

Answer to Anonymous Referee nr.1

We thank Anonymous Referee nr.1 for their thoughtful comments which allowed us to improve the model and the manuscript. We especially appreciated the Referee's corrections regarding the benthic model and describe below our related changes to the code. We also provide a point by point answer to all of their comments. The Referee's comments are highlighted in blue, actual changes to the manuscript are highlighted in red.

R1C1)

The model for phosphorus (P) degradation in marine sediments considers aerobic respiration (Eq. 11) but seems to ignore anaerobic degradation. As a result the burial efficiency increases when oxygen is deleted in ambient bottom waters whereas the available observations show that P burial efficiency actually decreases under low-oxygen conditions (Slomp et al., 2002; Van Cappellen and Ingall, 1994; Wallmann, 2010). The authors should try to change their benthic model (i.e. include anaerobic degradation and enhanced P release under anoxia) or explain why they apparently ignore the strong evidence for enhanced benthic P release under low oxygen conditions.

We agree with Referee nr.1 that our model was failing at correctly representing the dependence of P degradation and burial on O₂ concentration, and have therefore modified the benthic model accordingly.

Our new model representation of the sediments includes an enhancement of the rate of P_{org} remineralization (+25%) and decrease of Ca-P burial (-50%) under anoxic conditions compared to oxic conditions, in line with Slomp & Van Cappellen 2007. The new equations are described in detail in subsections 2.2.4 and 2.2.5 of the revised paper, and can be read in full in the paper's appendix. The two new parameters determining changes in the rates of remineralization and Ca-P formation under anoxic conditions have been added to Table 4.

Despite these changes, our model results and conclusions regarding P and O₂ concentrations as a function of the particle remineralization lengths (Figure 4 and following ones) remain the same.

- New formulation of sediment P_{org} remineralization for the sediment box i overlaid by the deep ocean box j:

$$SedRem_{ox}^i = rm_r \cdot SedP_{org}^i \cdot (O^j / (O^j + K_O^s))$$

$$SedRem_{an}^i = (rm_r \cdot fe_{an}) \cdot SedP_{org}^i \cdot (1 - O^j / (O^j + K_O^s))$$

where $fe_{an}=1.25$ is the remineralization rate enhancement factor in anoxic conditions.

- New formulation of CaP formation for the sediment box i overlaid by the deep ocean box j:

$$CaPform_{ox}^i = CaP_r \cdot (SedP_{org}^i)^2 \cdot (O^j / (O^j + K_O^s))$$

$$CaPform_{an}^i = (CaP_r \cdot fs_{an}) \cdot (SedP_{org}^i)^2 \cdot (1 - O^j / (O^j + K_O^s))$$

where $fs_{an}=0.5$ is the Ca-P formation rate suppression factor in anoxic conditions.

The revised subsection 2.2.5 on sediment remineralization reads as follows:

In each sediment box i , remineralization of $SedP_{org}$ happens in a similar way to remineralization in the water column, with an aerobic and an anaerobic component. The first takes up oxygen from the overlaying deep-water box j and happens at a constant rate rm_r , while being limited by a Michaelis-Menten coefficient. Anaerobic remineralization releases its product to the atmosphere and happens at a faster rate $rm_r^* = rm_r \cdot fe_{an}$ with $fe_{an} > 1$, in agreement with recent observations and previous models (Slomp and Van Cappellen, 2006). Total sediment remineralization is therefore the sum of the two terms as in:

$$SedRem^i = rm_r \cdot SedP_{org}^i \cdot (O^j / (O^j + K_O^s)) + (rm_r \cdot fe_{an}) \cdot SedP_{org}^i \cdot (1 - O^j / (O^j + K_O^s)) \quad (11)$$

The revised subsection 2.2.4 on Ca-P formation reads as follows:

