

Original comments are given in black, our reply is given in red.

J. Segschneider (Referee)

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General comments:

The paper describes experiments with the Bern3D model in which the remineralization depth is shifted upwards and downwards by 25 m intervals. This is meant to represent temperature dependent remineralization in a warming/cooling ocean on glacial/interglacial time scales. The model is integrated for 100 to 200 kyr either in 'open system' mode (with an active sediment) or in 'closed system' mode (without an active sediment). Atmospheric pCO₂ and d13C are analyzed from these experiments and the main finding of the study is that pCO₂ changes are, on longer time scales than 1000 yr, significantly higher when nutrient deposition in the sediment is taken into account. This assumes that weathering fluxes are constant in time. The authors provide also a value of change in atmospheric pCO₂ per metre shift of the remineralization profile.

As such it provides a valuable contribution to the impact of changes in remineralization of organic matter on the carbon cycle, in particular regarding glacial/interglacial time scales. The paper is generally well written and figures and tables are well thought out. At some points it could be a bit more precise, and the guidance of the reader could be improved. Below are more specific comments that hopefully will improve the paper.

We thank the reviewer for his valuable comments that helped to improve the manuscripts and for his time and effort to review this manuscript.

Specific comments

General: POC/POM/POP are used, I suggest to stick to one name (POM seems most frequent)

Done. We checked the use of POC, POM and POP. We use now the term POM when referring to organic matter in a general sense, but still use POP and POC when fluxes of phosphate or carbon are discussed.

you do not discuss changes in surface alkalinity due to reduced productivity in the open system experiments. Is this because you found that it is irrelevant?

It is not the aim of this paper to discuss surface ocean biogeochemistry changes due to changes in marine productivity. Especially in the open system, the separation of production, remineralization and sedimentation effects are difficult to separate.

In our model, CaCO₃ export decreases in parallel to POM export except in the Southern Ocean where the rain ratio decreases (as silicic acid is not as depleted as phosphate, favouring diatoms w.r.t. calcifier). But this effect is confined to the SO. Thus, reduced productivity increases surface Alk (dominated by the weakened carbonate counterpump) and increases DIC (dominated by the weakened soft-tissue pump). This is in agreement with Segschneider et al. (2013) who find a decrease in TA for an increased rate of remineralisation.

To summarize this, we included the following sentence in the results section (p485, l14):

"The reduced export triggers some minor changes in the ecosystem structure in the Southern Ocean, where phosphate depletion favours the growth of diatoms, leading to a local decrease in the export rain ratio. The net effect of the production changes is thus a surface-ocean increase in DIC and Alk, except for the Southern Ocean where surface Alk remains constant."

Title: I suggest to state that atmospheric carbon dioxide is meant

Done. Word atmospheric added

Abstract p474 l3: I suggest to change 'provide a positive feedback under climate change' to sth like 'provide a positive feedback mechanism with atmospheric CO₂ and hence climate change'

Done. Text changed

l5 CO₂ -> atmospheric CO₂

Done.

l5/6 it is stated that the response of tracer fields for which observations and paleo proxies exist is analyzed, but there is never a comparison with proxies in the ms. nor are the proxies simulated that are mentioned in the 'Discussion and conclusion' section. so I suggest to either be more specific and come back to this in the text or remove the statement. (also p477 ln 5)

We removed the term paleo proxy from p477 ln 5.

A direct comparison with proxy data is not meaningful as the experiments here are of illustrative nature. However, we do discuss results for tracers for which direct observations and paleo proxy data exist. These include ¹³C, CaCO₃ and POM burial, oxygen and carbonate ions. Thus, we left the text in the abstract unchanged as we view the statement as correct

l8 it is not the 'initial' response, but the 'long term' response in atm. CO₂ which is amplified by the sediment burial-nutrient feedback (see Fig. 7a) (also p477 l18)

Done. Word 'initial' deleted

l8/9 why is this called a 'temporary' imbalance? (It is called 'transient' on p476 l17, which I find more appropriate, and 'sustained imbalance in Sec 3.1.2, p489 l6)

Done. 'temporary' replaced by 'transient' and 'sustained' by 'long-lasting'

l13/14 I suggest to insert 'atmospheric' before d13C signatures and CO₂ sensitivity

Done. 'Atmospheric' added for CO₂ sensitivity, but not for the δ¹³C signature as not just the atmospheric signature is changing.

