Response to Referee #1 (Anonymous)

We would like to thank the referee for the constructive comments. Below, we address in detail each point raised. For the sake of clarity, our replies are highlighted in blue, while quotes of updated manuscript sections are indicated in red.

General comments:

Comment #1:

This paper represents a brave and useful attempt to develop a generic approach of estuarine biogeochemistry. It defines archetypal types of estuaries, applies average constraints typical of the temperate climate zones of the world and applies a detailed hydro-sedimentary model coupled with a biogeochemical model to calculate hydro-sedimentary, C and nutrient behavior. The value of the parameters describing the kinetics of the biogeochemical processes is chosen on the basis of a comprehensive literature review, and sensitivity tests are performed with the range of parameters found in the literature. The value of a number of integrative indicators of estuarine biogeochemistry is calculated, including Net Ecosystem Metabolism, CO_2 efflux, C and N filtering capacity.

The major weakness of the work, to my eyes, lies in the lack of a clear discussion of the representativeness of the three types of estuaries considered. In the Summary, they are presented as "end members estuaries", which is completely unclear at that stage of the paper: what is a marine, a river or a mixed estuary? Later on we understand that these are not at all 3 end members but two extreme and one intermediate cases! (by the way, "mixed" is not the best name for the intermediate as it is very confusing!) Not all river-sea interface system are covered by these three type of estuaries.

We agree with the reviewer's point of view. The term "end-members" might be somewhat misleading. It refers to three idealized systems, which are in fact two extremes and one intermediate case. We thus modified all sentences using the term 'end members' throughout the manuscript.

The three idealized systems include not only the two main hydro-geometrical types of alluvial estuaries identified by Savenije (2005, 2012): funnel-shaped and prismatic systems; but also an intermediate type, which is a mixture of the former two (Savenije, 1992). Many systems in the world rather fall somewhere between the two extreme cases. Because of the non-linear response of biogeochemistry to hydrological forcing, we felt it was important to not only present simulations for two extreme cases but also for an intermediate situation. The results of our biogeochemical simulations evidence the fact that this intermediate case displays specific biogeochemical dynamics, which further justify our choice to work with three generic systems rather than just two. To clarify this aspect, the text has been modified.

We also understand the concern of the reviewer about the use of the term "mixed" to describe one of our idealized systems, which is often associated to estuarine classifications based on tidal wave type or vertical salinity dynamics (e.g. Savenije, 2012). However, Regnier et al. (2013b) and Volta et al. (2014) already used this definition to qualify a tidal estuary characterized by hydro-geometrical features and biogeochemical dynamics intermediate between a funnel-shaped (or marine-dominated) and a prismatic (or river-dominated) estuary. The current paper is explicitly following these studies and refers to them abundantly. We thus prefer to keep the terminology established in those publications. Nevertheless, in order to prevent any confusion, the following sentences, as well as Section 2.2 (Representative estuarine systems) have been modified to clarify what a mixed estuary is in this study.

PAGE 6352, line 4:

"... exchange - in three idealized tidal estuaries characterized by increasing riverine influence from a so-called 'riverine estuary' to a 'marine estuary'. An intermediate case called 'mixed estuary' is also considered. . C-GEM uses…"

PAGE 6352, line 12:
"… across the three idealized systems…"

PAGE 6352, line 24:
"… that all estuaries will…"

PAGE 6354, line 23:
"Next, three idealized systems, characterized by variable riverine influence and covering the main hydro-geometrical features of tidal alluvial estuaries, are modeled using the recently developed C-GEM modeling platform (Volta et al., 2014). These systems are designed to represent a tidal estuary dominated by marine characteristics, a tidal estuary dominated by its riverine characteristics and an intermediate case (so-called mixed system). Here, C-GEM uses…"

PAGE 6355, line 2:
"across the three idealized ~~end-member~~ systems and…"

PAGES 6357, line 27:
"Savenije (2005, 2012) identified two main estuarine types, which differ in terms of geometrical features, hydrodynamics characteristics and salt intrusion patterns:

