We greatly thank all the reviewers for their thorough and helpful comments which contribute to improving the manuscript.

Please find our point-by-point responses (in blue) in the following, and changes in the manuscript are *in italic* here.

RC1: Pierre ANSCHUTZ

It is always very interesting to test the knowledge we have about natural systems by translating them into equations in mathematical models. This allows first to test the validity of the equated processes and second to build scenarios according to environmental changes. This manuscript presents results of nutrient retention in estuaries of the French Atlantic coast obtained with a mathematical model entitled C-GEM.

Macrotidal estuaries are complex transitional environments. Modeling nutrients in these systems is a challenge, because the biogeochemical processes are numerous and complex and the physics of estuaries alone is the subject of complex 3D models. Here the choice was made to build a simplified one-dimensional physical model coupled with biogeochemical reactions involving dissolved N, P and Si compounds, as well as suspended particles. This model is applied to 7 estuaries of different sizes and the model outputs are compared to the available data for the tested period. The model could be criticized for being too simple (1-D), but the biogeochemical part is relatively complete and in the end the results are promising. This 1-D approach is a sufficiently precise step to obtain interesting results. I have a few remarks that concern the validation of the model, the tidal cycles, and points of detail described below.

We thank Prof. Pierre Anschutz for reviewing this paper and providing constructive and detailed comments. We revised the manuscript according to the specific comments below.

RC1.1: Line 40: It is conventional to write that estuaries, and more generally water bodies, are facing increasing anthropogenic impacts. For European estuaries, it would have been fair to write this in the late 1990s. Since then, there have been major efforts to improve water quality. Nitrate and phosphate levels are much lower today than 30 years ago. It would be more accurate to write something like "despite efforts to improve natural water quality since the 2000s, estuaries remain receptacles for nutrients and contaminants..."

AC1.1: Thank you for pointing this out. This remark is correct and we made the necessary change on Line 40 following your suggestion:

"Estuarine and coastal ecosystems throughout the world are some of the most heavily used and threatened natural systems (Barbier et al., 2011) despite the efforts to improve natural water quality since the implementation of the WFD in the early 2000s (Water Framework Directive, EU-WFD 2000). While some improvements have been observed in recent decades regarding some specific perturbations such as, for instance, a general decrease in riverine phosphorus loads across Europe (Romero et al., 2013; Grizzetti et al., 2012), estuaries are still facing significant anthropogenic pressures given that they are the receptacle of all the contaminants and nutrients from the upper river watersheds (Howarth et al., 2011), from both point sources (urban and industrial wastewater) and diffuse sources (agriculture)."

RC1.2: Table 1. I am a little confused to see that the Dordogne watershed is included in the third row of the table and not in the second. The same goes for the Nive, I suppose, in the Adour column. In general, this 3rd row (Estuary basin area) should be better explained or its name should be changed.

AC1.2: Indeed, in this study, the Dordogne river basin area should be included in the River basin area because its water and nutrient loads also enter the estuarine system as upstream boundary conditions for the C-GEM model. To prevent any confusion, a brief statement was added to the note of Table 1:

"(2) River basin area includes the basin area of the rivers directly flowing into the estuary."*

However, the Nive River was not explicitly considered in the study of the Adour estuary, as we couldn't find any data neither for water flux nor nutrient fluxes for this tributary. Therefore, the basin of the Nive River, which represents less than 10% of the total surface area, is not considered in the area of estuary in our table.

RC1.3: Section 2.3.1: In this manuscript, the model is a black box and it is necessary to consult the articles of Volta et al. to know the details of the modeled processes. For example, I tried to see how the interactions between SPM and phosphates were accounted for, but I could not find this information. Wouldn't it be appropriate to put the model elements in an appendix?

