Response to Anonymous Referee #2

We express our gratitude to Anonymous Referee #2 for his/her useful comments. Our response to the reviewer's comments and the corresponding revisions to our manuscript are described in detail below. The numbers of pages, lines, equations, tables and figures are those in the revised manuscript unless otherwise noted.

Comment 1:

"The distinct advantage of eLABS is the addition of water flow, which could couple the overlying water with sediment continuously. However, it is too rough for the model description and therefore its validity cannot be judged. For example, the proper treatment of the moving boundary when the sediment was moved by organisms is essential to get the flow field. Only constant flows imposed in the head or tail of the organisms may not sufficient. The pressure and velocity along the moving sediment is also important. The accuracy of boundary condition also largely depends on the grid resolution, especially in this case that the sediment occupied only one grid. Therefore, grid refinement is necessary to check the error bar. Similarly, the treatment of the boundary condition of oxygen on the moving sediment has to be careful to ensure the mass conservation. One could check the mass conservation of oxygen by turn off the oxygen consumption rate. The implicit and explicit finite-difference method as well as the boundary condition could be presented in the appendix to guide readers easier. Before considering the effects of biological, physical and chemical factors on bioturbation, the verification of numerical implement could also be put in the appendix. Organic matter is generally located in the solid particles and oxygen in water. How to calculate the rate with Eqs.(4) and (5) when OM and O2 are not at the same cell?"

Response:

The imposed constant flow rate is calculated based on the momentum changes of sediment particles moved directly by organisms as well as those through organisms' movements. Thus, temporal changes in boundary conditions caused by sediment particle displacements through organisms' movements, as well as those caused by organisms' movements themselves are adequately accounted for in the present study. We also updated eLABS (now v0.2) to enable the water flow simulation on a higher grid resolution than that on which animal behavior, oxygen and organic matter are simulated (e.g., 480×480 grid for water flow simulation vs. 240×240 grid for calculations of animal behavior, oxygen and organic matter). By this, sediment particles are occupied with more than one grid cell during the flow simulation. The default simulation for 1 model year with an increased grid resolution (480×480) for the water flow calculation shows no significant difference from that with the default resolution. Accordingly, we consider that the default resolution of the eLABS grid is sufficient for producing reasonable bioturbation results.

eLABS calculates and reports mass fluxes of oxygen caused by temporal change in the total amount of oxygen within the calculation domain, aerobic organic matter degradation, infaunal respiration, molecular plus eddy diffusion and advection, as well as the residual flux as a sum of the above fluxes, which ideally should be zero, at every time step. Numerical solutions by the finite difference method generate a non-zero residual flux of oxygen but this flux is generally insignificant. In eLABS v0.2, the absolute value of residual flux is generally less than $\sim 10^{-5}$ % of the absolute total oxygen consumption.

When locations of sediment and water particles are exchanged through pushing by the organism, their oxygen concentrations are also exchanged. The boundary condition for the oxygen calculation is updated based on pore geometry at every time step. Moving boundary conditions are thus accounted for. We also confirmed that moving boundaries do not cause any changes in oxygen concentrations by observing no changes in oxygen concentrations in a simulation where oxygen consumption and ingestion/egestion by infauna are excluded. Please note that when including ingestion, even assuming zero oxygen consumption, there can still be oxygen fluxes because sediment particles removed during ingestion are replaced by water particles with zero oxygen concentration. Although this does not cause any change in the oxygen amount at the time of replacement, more oxygen can be transported toward the replaced water particles in the following time steps, causing an oxygen transport flux. This oxygen flux accompanying ingestion is inevitable and insignificant (~1%) compared to oxygen consumption by respiration and organic matter degradation.

Organic matter decomposition in a given sediment grid cell in a given time step is calculated by first examining adjacent grid cells. We regard two grid cells as connected only when they share one cell edge (i.e., one grid cell has four connected neighbor cells at maximum). When one sediment grid cell is connected to a water/organism grid cell, then the degradation rate of organic matter is calculated using the oxygen concentration of the water/organism grid cell and the organic matter concentration of the sediment grid cell. This degradation rate information is shared with the water/organism grid cell to be used for the oxygen concentration calculation. When there are multiple water/organism grid cells connected to a sediment grid cell, degradation rates of organic matter are similarly calculated. The connected water/organism grid cells thus obtain information on organic matter degradation caused by reactions between organic matter in the connected sediment grid cell and oxygen in their own grid cells, while the sediment grid cell has information on degradation caused by the sum of reactions with all the connected water/organism grid cells. The above calculation is repeated for all sediment grid cells, by which each water/organism grid cell obtains information on organic matter degradation from all connected sediment grid cells.