1. funnel-shaped (or marine-dominated) estuaries that are typically characterized by a short width convergence length, b, and thus rapidly converging banks, a low freshwater discharge, a dome-shaped salinity profile with a small salinity gradient at the estuarine mouth and an intrusion of saltwater far upstream;
2. prismatic (or river-dominated) estuaries that are characterized by a theoretically infinite width convergence length, b, and, thus, a constant channel width, a high river discharge and a steep salt intrusion profile with a strong salinity gradient close to the estuary mouth and a short salt intrusion length.

These estuarine classes represent the extreme ends of the wide range of estuarine hydro-geometrical properties. As a consequence, a series of systems, which show intermediate conditions and fall in between the funnel-shaped and the prismatic end-member cases, can be hypothesized between them (Savenije, 1992). Physical…."

PAGE 6358, line 16:
"The identification of two end-member estuarine classes and an intermediate group, on the one hand, and the recognition…."

SECTION 2.2:
"In this study, we explore the link between biogeochemical dynamics and key hydro-geometrical properties in three idealized, tidal alluvial estuaries characterized by variable marine/riverine influence by means of a reactive-transport model. For this purpose, three idealized geometries are defined to be representative for the two extreme classes and the intermediate types as described in Sect. 2.1 (marine- and riverine-dominated estuaries and intermediate cases). The width convergence length, b, recognized as a shape and hydrodynamic key-parameter (see Sect. 2.1), is used to discriminate between the three estuarine types. First, a reference estuary, characterized by an idealized geometry resembling that tested in Volta et al. (2014), is defined. Then, its width convergence length (b=30 km) is decreased and increased by 50% in order to intensify the marine (b=15 km) and the riverine (b=45 km) character of the system, respectively. This allows defining two other idealized systems, which can be regarded as representative of the marine and river-dominated estuarine classes and between which the reference estuary can be considered an intermediate case. Henceforth, according to Regnier et al. (2013b) and Volta et al. (2014), the

marine-dominated estuary, the reference case and the riverine-dominated estuary will be referred to as the marine, the mixed and the riverine estuary, respectively. The estuarine width...... system. The geometrical features of the three idealized estuaries are illustrated in Fig. 1 and summarized, together with their hydrodynamic properties, in Table 1."

We also agree with the referee that in our study, which focuses on a limited set of systems tested, not all river-sea interfaces are represented. This is the reason why we highlighted in the manuscript that the results presented in our work cannot be considered as representative of the extremely wide spectrum of hydro-geometrical and biogeochemical characteristics of estuaries (page 6386 in the manuscript). The type of estuarine systems to which the model can be applied (i.e. alluvial estuaries) essentially corresponds to tidal estuaries as defined by Dürr et al. (2011) (please, see answer to following comment). We believe that the use of extended environmental databases (Section 2.3.5 in the manuscript) to deduce yearly-average conditions guarantees the representativeness of our simulations in terms of biogeochemistry and climate forcings at regional scale. In addition, comparing the estuarine shape and the hydrodynamic Canter-Cremers numbers (S and N, respectively; refer to page 6356 in the manuscript) characteristics of our three idealized cases (Table 1 in the manuscript) to those reported for tidal alluvial estuaries flowing in temperate zones ($2500<S>6000$, $N<0.05$; Savenije, 1992) allows noticing that all real-world systems fall in the range of hydrodynamic conditions tested in this study. As a consequence, we are confident that, although our idealized implementations likely do not cover all estuaries worldwide, they can be considered as representative of a certain range of estuarine conditions of tidal alluvial estuaries in temperate zone. To emphasize the representativeness of our idealized estuaries, especially in terms of hydro-geometrical features, a sentence has been added at the end of Section 2.2 (Representative estuarine systems):
"Table 1 also reveals that both the estuarine shape (S, Eq. 3) and the hydrodynamic Canter-Cremers (N, Eq. 4) numbers of the three idealized systems cover the whole range of observed values for temperate tidal estuaries ($2500<S>6000$, $N<0.05$; Savenije, 1992). As a consequence, they may be considered as representative of a large range of hydro-geometrical conditions observed in this type of estuaries."
Please, note that S values reported in Table 1 were not correct. They have been recalculated (now S= 2143, 4286, 6429 in the marine, mixed and riverine estuary, respectively) and the table has been updated accordingly.