Introduction

I26 'calls for' too strong? what about pCO₂ as driver of temperature changes?
suggest to replace 'tight coupling' by 'larger temperature changes than one would
expect from delta pCO₂ based on climate sensitivity of current climate models' if that
is meant

Done. Sentence deleted to avoid confusion.

I27 I suggest to change CO₂ drawdown 'during' the Last Glacial Maximum to 'leading
to' the last LGM

Done. Text modified as suggested.

p475 I14 to 'increase viscosity and thus the speed of sinking particles'?? sign correct
I would expect a smaller sinking velocity for increased viscosity. It should be ...'to
decrease viscosity and thus to increase the speed of sinking particles'
Taucher et al. 2014: 'As rising temperatures reduce seawater viscosity, the sinking
velocity of particles will accelerate'

Thank you – mistake corrected

I17/18 I suggest to delete the 'increase' before 'respired carbon storage'.... 'such
changes' refers also to Bendtsen et al, Taucher et al., and there the changes will
result in decreased respiration carbon storage in the deep ocean

Done. 'increase' deleted.

I19 Also the 'As a result' assumes that changes in remin-min-depth lead to 'increased'
storage in the deep. Deleting 'As a result' is an easy way out here, then the two
sentences are correct.

Done. Text modified as suggested.

p476 I3 'all these studies neglect ocean-sediment interactions' this is not strictly true,
e.g., the model of Segschneider & Bendtsen includes a sediment (see their Fig. 6) -
for the time-scales of 100 yr they discuss, the sediment is of minor importance, as
also seen in Fig. 7a of this ms. Also Tschumi et al. 2011 have an active sediment
included and discuss briefly the amplification of the closed system by taking into
account ocean-sediment interactions (their Section 2.3.3). I suggest to be a bit more
specific about how this study differs from the one of Tschumi et al. 2011 (e.g.,
different focus, constant physics...)

Done. Sentence changed to read: 'As a caveat, these studies either focus on the
decadal-to-century scale response (Segschneider, 2013) or neglect ocean-sediment
interactions and the weathering-burial cycle.'

Sentence added to clarify difference to study by Tschumi et al; 'However, these
authors did not investigate changes in the remineralization depth of POM.'

I19 Change 'These consequences' to 'The consequences of this imbalance' have not
been discussed...?

Done. Text modified as suggested.

p480 I12 an e-folding depth (I_POM): e-folding depth 'as length scale' (I_POM) would make it more easy to understand why it is called 'I_POM') and could avoid confusion throughout the text (where 'depth', 'mean remineralisation depth', 'profile', 'POM deepening' and 'length scale' are used for 'I_POM')

Done. Text modified as suggested.

I21 Is there really 'advection' in the sediment?

Done. 'advection' replaced by 'transport' to avoid confusion.

p483 I20 I suggest to change 'during the experiments' to 'during our experiments' to make clear that not the experiments in the referenced studies are meant

Done. Text modified as suggested.

Results

p485 I2 3.1 I_POM changes: I suggest a slightly more informative heading

Done. Heading changed to read: 'Changes in the remineralisation length scale of POM'

I4 I would not start the Results section by 'We start discussion by'....

Done. Text modified to read: 'We first analyze ..'

I11 'subsurface water' - you could be a bit more precise here. Is the water directly below the euphotic layer or within the euphotic layer meant?

Done. 'subsurface water' replaced with 'upper thermocline'.