AC1.3: We thank the reviewer for this suggestion. Upon reading the reviewer's comment, we acknowledge that, without explicitly describing the full set of equations governing the model, C-GEM appears as a black box in our manuscript. This was also suggested by other reviewers. We initially only provided references to Volta et al.'s work where all the model description is detailed in order not to dilute the message of our paper too much. Indeed, our study is more a model-wide application and not a new model development. In the updated version of the manuscript, we followed the reviewer's advice and included the equations governing all the biogeochemical state variables in the supplementary material.

We introduced the following statement at the beginning of section 2.3 of the manuscript:

"The extensive description of the model and its underlying assumptions is available in Volta et al. (2014) and the following sections only briefly describe the state variables and processes included in the biogeochemical module as well as the modifications introduced for the simulations discussed in this manuscript. However, all the equations governing the production and consumption reactions of all state variables as well as their parameterization are provided in the supplementary material."

Moreover, note that, in the current set-up of C-GEM, the adsorption and desorption of the particulate P on SPM is not included, which is now explicitly stated in the manuscript (see answer **AC1.17**) for further discussions as to what motivated this choice).

RC1.4: Line 177. The time resolution of the model is hourly and daily depending the parameter. However, the input data to the model does not have this resolution. Here, it is stated that the data was linearly interpolated to obtain the temporal resolution of the model. Could you give some indication of the frequency of acquisition of the measurements of the Naiades data set?

AC1.4: The calculation time step of C-GEM is relatively short (300 seconds) in order to comply with numerical stability constraints resulting from our advection scheme. This short time step also allows a fine representation of short-scale physical and biogeochemical processes that may occur in estuarine settings (tides or light-dependent biological processes, for instance). The hourly resolution at the marine boundary conditions is used in order to resolve tidal fluctuations and was only possible because another numerical model (ECO-MARS3D) is used to provide such high-resolution coverage. Upstream, however, the resolution of the boundary conditions is dependent on the sampling frequency of the available data. We clarified this in the updated manuscript and, in particular, provide the frequency of the measurements (including the data from NAIADES), which are now presented in section 2.2 Data Collection (in the second paragraph).

"The temporal resolution of the water quality data acquired is generally monthly or bimonthly. Chl a concentrations were usually available only from March to September (main phytoplankton growth period)."

RC1.5: Table 3: concentrations unit in μmol/L, and in Table 4, units in mg/L

AC1.5: The unit used in the model for its calculations is μmol/L while most of the collected data are in mg/L.

In this paper, simulations from the model were thus converted into the unit of mg/L to facilitate the comparison with measured data (in unit mg/L).

See also **AC2.3:** In general, μmol/L is frequently used in marine systems sciences while mg/L is more used in river systems investigations. Whereas, the calculations are made in moles in the model, in this study we used the mg/L (N, P, Si, C) instead of μmol/L to facilitate comparison with the observed data all in mg/L for the import from the rivers and within the estuaries. Also, we considered that the calculation of material fluxes is more meaningful when they are expressed with their respective molar mass (14, 31, 28, 12 respectively for N, P, Si, C). However, to reconcile the two disciplines we have added some important values in both units.

RC1.6: Table 4: the value of SPM concentration of the Dordogne is very high: it is not representative of the Dordogne river. It is most likely a value from a station located in the tidal estuarine part of the Dordogne river. The Dordogne is a river with many upstream dams: SPM concentrations are low until the tidally influenced zone is reached. It would be interesting for readers familiar with these estuarine systems to give the names of the stations used to define the river mixing end-members.

AC1.6: The Dordogne River in this study is considered as an input to the estuary with a daily time step in terms of water and biogeochemical elements, differently from the upstream of the Gironde (Garonne River) which is influenced by tidal cycles. The values used for the Dordogne river come from the closest sampling station to the confluence point (station number: 5026000) which is indeed influenced by the tide. The high annual mean value was caused by the SPM measured during Aug-Oct (for example, 7900 mg/L in Aug 2015, 3600mg/L in Oct 2015, 2400mg/L in Sept 2016) while in March the values were only 10-29 mg/L. The name and location of the station used as the boundary condition for the model for the Dordogne are now provided in the manuscript with a word of caution regarding the SPM concentrations at the end of section 2.3.3:

"The closest available sampling station (number: 5026000, from NAIADES) on the Dordogne river is around 32 km to the confluence."

