

Interactive comment on “Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO₂ rise” by T. Tschumi et al.

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We thank the reviewer very much for the careful reading of our manuscript and appreciate the constructive suggestions. Our response is given below.

As a major comment the reviewer recommends to expand the discussion of model results with respect to changes in the preformed and regenerated nutrient components in order to quantify the impact of the soft-tissue carbon pump on atmospheric carbon. As a response to this comment we have calculated and analyzed preformed and regenerated nutrient components for the model results of the windstress-experiments.

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Values for the efficiency of the soft-tissue pump (as defined in Ito and Follows (2005)) are reported in a new Table 2 and are displayed in a new Figure 8 (shown as Figure 1 in the supplement of this interactive comment). We have further added a new panel to Figure 11 displaying changes in zonal mean regenerated nutrient concentrations due to an 80%-increase in SO windstress. See also response to comment #9 below.

Please find below the point-to-point response regarding the minor comments:

1. p. 1898, l.2: 'initial driver' replaced by 'the dominant internal forcing mechanism'.
2. p. 1898, l.29: We have added the following text:

Jaccard et al. (2009) and Bradtmiller et al. (2010) recently have presented evidence for increased sequestration of remineralized carbon into the deep Pacific during the LGM. Their reasoning is based on the argument that a more efficient biological pump during glacial periods does not necessarily imply that total (= preformed + regenerated) nutrient concentrations in the deep ocean were significantly higher than during interglacials. Rather, the increase in biological pump efficiency would be mirrored in lower oxygen concentrations in the deep ocean together with an increase in regenerated nutrients which might be at least partially offset by a decrease in the preformed nutrient component (e.g. Ito and Follows (2005)).

3. p. 1899, l.27 – p. 1900, l.2: We have added the following text:

Recent studies have suggested that an increase in the glacial nutrient inventory might be linked to changes in ventilation at intermediate depths rather than to changes in sea-level. A decreased volumetric extent of oxygen minimum zones would have reduced both the marine sinks for NO_3^- (Deutsch et al. (2004)) and for PO_4^{3-} (Wallmann (2010)).

4. p. 1900, l.9: Publication date of Marchitto et al. (2005) corrected.

5. p. 1901, l.11: We have added the following text:

Note that a 30%-increase in whole-ocean nutrients during glacials is likely to be an upper limit of a realistic change (Deutsch et al. (2004); Wallmann (2010)).

6. p. 1910, l.8-110: We have added to following text:

Note that a glacial increase in export production in the North Pacific is at odds with paleoproductivity reconstructions (see Jaccard et al. (2009); Galbraith et al. (2007); Crusius et al. (2004)) suggesting that the history of export production from the North Pacific surface was predominantly controlled by processes other than changes in the whole-ocean nutrient inventory such as changes in water column stratification and associated upwelling of nutrients from the deep (Galbraith et al. (2007)).

7. p. 1913, l.28: As suggested by the reviewer, we have added two references: De La Rocha (2006) and Deutsch et al. (2004). Both papers deal with the interpretation of recorded changes in silicate and nitrogen isotope signatures. The potential role of long-term trends in isotopic signatures arising from weathering-sedimentation imbalances is mentioned in both publications but not taken into account or quantified explicitly.

8. p. 1917, l.1–5 and p. 1917, l.14–15: We have completely reformulated the corresponding paragraphs. The passage now reads:

The biological pump strongly dominates the net CO₂ response subsequent to wind stress changes in our model (see also Tschumi et al. (2008)). The effect of the solubility pump is minor as simulated changes

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in (potential) deep ocean temperature (below 2000 meters) are $\sim 0.5^\circ\text{C}$ at most (Table 2). This translates into a maximum effect on atmospheric CO_2 of roughly 5 ppm given the sensitivity of CO_2 -solubility to temperature in seawater (e.g. Sigman and Boyle (2000)). On the other hand, the imposed changes in ocean ventilation have a strong impact on the marine biological carbon pumps. Enhanced (reduced) ocean ventilation implies increased (diminished) upwelling of nutrients, thus promoting (weakening) biological export from the surface.

Table 2 indicates that organic matter export scales roughly linearly with ventilation in case of the on-states (rising by 2% per 100-year reduction in global deep water age). The marine silica cycle on the other hand reacts more sensitively to enhanced ventilation than to a slowdown. Opal export increases by 8% upon a 100 year-reduction in global deep water age and decreases by 2.3% per 100 year-increase. The full time-dependent response in POC and opal export is shown in Fig. 6c and 6d.

Note that the efficiency of the soft-tissue pump P^* , defined here as the ratio between regenerated and total phosphate in the deep ocean (Ito and Follows (2005)), behaves conversely, i.e. P^* increases as export production decreases parallel to slowed ventilation (Table 3). As long as NADW formation is active, a linear relation is found between atmospheric CO_2 and P^* (Figure 8), indicating a maximum impact of the biological pumps of 336 ppm at full efficiency. This value is close to the 312 ppm found by Ito and Follows (2005) on theoretical grounds. It follows that the predominant part of the simulated CO_2 response to changes in SO deep water formation is driven by changes in the biological pump efficiency.

When NADW formation shuts down in response to weak SO winds the relation between atmospheric CO_2 and P^* deviates from linearity

(Figure 8). Thus, the anomalous CO₂ reduction of ~10 ppm due to the AMOC collapse cannot be explained with changes in the biological carbon pumps. Further, the absence of a corresponding drop in global mean deep water temperature and in the global rain ratio (Table 2) seems to preclude a dominant role of the solubility and carbonate pumps. We conjecture that the simulated anomalous CO₂ drop in response to collapsed AMOC results primarily from an increase in the deep water DIC disequilibrium component (Marinov et al. (2008)).

The interplay between ocean ventilation, marine carbon cycling and atmospheric CO₂ displayed in our model experiments is in good agreement with the wind-experiments of Schmittner et al. (2007). However, the effect of AMOC shutdowns on marine carbon cycling in our experiments cannot be readily compared with the corresponding results of Schmittner et al. (2007) since AMOC is suppressed by freshwater forcing in the North Atlantic in their experiments rather than by weak SO winds.

9. p. 1922, l.22: Typo corrected.

10. p. 1925, l.3–10: We have added the following text:

This is consistent with deglacial CaCO₃ and organic matter flux reconstructions from the North Pacific (e.g. Jaccard et al. (2005); Galbraith et al. (2007)) as well as with CO₃²⁻ reconstructions based on benthic Zn/Ca measured in the deep equatorial Pacific (Marchitto et al. (2005)).

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