The authors introduce the definition of alluvial estuaries, but they do not indicate how this definition match with other estuarine typologies such as that of Dürr et al 2011. This question is crucial when global extrapolation are made from the model results: "The average C filtering capacities for baseline conditions are 40, 30 and 22 % for the marine, mixed and riverine estuary, respectively. Extrapolating these filtration rates to all tidal estuaries worldwide results in a global outgassing flux between 0.04 and 0.07 Pg C yr" How was this extrapolation done? What are tidal estuaries? Is the river type estuary a tidal estuary? What about other types of river-sea interfaces (deltas, fjords, lagunes,: : :)?

One of the fundamental pre-requisite of G-CEM is the dynamic interplay between the estuarine geometry and the hydrodynamic forcings of alluvial estuaries. This is the reason why C-GEM can only be applied to these systems. The global estuarine typology of Dürr et al. (2011) describes 4 types of estuaries: small deltas, tidal systems, lagoons and fjords. The latter two describe systems for which the geometry is largely independent from the hydrodynamics (the shape of fjords for instance has been carved by glaciers and the geometry of most lagoons is constrained by many other factors than hydrology alone). Both small deltas and tidal estuaries (as defined in Dürr et al. 2011) are shaped by the opposing forcing but an accurate representation of deltaic systems would require the implementation of branching which, while technically possible, is different for every system and does not allow for easy generalization. As a consequence, Dürr et al. (2011)'s type 2 estuaries essentially consist in systems corresponding to the alluvial estuaries investigated in this study, leading to a good overlap between this estuarine type and the domain of applicability of C-GEM. This compatibility was already put forth and discussed in Regnier et al. (2013b). To avoid confusion, the reference to Dürr et al. (2011)'s typology when tidal estuaries are mentioned has been made clearer in several sections of the text (see below).

Thanks to the compatibility between tidal estuaries as defined in Dürr et al. (2011) and the domain of applicability of C-GEM and to the unique set of generic model parameter provided in our work, we extend in this study the upscaling strategy proposed by Regnier et al. (2013b) for western-European tidal estuaries to all tidal systems in temperate regions. This allows estimating their average filtering efficiency of the incoming riverine material at a larger spatial scale, as well as to predict their response to future climate and land-use changes. However, we agree that applying the C filtering capacities simulated under average temperate environmental conditions to the global carbon load delivered from rivers to all tidal systems worldwide in order to extrapolate their CO_2 outgassing flux at global scale, as done in this work (and described in page 6385 of the manuscript), results in a rough first order estimate. Nonetheless, because our estimate can be compared to another, calculated differently, we felt it was worth presenting our calculations. Since this estimate is not a primary focus of our study, we removed the reference to these calculations from the Abstract and keep it only in the Conclusion of our manuscript in order to avoid any confusion about the aims of our study. In addition, we added a few sentences in the manuscript to better explain how calculations are performed, as well as to explicitly qualify our global CO_2 outgassing of first order estimate. Please, also note that, in the new version of the manuscript, we first provide an estimate for temperate tidal estuaries, which is more consistent with the systems discussed in the paper and only then, present our extrapolation to tidal estuaries worldwide.

Moreover, it should be noted that, in regions with sufficient data coverage, applications of C-GEM to specific estuaries could be performed in order to derive regional carbon budgets. In particular, such type of application has already been performed for the tidal estuaries surrounding the North Sea and is currently under review in Estuarine, Coastal and Shelf Science (Volta et al., under revision).