I12 how robust is the decrease in global export with respect to the neglection of remineralisation within the euphotic layer? If you would consider remineralisation in the euphotic layer, a downward shift of the remineralization profile would cause increased export.

Done. On average, export production is balanced by the input of nutrients into the euphotic zone. We thus assume that potential changes in the ratio between recycled and new production do not affect export out of the euphotic zone. We added the following caveat: "Note that we only consider changes in remineralisation below the euphotic zone."

I14 'leads to an initial spike in POM deposition' does not give the sign, so I suggest to change it to 'spike-like increase' and to add a ref to Fig.3d

Done. Text modified as suggested and reference to figure added.

I22ff would it be useful to add at the end of the sentence 'Second (the) whole ocean...'

...after the step change 'due to reduced productivity in the euphotic zone'?

Done. Text clarified by adding: 'due to excess burial of POP.

p486 l6 suggest to replace 'Finally' by 'Eventually' (I guess this is meant)

Done. Text modified as suggested.

l22 I suggest to insert 'decreased' between 'by' and 'calcite burial' to make the sentence easier to follow or perhaps reverse it: The loss of carbon due to enhanced burial of POM is counteracted by a small gain due to reduced calcite burial, while....

Done. Text modified by adding decreased.

p487 l7 suggest to add (Fig. 4a) after ocean

Done. Text modified as suggested.

l17 suggest to add (Fig. 4c) after deposition

Done. Text modified as suggested.

p488 l1 suggest to add (Fig. 5a) after PO4 inventory

Done. Reference to figure added at end of sentence.

l6 'As expected, this pattern is mirrored ...by DIC, oxygen, d13C
In the closed system, the patterns of oxygen and CO₃ are inverse to the pattern of PO₄ (see Fig. 5a, 5c, 5g) whereas for DIC it is similar (Fig. 5e) so I doubt that 'mirrored' is meant. I also assume that CO₃ is meant, not d13C, which is not shown in Fig. 5? Also I suggest to point to the figure panels and to add a 'not shown' for variables not in Fig. 5 (d13C, ALK, CaCO₃) in the text. (ALK is discussed relatively heavy in this section so you might want to show it in Fig. 5)

Done. Figure references added and text revised to read: "As expected, this pattern is similar in subsurface waters for DIC (Fig. 5e) and inverse for d13C (Fig. 8d) and oxygen (Fig. 5c) as these tracers are linked to PO₄ by constant Redfield elemental ratios in biological fluxes."

The pattern for Alk change is quite similar to the pattern of the carbonate ion change. An additional panel for ALK is added to Figure 5.

l25 I suggest to start a new subsection here and discuss the EOFs in more detail, or to skip this para and to skip Fig. 6 Why are the EOFs computed for (only) CO₃?

We decided to remove the material linked to the EOFs analysis, see also the comment to referee #1.

l27 I would change 'by 2' to 'the first two'

Done. Text modified as suggested.

l28 and insert 'of the principal components' after 'corresponding time series'

Done. Text modified as suggested.

I28/29 'The resulting patterns strongly resemble those shown with (in) Fig.5g and h, i.e. the open(-) and closed(-)system response'..... I recommend to be more precise: 1st EOF resembles open system (Fig. 5h), 2nd EOF resembles closed system (Fig. 5g)

Done. Text modified as suggested.

p489 l14 'The CO₂ decrease is more than 100ppm for a change in I_POM to 375m' Can you say if the implied temperature change is in agreement with LGM temperature?

It is beyond the scope of this MS to link CO₂ changes to temperature changes. Ice core data show that atmospheric CO₂ was about 100 ppm lower at the LGM than in the late Holocene. The associated radiative forcing contributed to the cold conditions at the LGM, but other forcings such as a higher albedo due to larger ice sheets and enhanced snow cover, changes in vegetation cover and dust loading contributed. For further information see Jansen et al (2007)

I21 check use of 'standard experiment' here. It has been referred to as I_POM=250m, here it seems to be used for I_POM=275m (also line 25)

Done. Text clarified to read: "Global export production decreases when increasing the remineralisation length scale in the standard model setup."

