Sensitivity of global ocean biogeochemical dynamics to ecosystem structure in a future climate

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[1] Terrestrial and oceanic ecosystem components of the Earth System models (ESMs) are key to predict the future behavior of the global carbon cycle. Ocean ecosystem models represent low complexity compared to terrestrial ecosystem models. In this study we use two ocean biogeochemical models based on the explicit representation of multiple planktonic functional types. We impose to the models the same future physical perturbation and compare the response of ecosystem dynamics, export production (EP) and ocean carbon uptake (OCU) to the same physical changes. Models comparison shows that: (1) EP changes directly translate into changes of OCU on decadal time scale, (2) the representation of ecosystem structure plays a pivotal role at linking OCU and EP, (3) OCU is highly sensitive to representation of ecosystem in the Equatorial Pacific and Southern Oceans. **Citation:** Manizza, M., E. T. Buitenhuis, and C. Le Quéré (2010), Sensitivity of global ocean biogeochemical dynamics to ecosystem structure in a future climate, *Geophys. Res. Lett.*, *37*, L13607, doi:10.1029/2010GL043360.

1. Introduction

[2] Anthropogenic emissions of fossil fuels are the main cause of the increase in atmospheric $[CO_2]$ started with the industrial revolution [*Barnola et al.*, 1995]. The increase in atmospheric $[CO_2]$ and the warming of the climate system influence the natural carbon cycle which could potentially amplify the initial change [*Friedlingstein et al.*, 2006]. The response of the carbon cycle to elevated $[CO_2]$ and climate change thus represents one of the major uncertainties in future climate projections [*Friedlingstein et al.*, 2006; *Le Quéré et al.*, 2007]. The future response of the climate system could be explored by using ESMs with the terrestrial and oceanic ecosystems that interact with climate via the carbon cycle.

[3] *Prentice et al.* [2001] showed that terrestrial ecosystem models, when projected into future climates [*Cramer et al.*, 2001], showed a wide spread in their projections of the land CO_2 sink. This feature can be mostly attributed to the fact that terrestrial ecosystem models are based on the ecosystem dynamics based on Plant Functional Types that have different physiological traits.

[4] Ocean ecosystem models evaluated in the analysis of *Prentice et al.* [2001] either completely lacked the explicit representation of ecosystem dynamics or implemented simple models based on a single type nutrient pool (N), phytoplankton (P), zooplankton (Z), and organic detritus (D) responsible for the export of carbon (so-called NPZD models) [*Franks*, 2002]. Ocean ecosystem models recently started to evolve from NPZD into Dynamic Green Ocean Models (DGOMs) that, following the example of terrestrial models, include several Plankton Functional Types (PFTs) and multiple nutrients limitation [*Aumont et al.*, 2003; *Moore et al.*, 2004; *Le Quéré et al.*, 2005; *Follows et al.*, 2007]. PFTs provide a link between ecosystem dynamics to biogeochemical cycles and climate.

[5] In this study, we compare the response of two DGOMs to climate change showing (1) how climate change might impact the pelagic ecosystem with consequences for EP and OCU and (2) how different ecosystem parameterizations trigger regional differences.

2. Methods

2.1. Ocean General Circulation Model

[6] We use ORCA-LIM, a global Ocean General Circulation Model (OGCM) including a Sea-Ice component [*Timmermann et al.*, 2005] to model the physical ocean that is based on OPA [*Madec et al.*, 1999] and LIM [*Fichefet and Morales-Maqueda*, 1999]. A more detailed description of ORCA-LIM coupled to biogeochemical modules is given by *Manizza et al.* [2008].

2.2. Dynamic Green Ocean Models

[7] We couple two different DGOMs to ORCA-LIM, PISCES-T and PlankTOM5. PISCES-T is a modified version of the PISCES model [*Aumont et al.*, 2003; *Bopp et al.*, 2003] representing the ecosystem dynamics based on two phytoplankton types (mixed-phytoplankton and silicifiers) and two zooplankton (micro and meso) types. PISCES-T also implements a new parameterization of mesozooplankton metabolism [*Buitenhuis et al.*, 2006].

[8] PlankTOM5 builds from PISCES-T, it has one additional phytoplankton PFT (calcifiers) [*Manizza*, 2006; *Vogt et al.*, 2010] and implements the ballasting effect of biogenic calcite and opal on large sinking particles. Both DGOMs implement phytoplankton growth co-limited by light, phosphorus, iron and silicate for silicifiers, and they are both coupled to ORCA-LIM *on-line*. All the simulations were initialized using observed fields of PO_4^{3-}, SiO_3^- and O_2, DIC, and Alkalinity of present climate.