Ca-P formation happens at a lower rate under low oxygen conditions ($CaP_r^* = CaP_r \cdot fs_{an}$ with $fs_{an} < 1$), in agreement with observations and previous models (Slomp and Van Cappellen, 2006). The transition from aerobic and anaerobic conditions is controlled by a Michaelis-Menten type of function of the oxygen concentration in the deep ocean box j overlaying the sediment box i . The oxic and anoxic terms sum to the total formation term as in:

$$CaPform^i = (SedP_{org}^i)^2 \cdot [CaP_r \cdot O^j / (O^j + K_O^s) + (CaP_r \cdot fs_{an}) \cdot (1 - O^j / (O^j + K_O^s))] \quad (8)$$

R1C2)

The shelf model ignores P burial in shallow-water shelf sediments even though observations in the modern ocean indicate that most burial of particulate organic matter (POM) occurs in the inner shelf region at < 50 m water depth (Dunne et al., 2007). The authors should try to change their benthic model to include shallow shelf burial or explain why they ignore burial in shallow shelf regions.

We agree with Referee nr.1 that a significant fraction of the burial of POM happens in the shallowest regions of the shelf. Some of this is heavily influenced by the input of sediments and POM from the land. This shallowest portion of the shelf is also the most influenced by the details of the local bathymetry, tides, sediment resuspension and bottom layer mixing (Hill et al., 2008; Simpson and Pingree, 1978), which have important consequences in terms of physical-biogeochemical interactions. Differently from other models which distinguish between shallow (< 50 m deep) shelf and slope region (e.g., Slomp & Van Cappellen, 2007), BPOP calculates the sedimentation and burial fluxes dynamically, and would therefore require accounting for extra physical processes and flux parameterizations to justify going to such a higher level of detail. As our principal focus is on the first-order response to changes in the biological pump, we think that a 4-box representation of the ocean and of its circulation is a reasonable simplification, allowing us to keep the number of parameters small. We therefore keep this suggestion in mind for future developments of the model.

R1C3)

Small (slowly sinking) particles are mostly degraded in the water column whereas a substantial fraction of the large (rapidly sinking) particles is not degraded but deposited at the seafloor. Consequently, large POM particles reaching the seabed are more reactive (fresher) than small (older) particles and the kinetic constant for benthic degradation should increase with increasing particle size (Stolpovsky et al., 2018). Since particle size (sinking speed, mineralization length) is the major parameter varied in the modeling, the authors should try to consider this effect in their benthic model.

We thank Referee nr.1 for this interesting suggestion regarding the relation that may exist between the particles' remineralization rates in the sediments and their size or sinking speed. As BPOP allows to explore a variety of different hypothesis, we have decided to test the possibility of having sediment remineralization rates that depend on the particle properties, and we show our results below.

However, we highlight that the remineralization length z_{rem} (around which the model is built) does not only depend on the particles' sinking speeds, but also on the particles' remineralization rates in the water column. By this definition, it may not be given that particles that have larger remineralization lengths (our "large particles") have also larger sinking speeds. They may instead just be more refractory to water column remineralization, which also allows the particles to be remineralized on average more at depth. Other factors, such as the fact that large particles are defined as a secondary product of the coagulation of smaller particles can also influence the liability the LP_{org} pool. For these reasons we take this suggestion as a sensitivity experiment, but do not include it in the revised baseline model.

As a simple hypothesis, we have assumed that the sediment remineralization rate rm_r increases linearly with z_{rem} by 40% of our baseline value going from $z_{rem} = 0$ to $z_{rem} = 450$ m, with the baseline value of rm_r being found at $z_{rem}=225$ m, which is in the middle of the full range of explored values. In each run, the remineralization rate is calculated separately for small and large particles according to their respective z_{rem} . The two types of particles in the sediments are then solved separately and remineralized according to their respective rate. We have re-run the model under this assumption and include below a few significant comparison plots of the results of both our baseline run (the one adopted in the model) and the sensitivity run.