Changes in manuscript (Page numbers/Line numbers):

We have added further explanation for the calculations of water flow, organic matter and oxygen based on the description presented in our response to the comment just above (P5/L33-P6/L1-3, P6/L13, P7/L31-P8/L5, P8/L24-P9/L2). We also added an appendix that shows several simulations including those without oxygen consumption to verify the conservation of oxygen in eLABS (Appendix A, P17/L11-26).

We did not add an appendix to present the finite difference method because the finite difference method is explained in many textbooks (e.g., Hoffmann and Chiang, 2000). Nonetheless, we added more explanations on the finite difference method in Section 2 (P7/L31-32). Although the reviewer suggested that boundary conditions may be described in appendices, we have already presented boundary conditions in Section 2. Accordingly, instead of adding an appendix, we added additional explanations of boundary conditions where necessary based on the comment by the reviewer (please also see our response to Other note 3 by Anonymous Referee #2) (P6/L10, P6/L11, P7/L26).

Comment 2:

"The model was run only once for one case study, which loose its generality. Lattice-automaton contains stochastic processes. It is better to consider different initial distribution the sediment and random generator for animal move. The ensemble averaged effects of biological, chemical and physical parameters on oxygen fluxes and rates of mixing in ocean sediments could provide a mechanistic explanation for empirical relationships observed in the modern ocean sediments, which is much more useful. Otherwise, it becomes meaningless due to large uncertainty and randomness. According to the model setup, the running will lead to a steady state. It the time is within geology years, one could compare the results in the steady state, which is comparable with the observed empirical relation."

Response:

We agree with the reviewer that ensembles of simulations will be useful to evaluate how much the stochastic process contributes to the bioturbation results. We ran each simulation five times to evaluate the contribution of stochastic processes. Different initial distributions of sediment can be considered by these multiple runs because initial distributions are randomly determined even assuming the same porosity. Next, we conducted simulations with different sediment porosity, which also creates different sediment particles distributions.

Although it is desirable to run the model on geological time scales (e.g., > 1000 years), this is difficult because of the relatively heavy calculation (a 1-yr simulation with the default setting takes ~2 days, meaning that a 1000-yr simulation will take ~2000 days or ~5 years). Nonetheless, porewater chemistry reaches steady state relatively fast compared to solid phase species (Archer et al., 2002). We also assume a decrease of organic matter concentration with depth as the initial condition, which may be regarded as steady-state distribution of organic matter (e.g., Van Cappellen and Wang, 1996). Then, the simulated profiles may be regarded to be close to those in steady state and be compared with modern sediment observations.

Changes in manuscript (Page numbers/Line numbers):
We added an appendix which shows additional simulations to illustrate the contribution of the stochastic process to bioturbation results (Appendix D, P18/L25-29). Where necessary, descriptions in Section 3 were also modified (P12/L1-2, P12/L13-14, P12/L27-28, P13/L28, P14/L12, P15/L23-24).

We added an explanation that assuming a decrease of organic matter with depth may help the model reach a steady state despite a relatively short run-time (P8/L24-25).

Other note 1:
"Page 5 /line 28: Non-local mixing of water (bio-irrigation) by infauna is already represented in LABS. In the original LABS, there is only non-local mixing of sediment and no bio-irrigation is presented."

Response:
In LABS, when a line of sediment particles is pushed by an organism, a water particle that exists at the far end of the line of pushed sediment particles is moved to the location where the sediment particle at the nearest end of the line of the pushed sediment particles was located before pushing (Choi et al., 2002). Thus, non-local mixing of water particles is implicitly realized in LABS. However, individual water particles are not tracked and since there are no tracers on water particles, the effect of non-local mixing of water cannot be evaluated in LABS.

Changes in manuscript (Page numbers/Line numbers):
We deleted '(bio-irrigation)' in the relevant sentence because non-local mixing of water in LABS is caused through particle displacements (please see above), but not directly by biological processes such as water-pumping action (Meysman et al., 2005) (P5/L29).

Other note 2:
"6/1-2: Many readers may not familiar with "marker and cell method". It is better to give some details. The references cited here (Hoffmann and Chiang 2000; Manwart et al 2002; Meysmann et al. 2005,2006b,2007; Volkenborn et al. 2012) are not properly."

Response:
We agree with the reviewer that the marker and cell method may not be familiar with all readers. Hoffmann and Chiang (2000) provided an explanation of the marker and cell method in their Chapter 8.7.1, and Manwart et al. (2002) utilized a marker and cell grid for their finite difference solution of

the Navier-Stokes equation. Thus, we consider these two references appropriate. Also, Meysman et al. (2005, 2006b, 2007) and Volkenborn et al. (2012) conducted water flow simulations within sediments based on Darcy and Navier-Stokes/Brinkman equations, respectively. Because these equations are based on the same fluid mechanics (e.g., Das, 1997, J. Can. Petrol. Technol., 36, 57-59), we also consider these references relevant.