PAGE 6352, line 17:

"…, respectively, while N filtering capacities, calculated in similar fashion, range from 22% for the marine estuary to 18 and 15% for the mixed and the riverine. Sensitivity …."

PAGE 6355, line 11:

"Most tidal estuaries are alluvial estuaries (Regnier et al., 2013b), which are defined as estuarine systems with movable beds, consisting of material from marine and terrestrial origin, and a measurable freshwater inflow (e.g. Hobbie, 2000; Savenije, 2005, 2012). The global distribution of alluvial estuaries is roughly equivalent to that of the tidal estuaries as defined in the estuarine coastal typology of Dürr et al. (2011). The approach developed here builds on this intercompatibility, already mentioned in Regnier et al. (2013b). In tidal estuaries, two different zones can be identified along their longitudinal gradient: …"

PAGE 6364, line 6:

"Values represent the average calculated over all watersheds in temperate regions that discharge to the sea through a tidal estuary. For these calculations, we use the estuarine coastal typology of Dürr et al. (2011) which identifies 4 types of estuaries: small deltas, tidal systems, lagoons and fjords. In this typology, tidal systems (type 2) represent a good approximation of the domain of applicability of C-GEM (Regnier et al., 2013b). NO_3 and …."

PAGE 6385, line 4:

"Extrapolating these filtration rates to the carbon loads of all temperate tidal estuaries worldwide, as defined in Dürr et al. (2011), results in a regional outgassing flux between 0.01 and 0.02 PgC yr^{-1}, assuming that the total amount of carbon delivered by rivers to these systems is 0.06 PgC yr^{-1} (calculated from Hartmann et al., 2009 and Mayorga et al., 2010). Moreover, a global CO_2 outgassing comprised between 0.04 and 0.07 PgC yr^{-1} can be calculated by extending these calculations to all tidal estuaries worldwide and assuming that the global amount of carbon delivered by rivers is 0.17 PgC yr^{-1} (calculated from Hartmann et al., 2009 and Mayorga et al., 2010). Since this estimate ignores that tropical and polar tidal estuaries may process riverine carbon differently than temperate systems, it only represents a first-order quantification of the CO_2 outgassing flux from tidal estuaries worldwide. Nonetheless, it is broadly in line with the recent global estimate calculated by Laruelle et al. (2013) (0.06 $PgCyr^{-1}$). In addition, results for ....”

Comment #2:

Another concern I have is about the structure of the biogeochemical model. When a sensitivity analysis is made by varying the parameters values, this does not tell anything about the uncertainties linked to the structure of the equations themselves! Let me take the example of denitrification, which completely governs the response of the model in term of N filtering capacity. The structure of the model does not take into account benthic processes. Yet, in the real world, these are likely to be dominant in nitrate elimination in all estuaries with oxic water column, which is the case for all simulations shown (oxygen concentration stays between 260 and 320 mM). The fact that the model nevertheless calculates some denitrification is because of the way denitrification is calculated, as a function of organic matter and nitrate concentration, with just an inhibitory factor of oxygen, which never completely vanishes, even at high oxygen concentration. This is a choice often made by other authors, but an on/off representation could be justified as well,…and would lead to completely different conclusions about the N filtering capacity.

The level of complexity and the structure of the equations applied in C-GEM are representative of the biogeochemical models implemented in the modeling studies we compiled. In this list, most of the models representing the same elements as those modeled in this study rely on 7 (e.g. Raillard and Menesguen, 1994; Arndt et al., 2009) to 15 state variables (e.g. Laruelle et al., 2009) and C-GEM uses 12, as was also done in Le Pape and Ménesguen (1997) and Solidoro et al. (2005). Moreover, Volta et al., (2014), Volta et al. (under review for publication in Estuarine, Coastal and Shelf Science) and Goossens et al. (in prep.) successfully applied the version of C-GEM presented in this manuscript (i.e. without benthic-pelagic exchange module) and properly capture the dominant biogeochemical features of two European (i.e. Scheldt and Elbe) and two American (i.e. Delaware and Altamaha River estuary) estuaries. Nonetheless, we agree with the referee that the lack of a benthic-pelagic coupling would limit the transferability of the results presented in this work to estuarine systems characterized by limited exchanges between sediment and the water column and relatively high O_2 levels. As such, the estimates we provide here for the N filtration capacity can likely be regarded as lower bond estimates. To discuss this aspect, the text in the manuscript has been modified (see below). Please, note also that the flexible structure of C-GEM allows a rapid incorporation of additional biogeochemical modules and that the development of an early diagenetic model for C, nutrients and O_2, suitable to be coupled to C-GEM, is already under way (Dr. S. Arndt, University of Bristol).