"The Dordogne River was considered as a source of biogeochemical elements for the Gironde estuary at the confluence. This ignored the tidal cycle effects on the tributary, and might cause deviations downstream the confluence."

Please see also **AC1.8**.

RC1.7: Page 12 and Fig 3. The model results are compared to values measured along the estuaries at two contrasting dates, one during a period of high tributary discharge and the other during a period of low discharge. However, one date, for example January 15, 2015, is a 24-hour period when there were 2 tidal cycles. For these macrotidal estuaries, it is likely that the timing of the tide plays an major role in the spatial distribution of the different compounds described here. However, I did not see when this tidal cycle effect was discussed. Do the model outputs correspond to a time of high tide? low tide? For an estuary the size of the Gironde, a given time corresponds to different moments in the tidal cycle upstream and downstream. This would need to be discussed.

AC1.7: We agree with the reviewer that, in estuarine systems, particularly in the most downstream section, the time of measurement may significantly affect the value of any given variable because of the tidal influence. Our model, with a calculation time step of the order of a few minutes (300 seconds), and hourly marine boundary conditions, perfectly resolves the tidal cycle. This was abundantly demonstrated in previous publications using C-GEM (Nguyen et al., 2020; Laruelle et al., 2019; Volta et al., 2016). Furthermore, the ability of C-GEM to capture tidal variations in the Seine estuary was demonstrated in Laruelle et al., 2019 with a similar set-up and transient simulations.

In our three years long simulations, the temporal resolution of the model outputs is set at 4 hours. This value was selected in order to limit the size of the output files but nonetheless provides most of the amplitude of the variation in concentration of the state variables of the model over a tidal cycle. In Figure 3, 4, S-1, S-2 and S-3, we thus do not indicate a single value for the different variables but an envelope that represents the amplitude of the variations over two tidal cycles for the considered date. The envelope consists of the maximum and minimum values over a span of 24 hours at a temporal resolution of 4 hours. For instance, significant tidal variations can be observed in the Charente for most variables in its downstream section. The temporal resolution of the model calculations and as well as that of its results files and the ability of the model to fully resolve tidal variations are explicitly stated in section 2.3.5 of the manuscript:

"The relatively short residence time, combined with hourly boundary conditions at the mouth of the estuary allows an accurate resolution of the tidal cycle in the estuaries, including during transient simulations as was demonstrated by Laruelle et al. (2019). The time resolution of the model outputs was set at 4 hours in order to minimize the size of the export files while capturing most of the tidal and diurnal variability. In the figures there-after, the envelope around the model

results represents the minimum and maximum values over two tidal cycles in order to provide the amplitude of the tidal influence on concentrations at different locations of the estuary."

RC1.8: Line 295 "…downstream of the confluence with the Dordogne tributary". This sentence implies that the Dordogne is a source of material for the Gironde estuary at the confluence. This ignores the reality of the environment. The Dordogne and the Garonne meet in the estuarine zone. At the confluence, the waters of the two rivers are very efficiently mixed by the tide: mixed waters of the Garonne and the Dordogne rise largely upstream of the confluence, up to the dynamic tidal limit, located on both rivers more than 70 km from the confluence (e.g. Parra et al., Continent Shelf Res 19, 135-150, 1999)

AC1.8: In this study, Dordogne was simplified as a source of material for the Gironde estuary at the confluence, which was the easiest way to set up the model for this study. Indeed, the purpose of the paper was to test the performance of a 1D model with simple inputs and settings on a variety of estuaries, e.g. with different geomorphologies, rather than focusing on one specific estuary, which can be done locally with more available data as the model is open source. The results presented in this paper showed that even with this simplification of the Dordogne River, the biogeochemical processes were well represented both along the estuary and on specific cross-sections.