Changes in manuscript (Page numbers/Line numbers):
We added an explanation for the marker and cell method and deleted Meysman et al. (2005, 2006b, 2007) and Volkenborn et al. (2012) from the relevant sentence (P5/L33-P6/L3).

Other note 3:
'6/11: For fluid the name "no-vertical-flux boundary conditions" is not used. Instead, slip boundary condition is common used. "Non-slip boundary" should be replaced by "No-slip boundary". "left and right boundaries are continuous" could be simply replaced by "periodic boundary condition".'

Response:
We meant zero pressure gradients by "no-vertical-flux boundary conditions". We agree with the reviewer on the other terminology.

Changes in manuscript (Page numbers/Line numbers):
We added '(zero pressure gradients)' in the relevant sentence (P6/L10). We used 'no-slip boundary' instead of 'non-slip boundary', and 'periodic boundary condition' to describe the left and right boundary conditions in the revised manuscript (P6/L11).

Other note 4:
"7/7: The shear velocity is usually resulted from a turbulence flow in the overlying water. Within the lowest portion of the planetary boundary layer a semi-empirical log velocity profile is used. However, in this paper, there is any external flow in the water and shear velocity lose its meaning."

Response:
The reason we introduced the shear velocity is to implement oxygen mixing caused by eddy diffusion to represent oxygen transport through turbulent flow above sediment (e.g., Volkenborn et al., 2002). Direct simulations of turbulent flow would require a gird with a higher resolution and increase the calculation time. By introducing the eddy diffusion term, which is formulated with the shear velocity (a higher shear velocity leads to a stronger eddy diffusion), the intensity of the current above sediments can be implicitly considered because an increase in the current intensity should be

accompanied with an increase in shear velocity (e.g., Pope et al., 2006).

Changes in manuscript (Page numbers/Line numbers):
We have added further explanations of the shear velocity in the revised manuscript (P12/L19-21).

Other note 5:
'9/32: Does "biodiffusion coefficients in the present study are obtained by calculating average values..." mean that Db is depth independent. Actually, Db depends on the sediment depth.'

Response:
Biodiffusion coefficients (D_b) can change with the sediment depth (Figs. 7, 11 and 15). We did not make any assumptions regarding the depth-D_b relationship. The D_b values are calculated based on displacements of sediment particles. Because averages of sediment particles displacements in individual depth layers are used for the calculation of D_b with depth, the calculated D_b values can change with sediment depth.

Changes in manuscript (Page numbers/Line numbers):
We have added further explanation of the calculation of D_b (P10/L28-29).

Other note 6:
'11/5: The unexpectedly larger of biodiffusion coefficient at ~7 to 8 cm depths results from only one sample run. If one runs more samples and average them, I think the "unexpectedly" will be disappear. It is not from non-local mixing.'

Response:
We have addressed the issue of stochastic process in our response to Comment 2 by Anonymous Referee #2.

Discontinuous displacements in sediments and thus the biodiffusion coefficient are more expected from non-local mixing than local mixing (e.g., Shull, 2001). Thus, a sudden large displacement in relatively deep sediment can be reasonably attributed to non-local mixing. Nonetheless, after conducting multiple runs for each simulation, the sudden change described in the relevant sentence of the previous manuscript was found to occur in some runs but not in others.

Changes in manuscript (Page numbers/Line numbers):
We have added an appendix to show the contribution of stochastic process to the bioturbation results in the revised manuscript (Appendix D, P18/L25-29). Where necessary, we modified descriptions in

Section 3 of the revised manuscript (P12/L1-2, P12/L13-14, P12/L27-28, P13/L28, P14/L12, P15/L23-24). We removed the relevant sentence as it applies to some runs but not others (P12/L1-2).

Other note 7:

'12/3: The authors mentioned that "advective water flow has only insignificant influences on bioturbation". In fact, people are more interested in the effect of bioturbation on the advective water flow and thereafter the bioirrigation, which might significantly change oxygen flux.'

Response:

Currently, eLABS cannot explicitly simulate the pumping action of infauna, which we plan to implement in future model developments, as described in Section 4. Nonetheless, we ran a simulation where the water flows imposed at the time of ingestion/egestion are increased arbitrary by factors between 10^2 and 10^4 to implicitly include a bio-irrigation effect. With increasing biologically induced water flows, more strong oxygen-mixing can be caused by advection and the bioturbation results are similar to those in a simulation with a high shear velocity. Hence it is possible to address the importance of bioirrigation during bioturbation in such simulations with increased advective water flows.

Changes in manuscript (Page numbers/Line numbers):

We added an appendix which shows simulations where water advection caused by infauna at the time of ingestion/egestion is increased by factors between 10^2 and 10^4 (Appendix E, P19/L2-14). We reference this appendix in the relevant sentence (P13/L4-5).