PAGE 6386, line 20:

“..biogeochemistry. In addition, the use of the generic modeling platform C-GEM, whose reaction network does not include an early diagenetic model at this stage, hampers the generalization of simulation results to estuaries that are typically subject to intense biogeochemical processing in sediments. For instance, the lack of a representation of denitrification in sediment might result in overestimations of the N export to the coastal ocean. As a consequence, the implementation of an early diagenetic model for carbon, nutrients and O_2 will be the next logical step to further improve our generic approach.

In the future, …”

Comment #3:

"No data is available to constrain average total organic carbon and suspended particulate matter concentrations at the lower boundary. Hence, both concentrations are arbitrarily set to 0, thus assuming that at a distance of 50 km from the estuarine mouth there is virtually no input flux of SPM and organic matter from the coastal shelf into the estuarine system during the flood tide." This is questionable!

We agree with the referee that this assumption is an oversimplification, but it was motivated by the lack of regional/global database to extract robust yearly-average lower boundary conditions for SPM and organic matter. Thus, in our simulations, we set both concentrations to 0 50 km away from the mouth of the estuary to reflect their low values typically observed on the shelf compared to those observed in rivers. For SPM, the local production of material due to the exchange with the sediment is enough to generate realistic profiles along the entire estuarine length and the input of suspended material from the sea is typically of second order compared to the local production (e.g. Ruddick et al., 2003). For organic matter, however, it is true (as shown in Arndt et al., 2011a) that the sea can import variable loads but, by setting our boundary condition to 0, we make the choice of only studying the fate of organic matter brought the estuary from the land by rivers. This assumption is now also explicitly mentioned in the text.

PAGE 6365, line 2:

"…lower boundary and both concentrations are arbitrarily set to 0. In the case of SPM, the implementation in C-GEM of a sediment transport module allows enough internal production of SPM to generate realistic profiles along the entire estuarine length. In addition, the low concentration reflects the low values typically observed on the shelf compared to those observed in shallow nearshore areas (e.g. Ruddick et al., 2003). On the other hand, although a variable load of organic carbon can be imported from the adjacent coast into the estuary (e.g. Arndt et al., 2011a) and assuming a TOC concentration of 0 at the lower boundary may thus be an approximation, our choice allows focusing on the fate of organic matter brought the estuary from rivers by minimizing the effect of organic matter produced and imported from the sea into estuaries. The second …."

Detailed formal remarks:

Remark #1:

"This dynamic interplay between hydrodynamics and morphology results in a continuum of estuarine shapes that cover the entire spectrum between two end-member cases: systems with rapidly converging banks and channels with parallel banks, which are rarely found in nature and are typically man-made (Savenije, 1992)." Unclear sentence: what are the two end members? What is rarely found in nature? And what is the third end member referred to in the Abstrat? Please rephrase!

The sentence has been modified to clarify what the two end-member cases are. Please, note that any reference to a third end-member in the Abstract and throughout the manuscript has been removed (see reply to comment #1).

PAGE 6355, line 23:

"…two end-member cases: 1) systems with rapidly converging banks towards the land and 2) systems characterized by parallel banks (Savenije, 1992)."

Remark #2:

At first sight Fig 3 looks rather redundant: only the x axes differ in scale. The point should be clearer by using the same scale. This is true, too, for the following figures!

