Biogeosciences Discuss., 6, 8101–8128, 2009
www.biogeosciences-discuss.net/6/8101/2009/

Biogeosciences
Discussions

Biogeosciences Discussions is the access reviewed discussion forum of *Biogeosciences*

Enhanced biological carbon consumption in a high CO_2 ocean: a revised estimate of the atmospheric uptake efficiency

R. Matear[1] and B. McNeil[2]

[1]Centre for Australian Weather and Climate Research (CAWCR), A partnership between CSIRO and the Bureau of Meteorology, Sydney, Australia
[2]Climate Change Research Centre, Faculty of Science, University of New South Wales, Sydney, Australia

Received: 23 February 2009 – Accepted: 30 July 2009 – Published: 10 August 2009

Correspondence to: R. Matear (richard.matear@csiro.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A recent mesocosm study under high CO_2 conditions has found phytoplankton carbon consumption is elevated beyond typical Redfield ratios (Riebesell et al., 2007). We investigate the efficacy of this elevated biological carbon consumption to increase global oceanic CO_2 uptake from the atmosphere in an ocean general circulation model (OGCM). In the OGCM, elevated biological carbon consumption throughout the ocean increased oceanic CO_2 uptake by 46 Pg C during 1800 to 2100 period, which is less than half the value estimated by (Riebesell et al., 2007). Our study's lower ratio of oceanic CO_2 uptake from the atmosphere caused by enhanced biological carbon consumption (export production) is due to a more realistic 3-D circulation and the resulting spatial patterns in the re-supply of carbon from the interior ocean to the surface. In our OGCM simulations, despite increased biological carbon export to the ocean interior, some regions like the eastern equatorial Pacific and Southern Ocean actually take up less CO_2 from the atmosphere. This is due to the pooling of exported carbon at intermediate depths within these regions (analogous to nutrient trapping) and its subsequent re-supply back to the surface that exceeds the enhanced biological carbon export in the high CO_2 world. Thus large-scale increases in biological carbon export can lead to some areas where surface ocean pCO_2 increases more rapidly than atmospheric CO_2. Furthermore, our results demonstrate that enhancing biological carbon export via other means such as iron fertilization is inefficient in regions like the Southern Ocean because of the rapid vertical re-supply of carbon-rich waters. This vertical resupply of carbon-rich waters in the Southern Ocean dampens the oceanic CO_2 uptake efficiency due to enhanced biological carbon consumption to be only 16% and suggests a very low efficacy of biological fertilization in the region.

1 Introduction

The oceanic biological pump is a fundamental process regulating atmospheric CO_2 (Martin, 1990; Volk and Hoffert, 1985). The biological pump involves carbon uptake by phytoplankton photosynthesis in the photic zone of the upper ocean and the subsequent vertical transfer of some this organic carbon into the ocean interior as dead phytoplankton and fecal matter of higher trophic organisms. As this organic matter sinks into the ocean interior it is remineralized back to its inorganic constituents. The net result is the biological transfer of carbon from the upper ocean into the ocean interior, which maintains a vertical gradient in total CO_2 (dissolved inorganic carbon) that increases with depth. Higher biological drawdown at the surface lowers CO_2 and enhances the oceans carbon uptake from the atmosphere.

Accelerating the biological transfer of carbon into the ocean interior provides a mechanism for sequestering more atmospheric carbon into the oceans. One way of enhancing the biological carbon pump is through fertilization of the surface ocean with iron or macronutrients in regions where phytoplankton are limited by nutrient availability. A number of modeling studies have assessed the potential of adding iron to the 25% of the surface ocean that appears iron limited to enhance oceanic carbon uptake (Gnanadesikan et al., 2003; Jin et al., 2008; Sarmiento and Orr, 1991b; Kurz and Maier-Reimer, 1993). Matear and Wong (1999) and Sarmiento and Orr (1991) estimated that continuing iron fertilization within the iron limited regions of the global oceans over 100 years would enhance oceanic uptake of atmospheric CO_2 by between 100–181 Pg C. The potential for enhanced biological carbon consumption can also be achieved through enhanced supply of macro-nutrients (inorganic Nitrogen or Phosphorus) in those vast regions of the ocean which are limited by these nutrients. A number of modeling studies have been performed in light of the potential for macro-nutrient fertilization (Dutkiewicz et al., 2006; Gnanadesikan and Marinov, 2008; Gnanadesikan et al., 2003; Marinov et al., 2008a; Matear and Elliott, 2004; Orr and Sarmiento, 1992). Whether biological carbon consumption is enhanced via iron-fertilisation or macro-nutrient fertilization, the efficiency of atmospheric CO_2 uptake by the ocean can be discussed in a similar way.

The most important question in relation to enhancing the biological carbon pump is its efficency in actually sequestering atmospheric CO_2 (will be referred to as atmospheric uptake efficiency in this paper). If one additional unit of oceanic CO_2 is consumed by biological production and transferred into the ocean interior, and this causes one unit of CO_2 to be taken out of the atmosphere. Under this idealized scenario, the atmospheric uptake efficiency of the enhanced biological carbon pump is 100%. As pointed out by Jin et al. (2008), the atmospheric uptake efficiency is important since it is a metric on the relative importance of the biological carbon pump in controlling atmospheric CO_2. But as demonstrated by numerous modeling studies, the atmospheric uptake effiency can vary between 10–90% (Dutkiewicz et al., 2006; Gnanadesikan and Marinov, 2008; Gnanadesikan et al., 2003; Jin et al., 2008; Matear and Elliott, 2004; Sarmiento and Orr, 1991a). The main mechanisms for differences in the atmospheric uptake efficiency are the effects from lateral and vertical mixing, the vertical-gradient in carbon (remineralization profile) and the spatial extent of the fertilization ‘patch’ are all important in determining the atmospheric uptake efficiency. For example, Jin et al. (2008) perform iron fertilization experiments within a model with different areal extents of the fertilized area. They find over ten years that the atmospheric uptake efficiency of a small iron-fertilized patch in the equatorial Pacific (92 000 km^2) to be 0.93 or 93% efficient, while the efficiency rapidly drops to 0.31 (31%) when the patch is widening to cover all of the Pacific Ocean (150 million km^2) (Jin et al., 2008). This low atmospheric uptake efficiency for ocean-wide fertilization experiments sets the context for the current model results of enhanced biological carbon consumption.