Our results show that there is no significant change in the model results that affects our primary conclusions from the baseline run. The main difference between the two sets of results consists in the facts that the sensitivity study shows a slightly stronger decoupling between the influence of the small and large particle remineralization lengths (respectively, z_{rem}^S and z_{rem}^L) on the equilibrium budgets and fluxes. The value of z_{rem}^S becomes even more influential for high z_{rem}^L , where the latter seems to make little difference in determining the equilibrium state of the model.

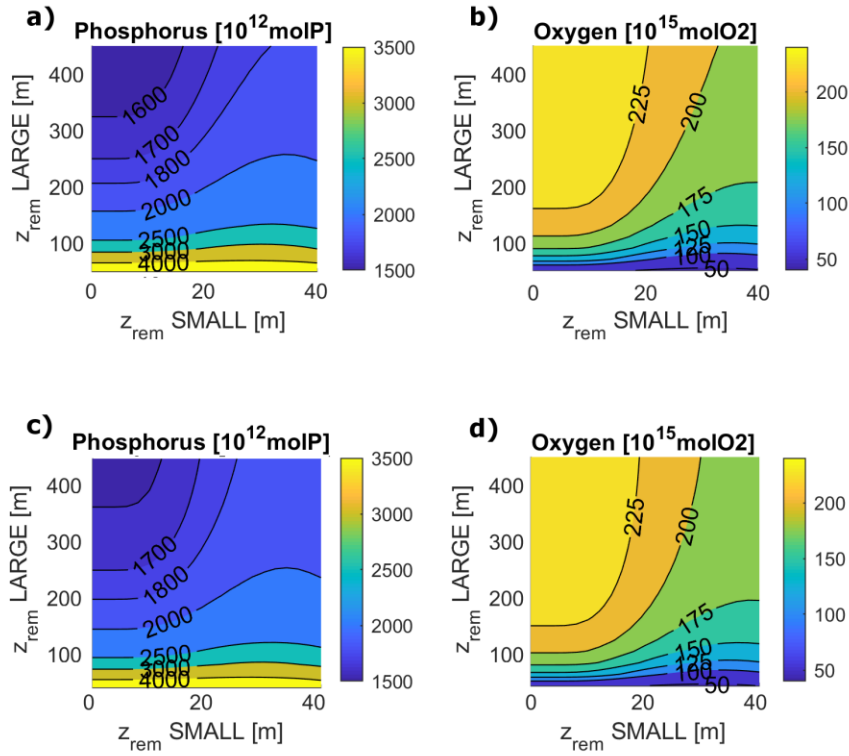


Figure R1-1: Ocean P and O₂ budgets for 2 model configurations: constant remineralization rate (subplots (a) and (b), new baseline); remineralization rate dependent on the particles' remineralization length (subplots (c) and (d)).