Words of cautions were added in discussion (4.1 Model Applicability and Limitations):

"The Dordogne River was considered as a source of biogeochemical elements for the Gironde estuary at the confluence. This ignored the tidal cycle effects on the tributary, and might cause deviations downstream the confluence."

Please see also **AC1.6**.

RC1.9: For some parameters shown in Figure 3 (and Fig S1), only the data from the river mixing end-member and the data from the marine mixing end-member are shown. There is no data in the estuarine part: we can therefore not talk about model validation here (e.g. the bottom graphs for the Loire). For the Adour, there is only one control point. Is it a point taken at high tide or low tide?

AC1.9: Figure 3 and Figure S-1 were dedicated to present the calibration results for 2015. Two specific dates were presented. In Figure 3 and Figure S-1, we presented all the data we could get for those dates. Monitoring along the estuaries was not carried out as frequently as on rivers, or/and the sampling data for estuaries are not accessible. Therefore, in Figure 3 and Figure S-1, there were no data for some variables along some estuaries, such as TOC, DO and Chl a for the Loire.

The validation was carried out through the whole 2014 and 2016 years, based on seasonal available data for the middle of the estuaries in Figure 4. Besides, through other estuaries where there were data, we can see that the model represents the longitudinal variations. Indeed, along the Adour estuary, there was only one station (station number: 5200200, from NAIADES) at 22 km within the estuary (Figure 3). However, the observations for this station fit rather well with the seasonal simulations for the period 2014-2015. Further, in Table 7, all the observations and corresponding simulations are taken into account for the evaluation of the model's performance.

Again, our approach was to analyze a variety of estuaries with the existing data aiming at pushing towards additional field investigations where no data exist on the French Atlantic coast but also for >90% of the world. We want to restate that one of the aims of our study is to provide new insight on smaller, seldom studied estuaries rather than exploring the few already well-known systems that only represent a fraction of the Atlantic French coastline. Besides, although a dedicated 3D model is obviously insightful for the rare systems where sufficient data are available, a simplified 1D model can be useful for exploring some hypotheses.

RC1.10: Generally speaking, most of the control points are located either at the level of the marine end-member or in the zone where the salinity is close to zero. There are not many control points in the salinity gradient area. This makes it difficult to claim that the model calibration is robust.

AC1.10: It is true for some estuaries, but for large estuaries, calibration/validation points (sampling stations) are also located along the estuaries, besides for both marine and riverine boundaries, except for some variables. Medium and small estuaries are shorter, and thus have fewer sampling points along the estuaries. We acknowledge that this can be a caveat for small estuaries, which can have an important impact on their adjacent coastal zone.

Validation stations far from the riverine boundary were added in the supplementary material (Figure S-3) to better show the performance of the model (see also below **AC1.12**).

We would also like to stress out that we performed an extensive data search to gather as much estuarine data as we could for all the modeled systems. The scarcity of sampling locations within the salinity gradient of smaller estuaries is obviously a hurdle in the way of a better understanding of the biogeochemical cycling of nutrients within these systems. However, we argue that ignoring such systems and leaving them out of modelling investigations until their data coverage improves, is not ideal and provides a skewed perception of the role of estuaries at the national scale. Rather, we advocate for a modeling strategy that relies on a simpler, yet robust and proven model with limited data demand, that allows regional application where data-rich and -poor systems can be investigated at the same time in order to progress toward a more representative regional picture of the role of estuaries as a filter between French watershed and coastal Atlantic waters.

RC1.11: Line 344: data expressed in % saturation would allow a more direct visualization of O2 consumption

AC1.11: Following the reviewer's suggestion, we now provide in the text some % saturation values between brackets in some places to help the reader interpret our O_2 concentrations.