A recent mesocosm experiment identified that rising CO_2 levels may provide another way of stimulating biological pump (Riebesell et al., 2007). The mesocosm study suggested enhanced biological carbon consumption in a high CO_2 ocean would increase the ratio of carbon to nutrients (nitrogen and phosphorus) for the exported particulate organic matter (POM). Riebesell et al. (2007) (henceforth referred to as R07), estimated that enhanced carbon export of POM with rising CO_2 would increase oceanic uptake of CO_2 from the atmosphere by 74 to 154 Pg C by 2100 under the IS92a scenario for a present day range of biological carbon export of between 8 and 16 Pg C y^{-1}, respectively.

The R07 estimate of the atmospheric drawdown of CO_2 due to enhanced biological carbon export was based on a simple box model. Clear details of their ocean model used to estimate the atmospheric uptake efficiency under enhanced carbon consumption are missing in R07, which makes it difficult to assess their estimates. Further, the physical re-supply of carbon and nutrients from the deep and intermediate ocean to the surface ocean may not be accurately simulated using simple box model. As with biological carbon pump perturbations using iron-fertilisation or macro-nutrient fertilization as discussed previously, the atmospheric uptake efficiency of the biological carbon pump is less efficient over large spatial scales. Here, we use a comple ocean general circulation model (OGCM) with an ocean carbon cycle to provide a more accurate assessment of the ability of enhanced biological carbon consumption to sequester additional CO_2 from the atmosphere.

The outline of the paper is as follows. In the method section, we describe the our OGCM-ocean carbon model and the model simulations used to investigate the efficiency of enhanced biological carbon consumption in sequestering atmospheric CO_2. In the results section, we present the key features of the model simulations and show that the atmospheric CO_2 uptake efficiency due to enhanced biological carbon consumption is about 0.3, i.e. 30% integrated over the global ocean. In the discussion section, we first compare our simulations with R07. Our simulations produce much lower carbon uptake efficiency than R07 and we investigate the processes responsible. Secondly, we use simulated oxygen fluxes and ocean oxygen concentrations, which can be directly compared to observations, to assess our hypothesis in what is driving the lower atmospheric CO_2 uptake efficiency. We then discuss the potential limitations of our study and that of R07 and identify some key future research effort.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

2 Methods

The OGCM – ocean carbon model used for the study is based on that of Matear and Hirst (2003). For this study, we use a suite of experiments driven by climatological forcing, a prognostic phosphate dependent export production parameterization and air-sea carbon flux based on the OCMIP-2 formulation (Najjar et al., 2007). The OGCM-ocean carbon model was first spun-up to steady state (4500 years of integration) after which it was integrated from 1800 to 1990 with observed atmospheric CO_2 levels and from 1990 to 2100 with the atmospheric CO_2 levels generated by (Joos et al., 1996) carbon model for the IS92a scenario (Fig. 1a). The various C:P ratio experiments are summarized in Table 1 and briefly discussed below.

In our simulations, the biological pump was modified to investigate the impact of enhanced biological carbon consumption and export as CO_2 concentrations increase in the oceans. In the original model formulation, particulate organic matter (POM) maintained a fixed C:P ratio of exported POM of 106:1 from the surface ocean. This is our control simulation (CpA). A second simulation was performed where POM carbon export increased as a function of atmospheric CO_2, which implies an increasing C:P of this exported organic matter (pA). Following R07, we parameterized the enhanced carbon with rising CO_2 according to the following scaling factor:

$$F_{\text{Scale}} = 1 + \frac{2}{700}\frac{16}{106}(pCO_2 - 280) \tag{1}$$

Therefore, at a pCO_2 value of 780 ppm, 22% more carbon is exported than in the case with a fixed C:P ratio; Note, the export of phosphorus is unaffected by the scaling factor; only carbon export changed.

A third simulation was performed to separate the impact of rising CO_2 in the atmosphere from the impact of enhanced carbon consumption on the oceanic uptake of carbon. We repeated the variable C:P experiment using the increased atmospheric CO_2 for the C:P ratio of exported carbon but for the air-sea CO_2 flux, the atmospheric CO_2 was fixed to 280 ppm (pA'). Hence, the model experiences the effect of enhanced biological carbon consumption without the increasing atmospheric CO_2 signal. To test the sensitivity of enhanced carbon consumption to oceanic $p\mathrm{CO_2}$, we did two additional simulations where oceanic $p\mathrm{CO_2}$ was used in Eq. (1) instead of the atmospheric value. Since oceanic $p\mathrm{CO_2}$ is what the phytoplankton experience, this set of simulations should be more realistic in representing the impact of enhanced biological carbon consumption on oceanic CO_2 uptake from the atmosphere. For this set of simulations, we first re-integrated the model to steady state (4500 years of integration) using $p\mathrm{CO_2}$ of the surface ocean in Eq. (1) to compute the C:P ratio of the exported POM (CpO). We then continued the simulation for the 1800 to 2100 period with the rising atmospheric CO_2 (Fig. 1a) while varying the C:P ratio using the $p\mathrm{CO_2}$ of the surface ocean in Eq. (1) (pO).

3 Results

Using results from the R07 empirical formulation we first explore how changing the biological carbon consumption with increasing CO_2 levels alters ocean carbon uptake from the atmosphere over 1800 to 2100 period. With the historical atmospheric CO_2 measurements and the IS92a projection (Joos et al., 1996), increased atmospheric CO_2 leads to increased carbon export and, as expected, a subsequent increase in oceanic CO_2 uptake from the atmosphere (Fig. 1b and c). To explore the atmospheric CO_2 uptake efficiency, we define a term called the AE-ratio. The AE is the ratio between the change in oceanic carbon uptake from the atmosphere and the change in biological carbon export. It is equivalent to the atmospheric CO_2 uptake efficiency definition ($\mathrm{Eff_{depl}}$) used by Jin et al. (2008).

$$\mathrm{AE} = \frac{\Delta \mathrm{AtmCO_2}}{\Delta \mathrm{Export}} \tag{2}$$

where the change is calculated over the 1800 to 2100 period (Table 1). Because of finite air-sea CO_2 exchange time and the fact that not all the increased biologically exported carbon from the surface ocean is permanently removed from contact with the atmosphere, the AE-ratio is less than one as discussed in the introduction and demonstrated by previous ocean fertilization simulations (Sarmiento and Orr, 1991a; Dutkiewicz et al., 2006; Gnanadesikan and Marinov, 2008; Gnanadesikan et al., 2003; Marinov et al., 2008a; Matear and Elliott, 2004).

By 2100 in the pA simulation, enhanced biological carbon consumption increases biological carbon export by 97 Pg C while oceanic CO_2 uptake from the atmosphere increases by only 31 Pg C (Fig. 1d). Under this scenario the AE-ratio is 0.32, implying a 32% atmospheric CO_2 uptake efficiency when stimulating the biological pump through enhanced carbon consumption.

