauer et al., 2013). In contrast, for the smaller alluvial estuarine systems, mechanistically rooted upscaling strategies need to be designed to better constrain their roles in the global carbon cycle (Bauer et al., 2013) and C-GEM is a tool of choice in this context. However, ...”

Comment #1:

TOC includes particulate matter that settles to the estuary bed, this function seems omitted from the model. The effect of this omission to the model performance is not known and need to be discussed.

The manuscript describes a version of C-GEM that is able to capture the main estuarine biogeochemical features of estuarine systems. As discussed in the limitations section (Section 5), this version does not include a benthic model and

C3000

deposition/re-suspension fluxes are, thus, omitted from the model. Therefore, the model does not account for POC degradation and burial in estuarine sediments. Nevertheless, estuarine POC is often composed of refractory material (Abril et al., 2002) with a variable, but relatively slow first-order decay rate and is considered essentially inert on seasonal-annual time scales (e.g. Soetaert et al., 1993; Regnier and Steefel, 1999; Vanderborght et al., 2007). The good fit between field measurements and variables tightly associated with organic carbon dynamics, such as for instance oxygen (Fig. 10 in the manuscript), supports this notion. The lack of an explicit representation of estuarine POC burial may result in an overestimation of estuarine POC export fluxes, but has no effect on the simulated biogeochemical dynamics as it makes ultimately no difference for estuarine biogeochemical process rates, CO₂ fluxes, NEM and nutrient filtering capacities if refractory POC is buried in the sediment or exported to the coastal ocean. We added a few sentences to the model description and we also emphasized these points in the model limitation section. The development of a benthic module, which will account for the deposition, consumption, burial and re-suspension of POC, similar to Arndt and Regnier (2007), is currently under way.

PAGE 5656, line 11:

“... pool. The latter is represented as a single pool including only the fraction of the organic carbon, which actively contributes to the short-term supply of inorganic nutrients (Regnier and Steefel, 1999). Thus, the model does not account for burial of (refractory) particulate organic carbon in estuarine sediments (Abril et al., 2002; Vanderborght et al., 2007). Organic matter is degraded ...”

PAGE 5676, line 16:

“... coupling. The resulting lack of a representation of particulate organic carbon burial might result in an overestimation of estuarine organic carbon export fluxes to the coastal ocean. The most ...”

C3001

Comment #2:

A full implementation of a benthic model may be challenging to the current C-GEM, but authors may consider to parameterize the major processes or fluxes between benthic-pelagic interfaces.

The version of C-GEM presented here does not include an explicit description of benthic processes and section 5 already discusses the limitations resulting from the absence of benthic-pelagic exchange in the model. Within the C-GEM framework (that aims at keeping data demand low), a process-based, coupled benthic module rather than a highly parameterized description would be the choice. The description and performance test of such a process-based benthic module would go beyond the scope of this paper and it will be thus the subject of a separate manuscript. However, it is already pointed out in the manuscript that the module structure of C-GEM would easily accommodate a benthic-pelagic coupling. We slightly modified the text in section 3.5.1 to stress the possibility of incorporating benthic-pelagic exchange processes within C-GEM.

PAGE 5663, line 2:

“... by, for instance, different phytoplankton groups or additional transformation processes, such as adsorption-desorption or benthic-pelagic exchange processes.”

NB. Please, note that the upgraded manuscript has been uploaded as supplement.

Literature cited in the responses:

Andersson, A. J., MacKenzie, F. T., and Lerman, A.: Coastal ocean and carbonate systems in the high CO₂ world of the anthropocene, *Am. J. Sci.*, 305, 875–918, 2005.

C3002

Abril, G., Nogueira, M., Etcheber, H., Cabeçadas, G., Lemaire, E., and Brogueira M. J.: Behaviour of Organic Carbon in Nine Contrasting European Estuaries. *Estuar. Coastal Shelf S.*, 54, 241-262, 2002.

Arndt, S. and Regnier, P.: A model for the benthic-pelagic coupling of silica in estuarine ecosystems: sensitivity analysis and system scale simulation, *Biogeochemistry*, 4, 331-352, doi:10.5194/bg-4-331-2007, 2007.

Arndt, S., Vanderborght, J. P., and Regnier, P.: Diatom growth response to physical forcing in a macrotidal estuary: coupling hydrodynamics, sediment transport and biogeochemistry, *J. Geophys. Res.*, 112, C05045, 2007.

Bauer, J. E., Cai, W.-J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., and Regnier P. A. G.: The Coastal Ocean as a Key Dynamic Interface in the Global Carbon Cycle, *Nature*, 504, 61-70, 2013.

Denamiel, C., Budgell, W. P., and Toumi, R.: The Congo River plume: Impact of the forcing on the far-field and near-field dynamics, *J. Geophys Res-Oceans*, 118, 964-989, 2013.

Gallo, M. N. and Vinzon, S. B.: Generation of overtides and compound tides in Amazon estuary, *Ocean Dynam.*, 55, 441-448, 2005.

Laruelle, G. G.: Quantifying nutrient cycling and retention in coastal waters at the global scale, Ph.D. Thesis, Universiteit Utrecht, The Netherlands, 2009.

Mackenzie, F. T., Lerman, A., and DeCarlo, E. H.: Coupled C, N, P, and O biogeochemical cycling at the land-ocean interface. In: *Treatise on Coastal and Estuarine*

C3003

Science, v. 5, J. Middleburg and R. Laane, eds., Elsevier, 317-342, 2012.

Regnier, P. and Steefel, C. I.: A high resolution estimate of the inorganic nitrogen flux from the Scheldt estuary to the coastal North Sea during a nitrogen-limited algal bloom, spring 1995, *Geochim. Cosmochim. Ac.*, 63, 1359-1374, 1999.

Regnier, P., Arndt, S., Goossens, N., Volta, C., Laruelle, G. G., Lauerwald, R., and Hartmann, J.: Modeling estuarine biogeochemical dynamics: from the local to the global scale, *Aquat. Geochem.*, 19, 591-626, 2013b.

Savenije, H. H. G.: Rapid assessment technique for salt intrusion in alluvial estuaries, Ph. D. Thesis, IHE Report Series 27, International Institute for Infrastructure, Hydraulics and Environment, Delft, the Netherlands, 1992.

Savenije, H. H. G.: *Salinity and Tides in Alluvial Estuaries*, 1st Edn., Elsevier, Amsterdam, the Netherlands, 2005.

Savenije, H. H. G.: *Salinity and Tides in Alluvial Estuaries*, 2nd Edn., available at: <http://salinityandtides.com> (last access: 10 August 2013), 2012.

Slomp, C. P. and Van Cappellen, P.: The global marine phosphorus cycle: sensitivity to oceanic circulation, *Biogeosciences*, 4, 155–171, doi:10.5194/bg-4-155-2007, 2007.

Soetaert, K., Herman, P. M. J., and Scholten, H.: *MOSES: Model of the Scheldt estuary. Ecosystem model development under SENECA*. CEMO/ NIOO, Yerseke, the Netherlands, 1993.

Vanderborght, J. P., Folmer, I., Aguilera, D. R., Uhrenholdt, T., and Regnier, P.: Reactive-transport modelling of a river-estuarine-coastal zone system: application to

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the Scheldt estuary, *Mar. Chem.*, 106, 92-110, 2007.

C3005