RC1.12: Figure 4. Simulated and measurement of salinity are important information that is missing here. Indeed, it is stated in line 316 that the stations were chosen in such a way that they are not too influenced by the marine boundary. But these stations should not be strongly influenced by the river boundary as well. Indeed, according to figure 3, all stations in figure 4 are in the area where the salinity is close to 0.

Here again the question of the tide comes up: for the selected stations what is the variation of the concentrations during a tidal cycle in summer, in winter, during spring tides or neap tides? This aspect is not discussed here. Measurements on tidal cycles probably do not exist, but can the model simulate them? If not, this role of the tide should still be discussed.

AC1.12: Salinity were added in Figure 4 and S-2.

Validation stations far from the riverine boundary were added in the supplementary material (Figure S-3) to better show the performance of the model.

Again, we understand the valid concern of the reviewer regarding the potential effect of tides on the results and acknowledge that it was an oversight on our part not to explicitly state that the model does capture tides (see answer **AC1.7**) and how we tried to represent tidal variations onto our figures by representing the minimum and maximum values over two tidal cycles onto our graphs. These do provide an estimate of the tidal influence on the concentrations simulated by the model in the most downstream sections of the estuaries.

RC1.13: Section 3.2.1: in this paragraph I found it difficult to know whether reference was made to flows from estuaries or river flows into estuaries.

AC1.13: In order to be more explicit, "ingoing" and "outgoing" were changed to "import" (to the estuary) and "export" (from the estuary), respectively, throughout the manuscript.

RC1.14: In line 361 and in table 8, the flow results are given with 2 decimal places. Is this level of precision justified?

AC1.14: We agree that the two decimals are not justified and they were modified accordingly to only 1 decimal place.

RC1.15: Line 373: "They accounted for about 80% of the total water discharge from all the estuaries on the French Atlantic coast and 83% of the total watershed areas on the French Atlantic coast, and hence a similar proportion of the nutrient fluxes.": The missing 20% are represented by small rivers with small estuaries. As a result, this 20% certainly has a lower nutrient retention rate than the average of the estuaries studied here. Thus, the contribution to the nutrient flow to the Atlantic coast of this 20% is probably higher than 20%.

AC1.15: You are right about this. The sentence has been changed as follows:

"*They accounted for about 80% of the total water discharge from all the estuaries on the French Atlantic coast (based on long-term analysis of runoff data from French national databases) and 83% of the total watershed areas on the French Atlantic coast. However, under the assumption (supported by our simulations and previous literature, e.g. Nixon et al., 1995) that smaller estuaries such as those not considered in our study, likely have smaller retention rates, these 7 estuaries might produce nutrient fluxes slightly lower than the 80% of the total water fluxes of the French Atlantic coast.*"

RC1.16: Are the nutrient import data in Table 8 and Figure 7 direct outputs from C-GEM? It is not clear to me

AC1.16: Yes, they are. In the first paragraph of section 3.2.1, it pointed out that the values in Table 8 were calculated from model. Figure 7 used the values calculated from the fluxes which were calculated from the model.

RC1.17: Table 7: TP values do not take into account the P associated with inorganic particles. However, some of this P is desorbed in the salinity gradient, so that an estuary can become a source of DIP (e.g. Deborde et al. 2007 L&O 52, 862-872). Is this reaction taken into account in the model?

AC1.17: In its current state, the model does not take into account this process. The limitations of the model associated with its current level of complexity (i.e. lack of explicit representation of the sorption/desorption mechanism for P or the crude representation of the interaction with the sediment) are now discussed in the second paragraph in section 4.1, which was entirely rewritten. This new section also includes justification for our choice to use a relatively simple biogeochemical module in our simulations. Further considerations about the matter are also available in answer **AC3.9**. We thank the reviewer for the reference provided that now is cited in our manuscript.