As expected by 2100, increased biological carbon export occurs across the entire ocean surface in varying degrees of magnitude, yet, there are large regions where the net air-sea flux of CO_2 declines (Fig. 2). The most prominent regions where we find a decrease in net carbon uptake from the atmosphere are in the Eastern Equatorial Pacific and Southern Ocean. The only foreseeable mechanism that could lead to CO_2 outgassing under enhanced biological carbon export would be the pooling of dissolved organic carbon (DIC) beneath the euphotic zone of these regions (Fig. 3), which would lead to an increase in the re-supply of DIC to the surface that must be higher than the associated increased in biological carbon export. We will explore this response in the discussion section.

We also explored the extent to which the uptake of anthropogenic CO_2 from the atmosphere and its subsequent transport in the oceans by the circulation may influence the atmospheric CO_2 uptake efficiency under enhanced carbon consumption. From the difference between the pA' simulation and the Control simulation for year 1879, virtually identical results were found in comparison to the case where we included rising CO_2 levels in the atmosphere (Fig. 4). Without rising CO_2 in the atmosphere the AE-ratio was 0.29 (29%), which was slightly less than the 0.32 (32%) calculated when we included the rising atmospheric CO_2 signal. Thus ocean uptake of anthropogenic carbon from the atmosphere has only a minor effect on the atmospheric CO_2 uptake efficiency of the enhanced biological pump.

In the oceans, biological carbon consumption that depends on CO_2 levels should be set by the pCO_2 of the surface ocean and not that of the atmosphere. To assess the impact of using pCO_2 of the surface ocean carbon, we re-ran the control (CpO) and perturbation (pO) simulations using pCO_2 of the surface oceans in equation 1 to set the C:P ratio of the exported carbon. After the spin-up phase, the oceans with a variable C:P ratio of POM (CpO) stored about 25 Pg C more than the control simulation with a fixed C:P ratio (Control). The greater uptake in the CpO simulation occurred because it had greater biological export production than the fixed C:P simulation (7.95 versus 7.9 Pg C). Export production was greater because the most productive regions of the ocean tend to be regions where the oceanic pCO_2 was greater than the atmospheric value of 280 ppm. Hence, with the variable C:P formulation, these regions exported more carbon from the upper ocean than the fixed C:P case.

Using the surface ocean pCO_2, the increased biological carbon consumption over the 1800 to 2100 period (pO–CpO) increased biological carbon export and oceanic carbon uptake from the atmosphere by 86 and 28 Pg C, respectively (Table 1 and Fig. 4). Both the increased biological export and oceanic carbon uptake is slightly less than the simulation that used atmospheric pCO_2 in Eq. (1), but the AE-ratio (0.32) was consistent with the simulations that used the pCO_2 atmosphere in the variable C:P ratio POM.

4 Discussion

4.1 Comparison with R07

R07 used their in-situ results to estimate how enhanced biological carbon consumption and export would alter oceanic carbon uptake from the atmosphere. For a present-day value of biological export production of 8 Pg C, R07 estimated by 2100 an increase in export of 100 Gt, which results in an increase in oceanic carbon uptake from the atmosphere of 76 Pg C. From their 1-D vertical box model, the AE-ratio is high (0.76). In comparison, our OGCM simulations produced a much smaller AE-ratio (~0.3). Our simulations, like others previously (Gnanadesikan et al., 2003; Jin et al., 2008; Marinov et al., 2008b), show that with the atmospheric CO_2 uptake efficiency of enhanced biological carbon export was spatially variable and intimately linked to how oceans re-distributed the exported carbon into the ocean. The lateral and vertical mixing of ocean circulation modified the distribution of carbon in the interior of the ocean, which over time resurfaces in ocean regions where the interior waters are ventilated. These ventilated areas alter the potential for the ocean to take up additional carbon under a scenario of enhanced biological carbon consumption.

4.2 Regional variations to the AE-ratio: the importance of mixing

The atmospheric CO_2 uptake efficiency of enhanced biological carbon consumption varies significantly throughout the oceans (Fig. 6). Although the globally averaged uptake efficiency (or AE ratio) is ~30%, the sub-tropical gyres in both hemispheres was found to have AE ratios of >100% (Fig. 6) – suggesting efficient biological CO_2 sequestration from the atmosphere and a spatial disconnect between where increased carbon export and increased carbon uptake occur. However, the high latitudes and the eastern equatorial Pacific are regions however, where AE-ratios are even less than 0 (Fig. 6), giving a net outgassing of CO_2 from the ocean under enhanced biological carbon consumption. Why is there such strong regional variability (0–100%) in our projections of the AE-ratio under enhanced biological carbon consumption?

At steady state, the biological pump sets up a weak gradient in DIC between the surface and the deeper ocean (Fig. 5). Additionally, subduction of Southern Ocean surface waters into ocean acts as a conduit for transporting the carbon and nutrients from the higher to the lower latitudes of both hemispheres (Sarmiento et al., 2004). Upwelling of older carbon-rich waters in the Southern Ocean and equatorial Pacific sets up a natural outgassing of CO_2 from the ocean as opposed to the natural net CO_2 uptake in the mid-latitudes. Under enhanced biological carbon export, the biological pump amplifies the vertical DIC gradient (Fig. 5). The enhanced biological pump means greater CO_2 uptake in the mid-latitudes, but more outgassing in regions like the Southern Ocean and eastern equatorial Pacific. Our simulations illustrate the importance of the physical re-supply of DIC on the regional response on the efficiency of enhanced biological carbon uptake under high atmospheric CO_2 conditions.

The amplified vertical gradient in DIC leads to a "short-circuiting" of the potential increased biological carbon export by the lateral/vertical entrainment that leads to an outgassing in Southern Ocean and eastern equatorial Pacific. In these regions, large-scale increases in biological carbon export can cause the $p\mathrm{CO}_2$ of the surface ocean to increase at a rate that is faster than the rate of atmospheric CO_2. Decadal $p\mathrm{CO}_2$ observations in some ocean regions show $p\mathrm{CO}_2$ to increase faster than the rate of atmospheric growth (Metzl 2009; Bates et al., 2002). Increases in carbon export and this short-circuiting mechanism provides one way producing such observations without invoking changes in circulation.