I22 'to disentangle the influence of the reduced export flux vs. the change in remineralisation profile' is this possible using this setup? Also, by disentangling, I would expect some more elaborate results, e.g., change in remin causes this and export causes that, not just the factor of 2-4 for the (unrealistic) constant export exp.

Done. "disentangle" replaced by "explore".

p490 l3 It might be useful to explain why these experiments have been made. Is there a reason to assume that changes in remin-depth have occurred in confined regions during glacial periods?

Done. Sentence added: "The hypothesized change in the remineralisation depth may be different in different regions."

p491 l10 what is meant by 'checked by' here? balanced?

Done. 'checked by' replaced by 'balanced by'.

Discussion and conclusion

p494 l22 It is shown that 'on long time scales' ocean sediment interaction...

Done. Text modified as suggested.

p497 l5 Gangstoe et al. 2011 ...did not apply a sediment model. Even though Gangstoe et al do not mention a sediment module, PISCES usually runs with active sediment, so it may be worthwhile to check if this statement is correct.

Done. Statement is correct.

Fig. 8a any idea why the red lines ($\delta^{13}\text{C}$ open system) in Fig.8a cross all at 50 kyr and at the level of the control experiment?

As all the perturbation experiments underly the same timescales of re-adjustment as they lay within the quasi-linear regime. Due to reasons of symmetry, this crossing must take place at the level of the control experiment.

Fig. 10 does not show a 'map'.

also it would be helpful to state the times for which the plots are produced

Done. Word 'Map' deleted and the following text is added in the caption: ' and for equilibrium (see main text).' It is explained in Section 3.3 how equilibrium values are estimated.

is it easy to understand why the open system amplification is highest around $I_{\text{POM}} = 250\text{m}$? I guess this is due to the division by small numbers (closed system response is close to zero for $I_{\text{POM}}=250\text{m}$), so this may be a bit misleading as it implies that the open system amplification is particularly strong for small perturbations of I_{POM} .

It is not straightforward to understand why the amplification is larger for small perturbations in I_{POM} as changes in ratios are difficult to interpret in such a non-linear and complicated system. However, we note that the amplification shows a decreasing trend when increasing I_{POM} over the range from 250 to 360 m (color gradient in figure 10c). Thus, we consider the results shown in Fig. 10c as numerically robust .

Technical errors

p474 l 10 ...lead to sustained changes 'in' the ('in' missing)

p475 l 21 This mechanisms (sgl/pl)

p478 l3 correct 'arithmically'

p479 l3 correct calcifer

p480 l17 change 'lengthscale' to length scale

p483 l16 change 'as induces' to 'as induced'

p481 l23 change 'prescribed to' to 'set to' or 'prescribed as'

p482 l2 change 'Global integrated' to 'Globally integrated'

p484 l7 change 'describe' to 'describes'

p487 l2 change to ...after 32kyr (Fig.3g) (not 3f)

l18 change 'region' to 'regions'

l20 change Indian ocean to Indian Ocean

p488 l16 change 'As a results' to 'As a result'

l21/22 change This ... 'anomalies are' to 'anomaly is' (or 'These...')

p490 l3 change 'pumps' to 'pump'

p492 l16 dot is missing after 'in sensitivity simulations'

Done. (logarithmically is correct)

References:

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Btiesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D.: Palaeoclimate, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge United Kingdom and New York, NY, USA, 433-497, 2007.

Segschneider, J. and Bendtsen, J.: Temperature-dependent remineralization in a warming ocean increases surface pCO₂ through changes in marine ecosystem composition, Global Biogeochem. Cy., 27, GB004684, doi:10.1002/2013GB004684, 2013