"*In its current setup, the biogeochemical module of C-GEM considers some of the most essential biogeochemical processes and reactions (i.e. primary production, organic matter degradation, denitrification…). In spite of generally good ability of the model to capture the main spatial and temporal biogeochemical dynamics of the different systems studied (i.e. longitudinal, seasonal and amplitude of the variations of nutrients carbon and oxygen fields), several potentially important processes contributing to the N and P cycling in estuarine environments in particular are still ignored or largely simplified. These include benthic-pelagic exchanges, sorption–desorption of phosphorus, mineral precipitation or a more complex representation of the biological planktonic/benthic compartments (such as grazing by higher trophic levels, or multiple reactive organic carbon pools for instance). This limits the depth of mechanistic understanding that the model can provide of nutrient cycling, particularly regarding interactions between pelagic and benthic compartments which can significantly influence the intensity but also the timing of nutrient and organic matter cycling in estuaries (Laruelle et al., 2009). The addition of a full diagenetic module at each grid cell of our model would be possible but would also increase its calculation time by one order of magnitude and require a very long spin-up to generate initial conditions for the benthic species. There exist simpler benthic modules of lower complexity, which would limit the computation cost of adding an explicit representation of benthic processes (see Soetaert et al., 2005) but those would nonetheless significantly increase the data demand of the model to be properly calibrated. Thus, while we believe the inclusion of an explicit benthic compartment to our model is the way forward on the long run, such an increase in complexity without sufficient data for a proper calibration and evaluation might introduce more uncertainty than actual mechanistic understanding to the model. In the present study, a simple representation of particulate matter burial was nonetheless implemented and applied to phytoplankton and TOC to provide a first-order representation of the process, which is necessary to evaluate the retention of carbon and nutrients within the system. We believe this addition, coupled with denitrification provides a first insight on the main pathways removing nutrients from estuaries.*"

Please see also **AC1.17**, **AC2.2**, **AC2.11** and **AC2.12, AC3.9** for new inputs on N,P cycling and TP:TN ratio.

RC1.18: Fig. 7: This figure shows average calculations of retention rates and residence times at the annual scale. For me, an annual average is meaningless and does not explain the relationship between the two parameters. It would be more interesting to compare these two properties in flood and low water periods. The relationship should certainly be better and the processes that go with it should be easier to explain.

AC1.18: Thanks for your suggestion. Figure 7 presented firstly on an annual average was to show that generally, the larger residence time caused a larger retention rate. According to your suggestion, we added a figure of average calculations of retention rates and residence times for the summer season (May-Oct) which further showed that the estuaries had larger residence time during the dry season, which also led to larger retention rates.

The text was modified accordingly:

"We also calculated retention rates and residence times for summer season (May-Oct) which further showed that the estuaries had larger residence time during the dry season, which also led to larger retention rates. The linearity of the relationship is not so well adapted, % retention plateauing at high residence times."