4.3 Using observational oxygen constraints to assess the model

The regions of CO_2 outgassing under enhanced carbon consumption are closely related to where remineralized carbon is exposed to the atmosphere. To illustrate these regions we use the biological flux of oxygen, which is computed as the oxygen flux with the thermal effect removed (using the heat flux). The biological oxygen flux into the ocean is computed as

$$F_{\mathrm{Bio}} = F_{\mathrm{total}} - \frac{\partial[O_2^{\mathrm{sat}}]}{\partial T}\frac{Q}{c_p} \tag{3}$$

where F_{total} is the total oxygen flux into the ocean ($\mathrm{mol\,O_2\,m^{-3}\,y^{-1}}$), $\partial[\mathrm{O}_2^{\mathrm{sat}}]/\partial T$ is temperature change in oxygen solubility ($\mathrm{mol\,O_2\,m^{-3}\,K^{-1}}$) (Weiss, 1970), Q is the simulated heat flux into the ocean ($\mathrm{W/m^2}$), c_p is the heat capacity of the seawater ($\mathrm{J\,m^{-3}\,K^{-1}}$). Water with high carbon remineralization content will be associated with very low oxygen concentrations and when this low oxygen water is ventilated it will generate an oxygen flux into the ocean. This reveals where remineralized organic matter is brought to the surface in the model.

Although the model is not perfect, the derived estimates of large F_{bio} into the Southern Ocean and high latitude Pacific and Atlantic Oceans (Fig. 7) are generally consistent with the limited observational estimates of this flux (Gruber et al., 2001); the comparison of which is summarized in Table 2. In the extra tropical southern hemisphere, the model simulations and the observational estimates show good agreement. Both show a large biological oxygen flux into the Southern Ocean with a large outgassing in the temperate region. The consistency provides some confidence that our simulated AE ratio are realistic in these regions. In the tropics, our simulations show a smaller biological outgassing of oxygen than the observationally derived estimate. This suggests our model is over-estimating the regional ventilation of carbon-rich and oxygen-poor water, which should lead to an under-estimate of the AE-ratio in the region. In the Northern hemisphere extra-tropical regions, we simulate less biological oxygen flux into the oceans than observationally derived estimates. The implication is that in these regions we may overestimate the AE-ratio.

Another way to assess remineralization in the model simulations is to compare Apparent Oxygen Utilization (AOU) with observations (Fig. 8). The simulated AOU field generally reproduces the observations but with the tendency to under-estimate AOU in the Southern Ocean. This underestimate of AOU should be associated with a reduced estimate of the F_{bio} and a reduced outgassing of carbon when elevated carbon of the enhanced biological carbon export simulation is exposed to the atmosphere. Hence, the model simulation may under-estimate this short-circuiting feedback on the atmospheric CO_2 uptake efficiency of enhanced biological carbon consumption in the Southern Ocean.

The rapid sinking of exported organic matter provides an efficient means of transporting carbon into the ocean, but the return of this water back to the surface occurs through a more complicated and varied process. Both the rate at which the remineralized water is ventilated along with its AOU concentration will set the rate at which the short-circuiting of the enhanced biological carbon export occurs. For this water to impact the estimated AE ratio, the remineralized water must be ventilated within only a few decades of receiving the increased biologically exported carbon. For tracer observations, we can estimate the time since a water was last ventilated, but it is more difficult to determine the time until the sub-surface water will be reventilated.

The short-circuiting of the enhanced biological carbon export shown in this study (Fig. 7 bottom) also has implications for sequestration of carbon by iron fertilization. That is, the potential to sequester carbon by iron fertilization relies on the ability to enhance the biological export carbon to increase oceanic carbon uptake from the atmosphere. Our simulations show that in regions where iron fertilization could be used to enhance the carbon export like the eastern Equatorial Pacific and Southern Ocean the AE-ratio is low. In particular, in regions like the Southern Ocean where the oceanic carbon uptake from the atmosphere was only 15% of the increased biological carbon export; a substantial portion of the biologically exported carbon is rapidly re-supplied to back the surface. The Southern Ocean is a region that is not macronutrient limited and the re-supply of remineralized C and P back to the surface does not further stimulate export production but it does enhance carbon outgassing.

4.4 Limitation of enhanced biological carbon uptake

The original focus of this paper was to explore whether 3-D circulation in the ocean modifies the potential of the oceans to take up more carbon from the atmosphere with enhanced biological carbon export. Although the OGCM is a simplification of the real ocean and there is some uncertainty associated with the 3-D circulation, the clear message to emerge is that enhanced biological carbon export is not as efficient as originally suggested by R07, which is more consistent with previous macro-nutrient and iron-fertilisation studies. However, two key biological processes not considered in this study may affect the ocean's response to increased biological export of carbon.

First, the atmospheric CO_2 uptake potential could be affected by changes in Dissolved Organic Carbon (DOC) production that may complement increased carbon export. Since the DOC produced would tend to accumulate near the surface it would tend to reduce sequestering efficiency of carbon with increased biological carbon export because some of it would be remineralized and the carbon returned to the atmosphere. Therefore, our simulations without this effect should have a greater AE ratio (higher atmospheric uptake efficiency) than simulations that include a DOM pool that increases with increasing biological carbon consumption.

Second, there is also potential for changes in the remineralization of the POM. For example, deeper remineralization of C relative to P under enhanced biological carbon export. Jin et al. (2008) showed the importance of the depth-dependency of biological production in spurring varying magnitudes in atmospheric CO_2 uptake efficiency from the biological pump. Similarly a deeper or shallower remineralization profile of organic carbon would change the vertical gradient in CO_2 in a way which could either amplify or depress the oceans CO_2 uptake potential from the atmosphere. Although we did not explore these particular processes in our study, the potential to alter the AE ratio (atmospheric uptake efficiency) should be explored. Unfortunately, at this stage there is limited information to guide how to parameterize the change in the remineralization of organic C and P under elevated biological carbon consumption. Furthermore, as shown by Oschlies et al. (2008) the enhanced carbon utilization of R07 may feedback on the remineralization of sinking POM by expanding the oxygen minimum zones enabling the oceans to sequester more carbon.

The R07 result showing CO_2 fertilization of phytoplankton in a high CO_2 world is a significant finding. However, like all mesocosm experiments, the application of a single species perturbation and extrapolating it to all phytoplankton species in the ocean is premature without future verification among different species. This will be important future research. Furthermore, we must be cautions when trying to apply such a result throughout the worlds ocean. As shown here, the application of the R07 finding with an ocean model shows extreme variability depending on the ocean basin. For example, the atmospheric CO_2 efficiency of the R07 findings are 100% in the sub-tropical gyres but decreasing to below 0% in the Southern Ocean and equatorial Pacific. This illustrates the importance of understanding the physical mixing feedbacks in applying the R07, or any biological fertilization scenario as it is these processes which will ultimately determine the degree to which biological fertilization can drawdown atmospheric CO_2 levels.