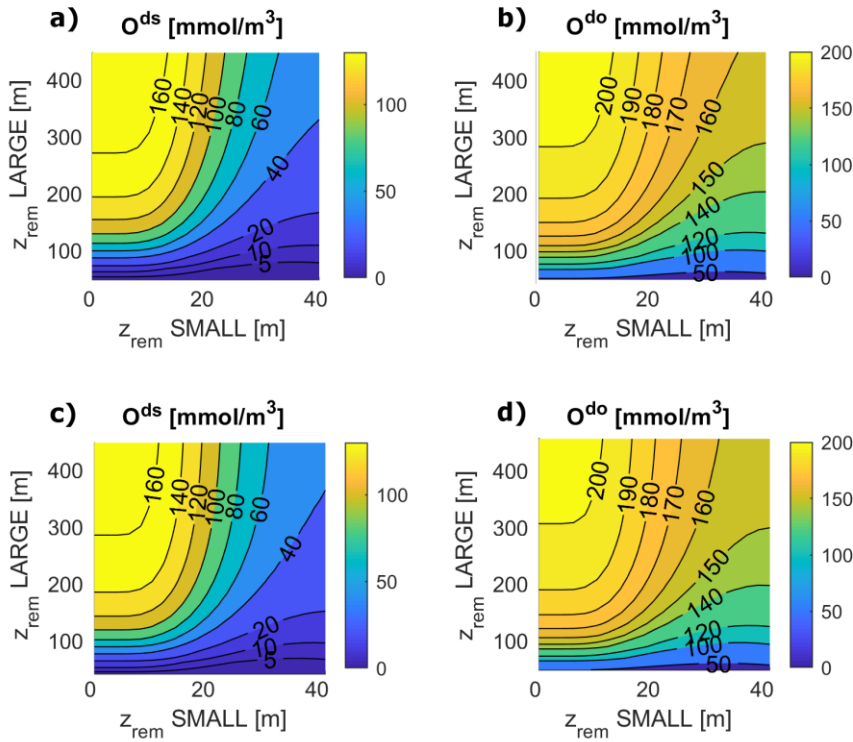


Figure R1-2: Oxygen concentrations in the deep shelf (ds) and in the deep open ocean (do) for 2 model configurations: constant remineralization rate (subplots (a) and (b), new baseline); remineralization rate dependent on the particles' remineralization length (subplots (c) and (d)).

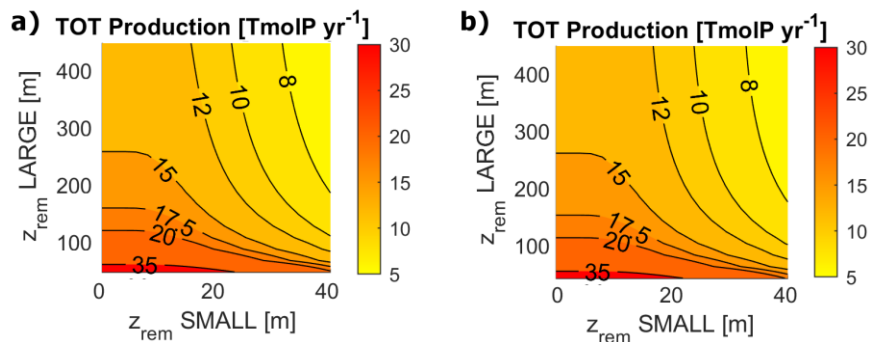


Figure R1-3: Total ocean production for 2 model configurations: constant remineralization rate (subplots (a) and (b), new baseline); remineralization rate dependent on the particles' remineralization length (subplots (c) and (d)).

R1C4)

Considering these model limitations, I do not know whether the authors' conclusion: "shelf ocean anoxia can coexist with an oxygenated deep ocean" (abstract, line 19) is really valid. Moreover, this conclusion depends on the model assumption that deep water formation takes place in the open ocean. This assumption is questionable since much of the modern deep water formation happens at continental margins. If these margin sites are oxygen depleted the resulting deep water would also be oxygen depleted.

We have changed the wording in the abstract to say that the results "suggest" this can happen (rather than "highlight" that it can) – the use of the word "can" should anyway have been taken to imply this is one of several possibilities. Regarding the impact of our representation of ocean circulation on the modelled oxygen distribution, in the modern ocean, deep water formation happens mostly at very high latitudes i.e., in the subpolar North Atlantic (Labrador Sea and Greenland Sea), in the Southern Ocean (Weddel Sea and Ross Sea). Both regions are characterized by physical and biogeochemical properties that differ substantially from our representation of a shelf sea, which is not intended to include polar and subpolar regions of sea-ice cover, continental ice shelves, deep convection etc. Therefore we don't think that attributing deep water formation to the shelf sea in our model would be the correct way to represent ocean circulation. Furthermore, our estimate of open ocean mixing and vertical exchange of water refers mostly to open ocean fluxes both at high and at low latitudes, and is in line with current estimates (Sarmiento and Gruber, 2006; Ganachaud and Wunsch, 2000). Instead it is our assumption of a circulation flux from the deep open ocean to the shelves, which thus boosts shelf nutrient concentration, which is more critical for determining the modelled oxygen distribution.

Bibliography (Answers to Anonymous Referee nr.1)

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