Figure 3 aims at illustrating how geometrical features of the three idealized estuaries vary along their longitudinal axes and complements information provided in Table 1. However, we agree that the use of a logarithmic scale for the y-axis does not resolve all the geometrical differences across the three estuarine systems. Figure 3 has thus been modified and its caption has been modified accordingly. On the other hand, we believe that the other figures illustrating the longitudinal variability of hydrodynamics, transport and biogeochemical dynamics in the three systems allow for rapid qualitative and quantitative comparisons between estuaries and we prefer to maintain the current format.

NEW FIGURE 3:

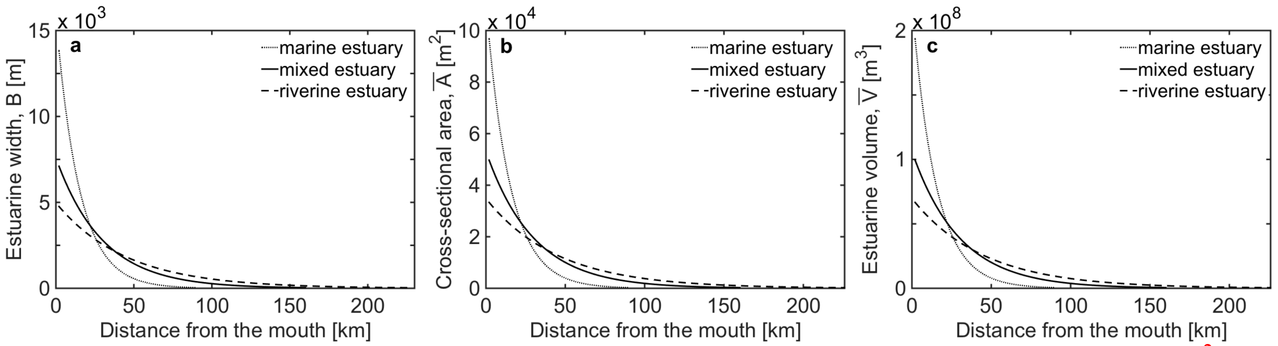

Figure 3. Variability along the estuarine axis of a) width B (m), b) cross-sectional area $\overline{A}$ (m^2) and c) volume $\overline{V}$ (m^3) in the three idealized estuaries. Note that the estuarine length EL (km) varies across systems. $\overline{A}$ is calculated as the product of the tidally-averaged depth $\overline{H}$ ($\overline{H}$=7m along EL) and B and $\overline{V}$ is the product between $\overline{A}$ and Δx. Profiles are obtained by using geometrical parameters reported in Table 1.

Remark #3:

Table 8: problem with the alignment of figures in column a (shift of 1 line)

Table 8 has been updated. Please, find the new Table here below.

Biogeochemical indicator [unit]	**Estuarine type**		**Scenario simulation** (a) Baseline (Year 2000)	(b) Future (Year 2050)
NEM [kmol C d^{-1}]	MAR		-916	-867 (-5%)
		R	859	812 (-6%)
		D	79	81 (+3%)
		NPP	22	23 (+4%)
	MIX		-8161	-7703 (-6%)
		R	7664	7197 (-6%)
		D	492	503 (+2%)
		NPP	-5	-2 (+56%)
	RIV		-21476	-20601 (-4%)
		R	20199	19283 (-5%)
		D	1299	1347 (+4%)
		NPP	21	29 (+35%)
FCO_2 [kmol C d^{-1}]	MAR		-2018	-1606 (-20%)
	MIX		-10940	-10033 (-8%)
	RIV		-25612	-24474 (-4%)
FC_{TN} [%]	MAR		22	20 (-9%)
	MIX		18	17 (-9%)
	RIV		15	14 (-8%)
FC_{TC} [%]	MAR		40	33 (-19%)
	MIX		30	28 (-7%)
	RIV		22	21 (-5%)

Literature cited in the responses:

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