5 Conclusions

We explored the efficiency of increasing biological carbon consumption and export to increase the oceanic uptake of CO_2 from the atmosphere (defined here as the AE-ratio). Our OGCM simulations suggest an AE ratio of ≈0.3, which is much lower than the value determine by R07. Our results are also consistent with other model simulations that use macro-nutrient or iron fertiliation scenarios. For a scenario where the present-day global carbon export is 12 Pg C/y, a more realistic representation of ocean mixing lowers ocean CO_2 uptake from the atmosphere due to enhanced biological carbon consumption from 116 Pg C to 46 Pg C by 2100. The efficiency would be furthered altered if the empirical results of enhanced carbon consumption with higher CO_2 by R07 was not be applicable to all phytoplankton found in the ocean.

Our main finding here, is that the potential for enhanced biological carbon consumption to increase oceanic CO_2 uptake needs to account for the 3-D nature of ocean circulation. As expected, increased biological carbon export from the upper ocean enhances the DIC gradient in the ocean in our simulations. This enhanced DIC gradient coupled with vertical re-supply and deep water ventilation in regions like Southern Ocean and equatorial Pacific can rapidly return the enhance biological carbon back to the surface ocean – thereby diminishing the overall atmospheric CO_2 efficiency. In the Southern Ocean, this short-circuiting of biological carbon transport into the ocean away from contact with the atmosphere could help explain the slow 100 ppm drawdown in atmospheric CO_2 between the interglacial and glacial periods because stimulating the biological pump in the region is such an inefficient process.

References

Bates, N. R., Pequignet, A. C., Johnson, R. J., and Gruber, N.: A short-term sink for atmospheric CO_2 in Subtropical Mode Water of the North Atlantic Ocean, Nature, 420, 389–393, 2002.

Conkright, M. E., Locarnini, R. A., Garcia, H. E., O'Brien, T. D., Boyer, T. P., Stephens, C., and Antonov, J. I.: World ocean atlas 2001: Objective analyses, data statistics and figures. Technical report, edited by: Conkright, M. E., Locarnini, R. A., Garcia, H. E., O'Brien, T. D., Boyer, T. P., Stephensand, C., and Antonov, J. I. 2002: World OCEAN ATLAS 2001: Objective Analyses, Data Statisticsand Figures, CD-ROM Documentation. National Oceanographic Data Center, Silver Spring, MD, 17, 17 pp., 2002.

Dutkiewicz, S., Follows, M. J., Heimbach, P., and Marshall, J.: Controls on ocean productivity and air-sea carbon flux: An adjoint model sensitivity study, Geophys. Res. Lett., 33, L02603, doi:10.1029/2005GL024987, 2006

Gnanadesikan, A. and Marinov, I.: Export is not enough: nutrient cycling and carbon sequestration, Marine Ecology-Progress Series, 364, 289–294, 2008.

Gnanadesikan, A., Sarmiento, J. L., and Slater, R. D.: Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production, Global Biogeochem. Cy., 17(2), 1050 pp., 2003.

Gruber, N., Gloor, M., Fan, S. M., and Sarmiento, J. L.: Air-sea flux of oxygen estimated from bulk data: Implications for the marine and atmospheric oxygen cycles, Global Biogeochem. Cy., 15(4), 783–803, 2001.

Jin, X., Gruber, N., Frenzel, H., Doney, S. C., and McWilliams, J. C.: The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump, Biogeosciences, 5, 385–406, 2008,
http://www.biogeosciences.net/5/385/2008/.

Joos, F., Bruno, M., Fink, R., Siegenthaler, U., Stocker, T. F., and LeQuere, C.: An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus Series B-Chemical and Physical Meteorology, 48(3), 397–417, 1996..

Key, R. M., Kozyr, A., Sabine, C. L., Lee, K., Wanninkhof, R., Bullister, J. L., Feely, R. A., Millero, F. J., Mordy, C., and Peng, T. H.: A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). Global Biogeochemical Cycles, 18(4), GB4031, doi:10.1029/2004GB002247, 2004.

Kurz, K. D. and Maier-Reimer, E.: Iron fertilization of the austral ocean - the Hamburg model assessment, Global Biogeochem. Cy., 7, 229–244, 1993.

Marinov, I., Follows, M., Gnanadesikan, A., Sarmiento, J. L., and Slater, R. D.: How does ocean biology affect atmospheric $p\mathrm{CO}_2$? Theory and models, J. Geophys. Res.-Oceans, 113(C7), C07032, doi:10.1029/2007JC004598, 2008a.

Marinov, I., Gnanadesikan, A., Sarmiento, J. L., Toggweiler, J. R., Follows, M., and Mignone, B. K.: Impact of oceanic circulation on biological carbon storage in the ocean and atmospheric $p\mathrm{CO}_2$, Global Biogeochem. Cy., 22, GB3007, doi:10.1029/2007GB002958, 2008b.

Martin, J. H.: Glacial-Interglacial CO_2 change: The iron hypothesis, Paleocenogr., 5(1), 1–13, 1990.

Matear, R. J. and Elliott, B.: Enhancement of oceanic uptake of anthropogenic CO2 by macronutrient fertilization, J. Geophys. Res.-Oceans, 109(C4), C4001, doi:10.1029/2000JC000321, 2004.

Matear, R. J. and Hirst, A. C.: Long term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming, Global Biogeochem. Cy., 17(4), 1125, doi:10.1029/2002GB001997, 2003.

Matear, R. J. and Wong, C. S.: Potential to Increase the Oceanic CO_2 Uptake by Enhancing Marine Productivity in High Nutrient Low Chlorophyll Regions, in: Greenhouse Gas Control Technologies, edited by: Eliasson, B., Riemer, P., and Wokaun A., Pergamon, Interlaken Switzerland, 249–253, 1999.

Metzl, N.: Decadal increase of oceanic carbon dioxide in southern indian ocean surface waters (1991–2007), Deep-Sea Res., 56, 607–619, 2009.

Najjar, R. G., Jin, X., Louanchi, F., Aumont, O., Caldeira, K., Doney, S. C., Dutay, J. C., Follows, M., Gruber, N., Joos, F., Lindsay, K., Maier-Reimer, E., Matear, R. J., Matsumoto, K., Monfray, P., Mouchet, A., Orr, J. C., Plattner, G. K., Sarmiento, J. L., Schlitzer, R., Slater, R. D., Weirig, M. F., Yamanaka, Y., and Yool, A.: Impact of circulation on export production, dissolved organic matter, and dissolved oxygen in the ocean: Results from Phase II of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP-2). Global Biogeochem. Cy., 21(3), GB3007, doi:10.1029/2006GB002857, 2007.

Orr, J. and Sarmiento, J. L.: Potential of marine macroalgae as a sink for CO_2: constraints from a 3-D general circulation model of the global ocean, Water, Air and Soil pollution, 64, 405–421, 1992.