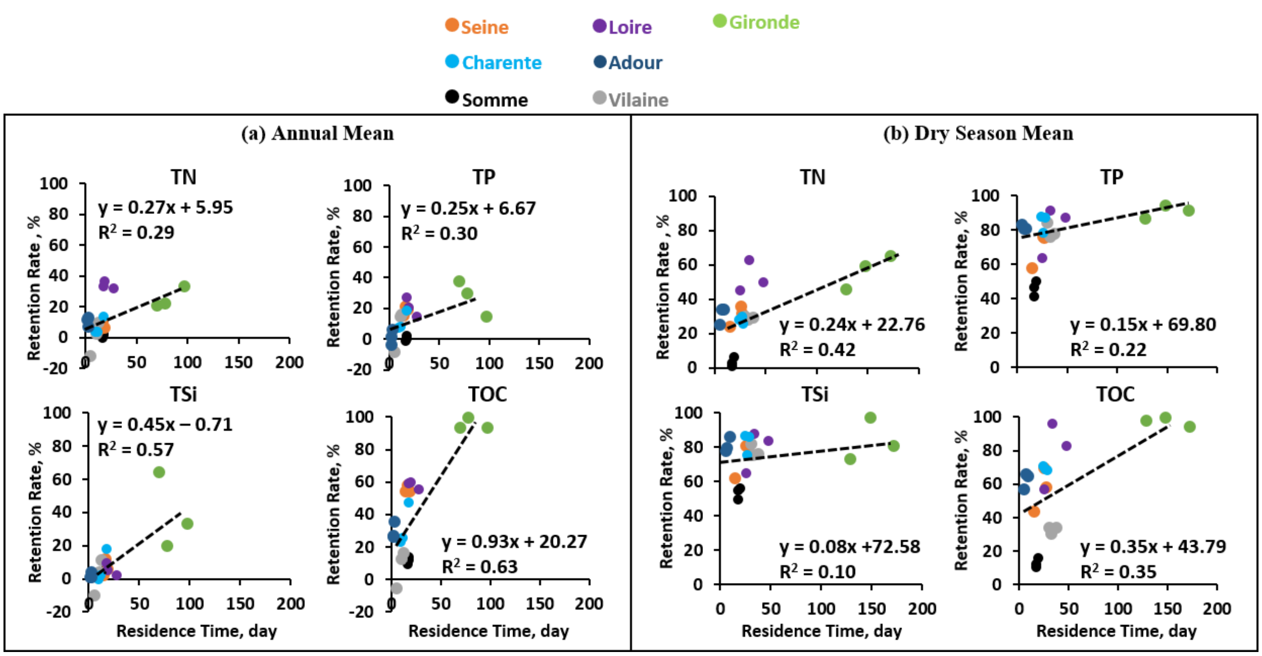

Figure 1 The relations between the annual retention rate for nutrients (total nitrogen (TN), total phosphorus (TP), total silica (TSi), and total organic carbon (TOC)) and the fresh water residence time for the estuaries studied (the Somme, Seine, Vilaine, Loire, Charente, Gironde, and Adour estuaries) for the 3 years 2014–2016. (a). Annual mean; (b). Summer season (May-October) mean.

RC1.19: Line 472: simulations do not resolve the tidal cycles.

AC1.19. We apologized again for not being clear enough on this issue in the manuscript**.** The model does totally resolve tidal cycles for hydrology and biogeochemistry. Please see answers AC1.7 and AC1.12 for further information on the matter.

RC1.20: Line 481 to 486: I have the impression that we are going in circles in this paragraph.

AC1.20: The sentence was updated

"Further, solid results were gained elsewhere with C-GEM supporting its genericity. i.e. carbon processing in the six major tidal estuaries (length >80 km) flowing into the North Sea (Volta et al., 2016b), biogeochemical dynamics and CO_2 exchange in three tidal estuaries (length >90 km, Volta et al. 2016a), CO_2 evasion on 42 tidal estuaries along the US east coast (Laruelle et al., 2017) and the Seine (Laruelle et al., 2019), biogeochemical processes and fluxes on a tropical estuary (Nguyen et al., 2021)."

RC1.21: Line 503: perhaps it should be recalled here that the link between water residence time and nutrient retention is a known phenomenon for lakes, wetlands or dams and that it is this principle that leads to the restoration or construction of wetlands

AC1.21: A sentence has been added to address this question.

"*The role of residence time on nutrient retention/elimination is not only the fate of estuaries but also of rivers, stagnant systems (lakes, ponds and reservoirs), and also wetlands. This function can be valued for reducing contaminations and sometimes even promoted for restauration although the best way is to limit the amount of fertilizer added (Bernot and Dood, 2005)."*

RC1.22: The first paragraph of section 4.3 should be included in the introduction

AC1.22: Thanks for this suggestion, and the correction was made in the first paragraph of the Introduction.

I hope that my comments and considerations will make it possible to better highlight the quality of the results of this modelling, which has interested me greatly.

We greatly acknowledge Prof. Pierre ANSCHUTZ for his constructive remarks based on a large view on estuaries, specifically here those of the French Atlantic coast. We indeed believe that his insightful comments helped us improve our manuscript.