Oschlies, A., Schulz, K. G., Riebesell, U., and Schmittner, A.: Simulated 21st century's increase in oceanic suboxia by CO_2-enhanced biotic carbon export, Global Biogeochem. Cy., 22, GB4008, doi:10.1029/2007GB003147, 2008.

Riebesell, U., Schulz, K. G., Bellerby, R. G. J., Botros, M., Fritsche, P., Meyerhofer, M., Neill, C., Nondal, G., Oschlies, A., Wohlers, J., and Zollner, E.: Enhanced biological carbon consumption in a high CO_2 ocean, Nature, 450, 7169, doi:10.1038/nature06267, 2007.

Sarmiento, J. L., Gruber, N., Brzezinski, M. A., and Dunne, J. P. High-latitude controls of thermocline nutrients and low latitude biological productivity, Nature, 427(6969), 56–60, 2004.

Sarmiento, J. L. and Orr, J. C.: 3-Dimensional simulations of the impact of southern-ocean nutrient depletion on atmospheric CO_2 and ocean chemistry, Limnol. Oceanogr., 36(8), 1928–1950, 1991a.

Sarmiento, J. L. and Orr, J. C.: Three-dimensional simulation of the impact of the Southern Ocean nutrient depletion on atmospheric CO_2 and ocean chemistry, Limnol. Oceanogr., 36, 1928–1950, 1991b.

Volk, T. and Hoffert, M. I.: Ocean carbon pumps: Analysis of relative strengths and efficiencies in Ocean driven atmospheric CO_2 changes, in: The carbon cycle and atmospheric CO_2: natural variations archean to present, edited by: Sundquist, E. T. and Broecker, W. S., American Geophysical Union, 99–110, 1985.

Weiss, R. F.: The solubility of nitrogen, oxygen and argon in water and seawater, Deep Sea Res., 17, 721–735, 1970.

Wong, C. S., Whitney, F. A., Crawford, D., Iseki, K., Matear, R. J., Johnson, W. K., Page, J. S., and Timothy, D.: Seasonal and interannual variability in particle fluxes of carbon, nitrogen and silicon from time-series of sediment traps at Ocean Station P, 1982–1993: relationship to changes in subarctic primary productivity, Deep Sea Res. II, 46, 2735–2760, 1999.

Table 1. Model experiments used in this study.

Experiment	Description	Integrated change in biological carbon export through 50 m (Pg C)[b]	Integrated change in carbon uptake by the ocean (Pg C)[2]	Atmospheric CO_2 Uptake Efficiency (ratio between the change in biological carbon export and the oceanic uptake of CO_2 from the atmosphere)
CpA	Fixed C:P ratio of POC			
pA	Variable C:P ratio of POC as function of pCO_2 atmosphere[a]	97.3	30.9	0.32
pA'	As pAtm but with no uptake of anthropogenic carbon	97.3	28.3	0.29
CpO	Spin-up case of the ocean with variable C:P based on pCO_2 of the surface ocean[a]			
pO	Variable C:P ratio of POC as function of pCO_2 ocean[a]	85.5	27.6	0.32

[a] We consider two different parameterizations of a variable C:P ratio of exported POC. One uses atmospheric pCO_2 to determine the C:P ratio of POC, while the second uses the spatially and temporally varying oceanic pCO_2 of the corresponding surface ocean simulation. [b] The integrated change in export production of C and uptake are based on the difference between the experiment and the corresponding and control run except for pA' and pO where change is relative to the value in the year 1879 of the CpA and CpO, respectively.

Table 2. A comparison of the biological oxygen flux into the ocean.

	Gruber et al., 2001[a]	Model simulations
Region	Tmol/yr	Tmol/yr
Global	0	2
Northern North Pacific and Northern North Atlantic	39.7	19
Temperate North Pacific and Temperate North Atlantic	50.1	−24
Tropics (13° S–13° N)	−124.6	−22
Temperate Southern Hemisphere (13° S–36° S)	−50.5	−53
Southern Ocean (36° S–90° S)	85.3	82

[a] Estimated by Gruber et al 2001 (see their Table 3 “Balanced Constraint” column) with the values simulated by the control run of the model. See Fig. 3 of Gruber et al., 2001 for the definition of the ocean regions.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

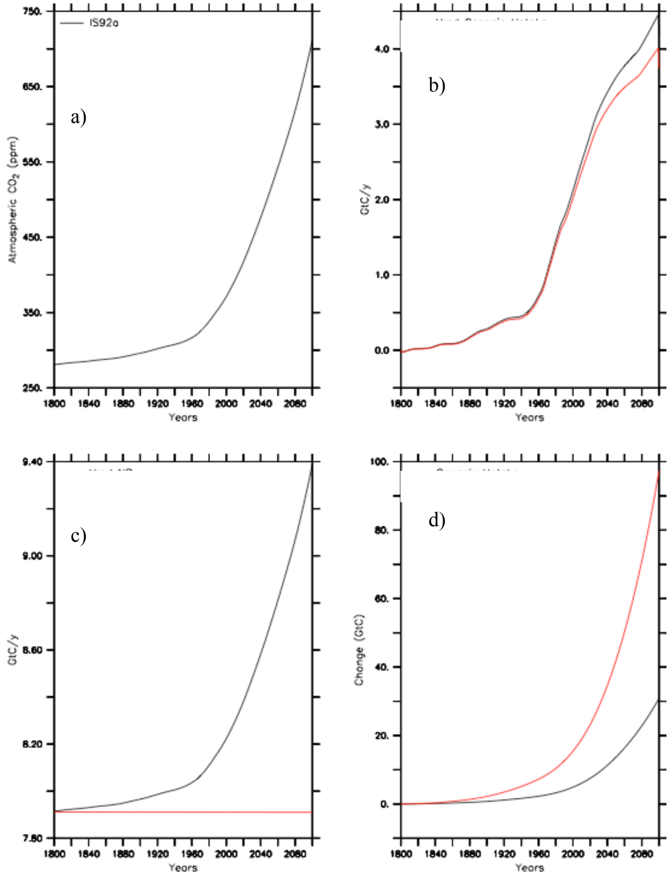
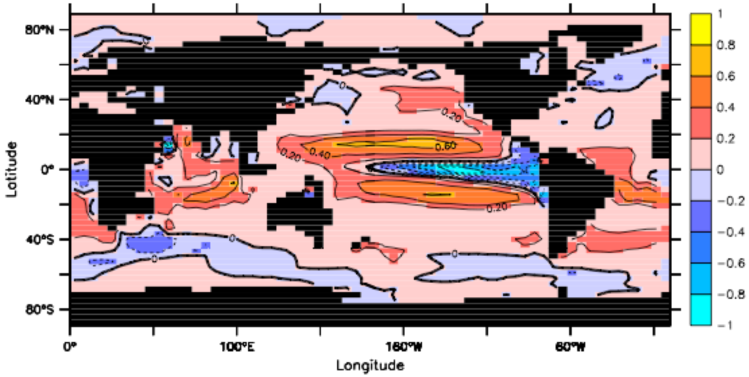


Fig. 1. **(a)** Atmospheric CO_2 levels (ppm) based on observed and Joos et al. (1996) box model projection with the IS92a emissions scenario. **(b)** Simulated Oceanic uptake of carbon (Pg C/y) with constant (CpA, red line) and variable C:P ratio of exported POM (pA, black line). **(c)** Simulated export of organic carbon (Pg C/y) from the upper 50m with constant (CpA, red line) and variable C:P ratio of POM (pA, black line). **(d)** Simulated change (pA–CpA) in oceanic uptake of carbon and the export of organic carbon between the variable C:P and constant C:P ratio for POM (Pg C).



Change in ACO$_2$ Flux: Year 2100

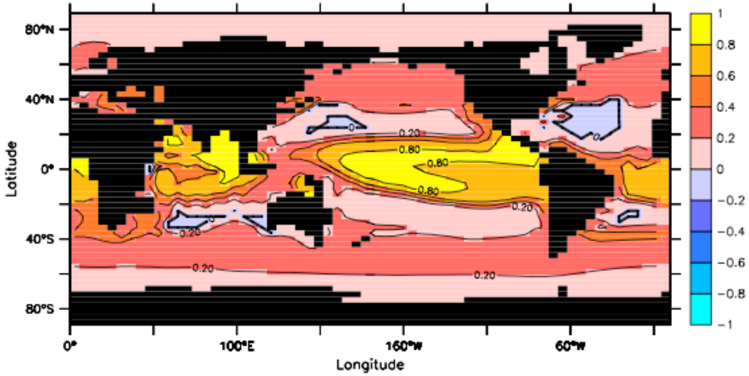
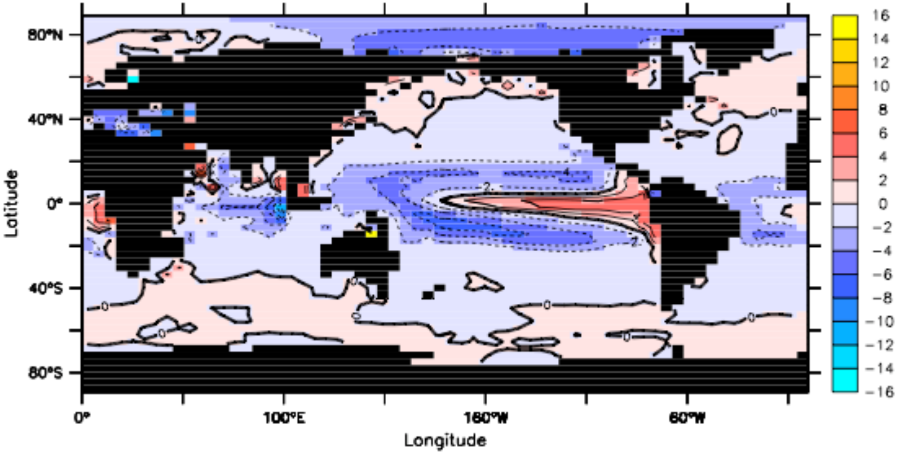


Fig. 2. The change between the variable C:P ratio of POM and constant C:P ratio (pA–CpA) for top) the air-sea flux of CO$_2$, and bottom) the EP of carbon at 50 m (both in mol C m^{-2} y^{-1} and in year 2100).



ΔACO$_2$: Year 2100 at base of MLD Max

Fig. 3. The change in Dissolved Inorganic Carbon between the variable and constant C:P ratio simulations (pA–CpA) at the base of the seasonal maximum mixed layer depth (in m mol m^{-3} and in year 2100).

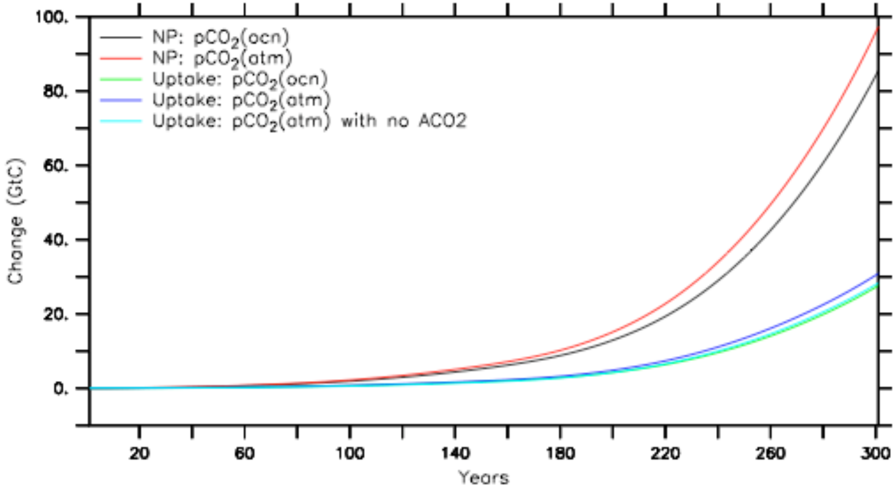


Fig. 4. Change in global export production of carbon and oceanic uptake of carbon between the variable C:P and constant C:P ratio for POM (Pg C). The black and green lines denote the difference between pO–CpO simulations, the red and blue lines denote the difference between pA–CpA simulations, and the cyan line denotes the difference between pA'–CpA.

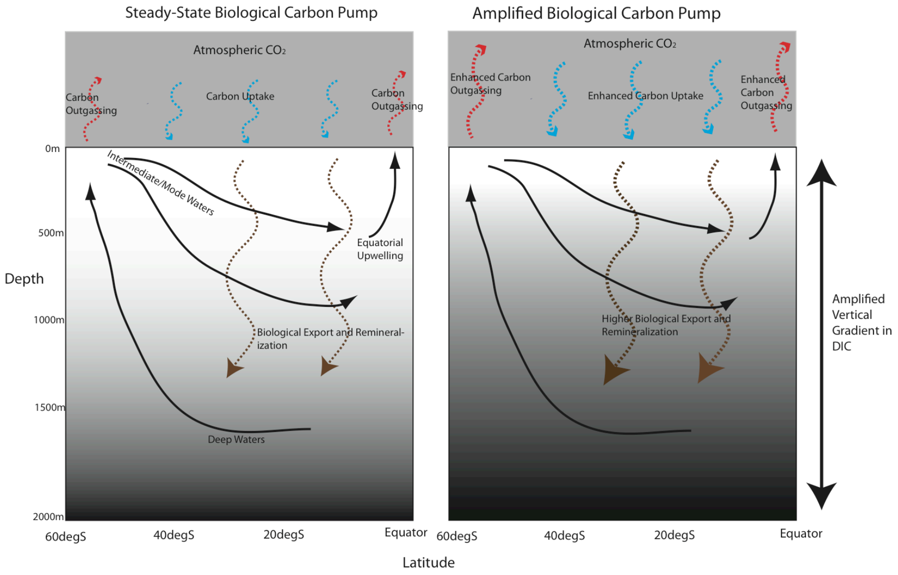


Fig. 5. Schematic of the biological and physical transport of carbon in the oceans.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

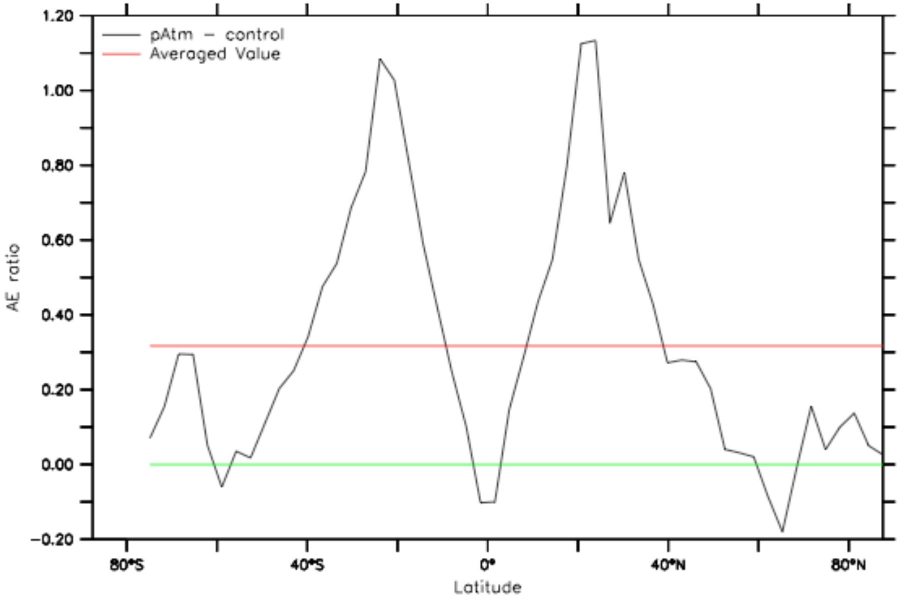


Fig. 6. Zonal averaged AE ratio (black line) and its global average (red line). The green line denotes an AE-ratio of zero.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

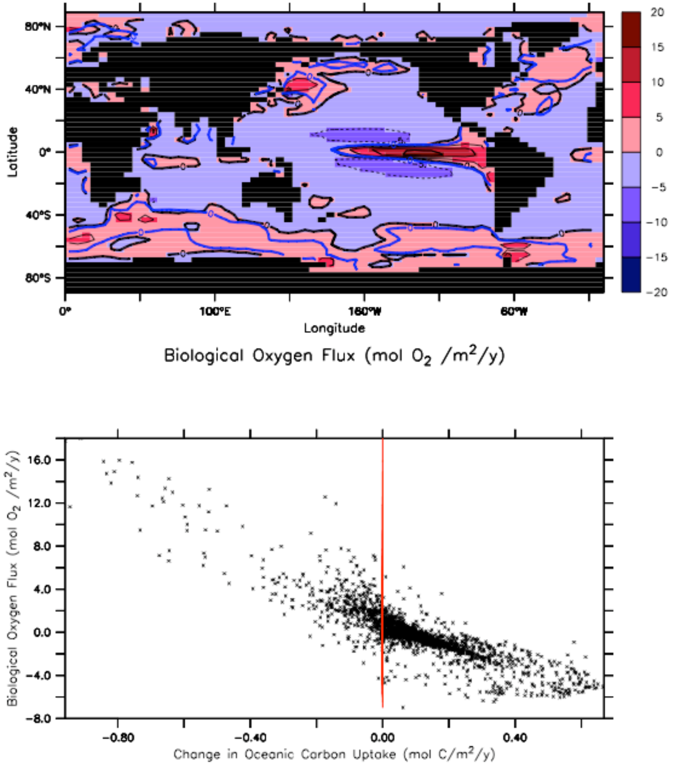
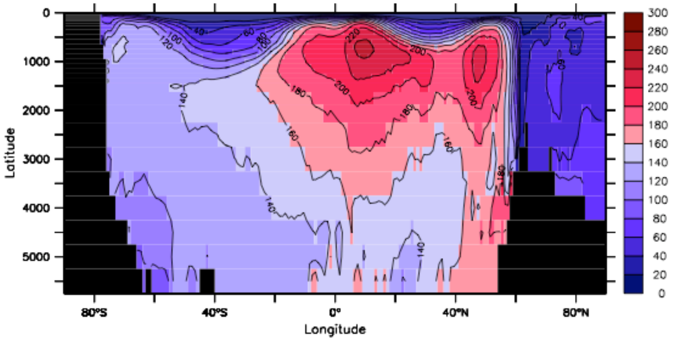
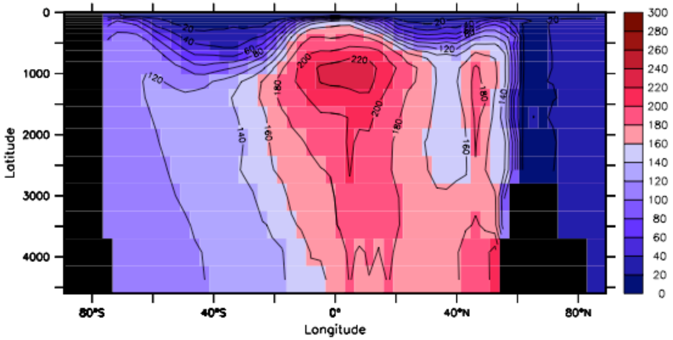


Fig. 7. Top: Biological oxygen flux (positive into the ocean) overlaid by blue contours line showing the region where the air to sea CO2 flux between the enhanced biological carbon export and the control run is negative (pA–CpA). Bottom: The change in oceanic carbon uptake versus the biological oxygen flux (Fbio) for each model grid point in the year 2100.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



Observed AOU: zonal−averaged



Simulated AOU: zonal−averaged

Fig. 8. Zonally-averaged AOU from the observations (Conkright et al., 2002) (top) and the model simulation (bottom).