2.3. Model Forcing Set-up

[9] For the control simulations, ORCA-LIM is forced by the atmospheric variables obtained from the NCEP/NCAR re-analyzed forcing [*Kalnay et al.*, 1996] from 1948 to 2004 for the (ψ_{NCEP}). For the climate change simulations, we first

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PISCES-T

PlankTOM5

△ Silicifiers

△ Mixed-Phytoplakton
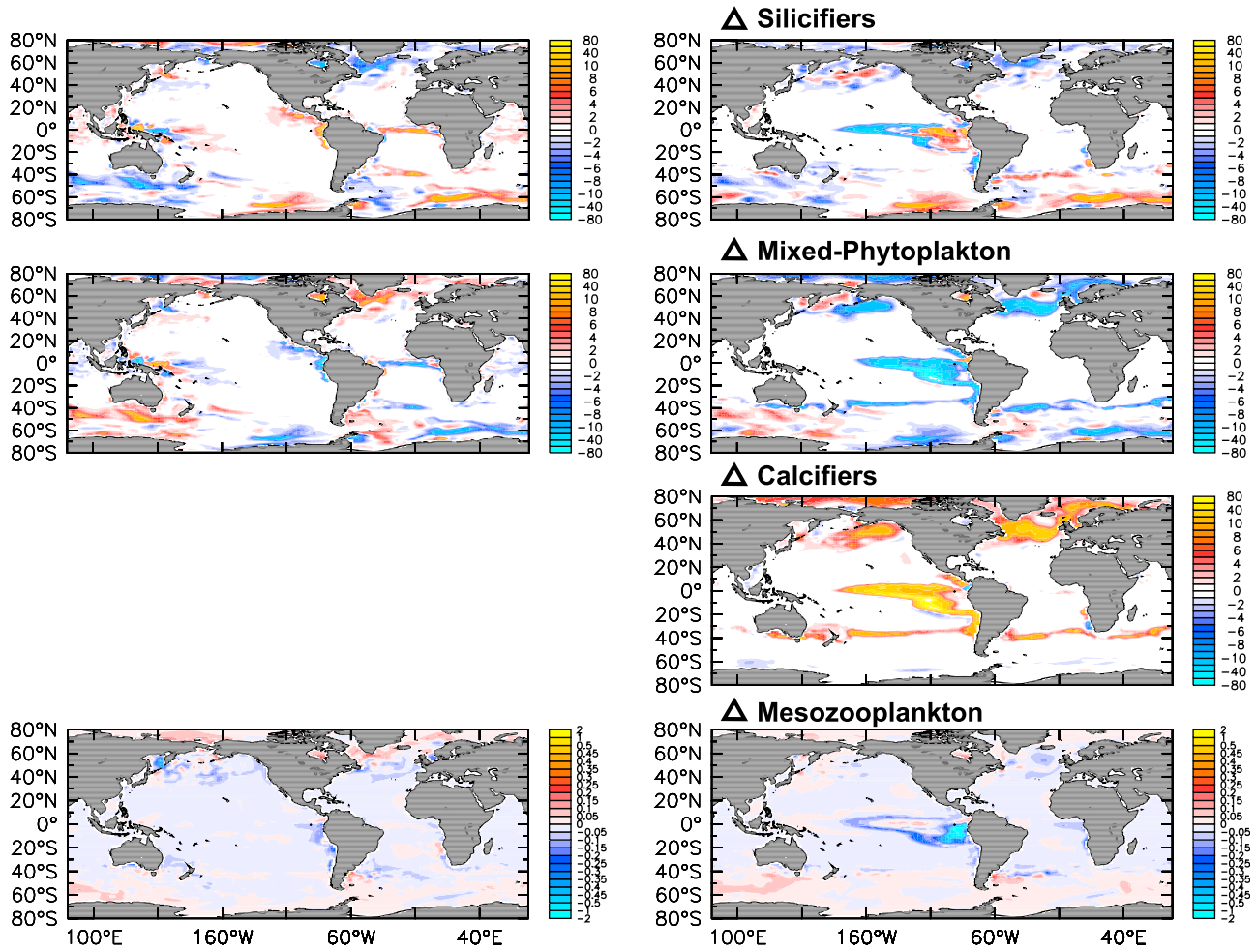
△ Calcifiers

△ Mesozooplankton

Figure 1. Change in RCC at ocean surface of (top) silicifiers, (top middle) mixed-phytoplankton, (bottom middle) calcifiers and (bottom) change in mesozooplankton biomass for (left) PISCES-T and (right) PlankTOM5 as average of the last five years. Units are % for RCC and μmolC L^{-1} for mesozooplankton.

calculated a climatic anomaly for each atmospheric variable contained in the re-analysis with a 30-year running mean ($\Psi_{IPSL_{30}}$). The climatic anomalies were obtained from the simulations carried out with the IPSL Earth System Model [*Friedlingstein et al.*, 2001] following the IPCC A2 scenario [*Nakicenovic and Swart*, 2000] for the period 2005–2061. We then obtained climate change forcing (ψ_{CC}) for the projected period 2005–2061 adding the smoothed anomalies to the unsmoothed NCEP/NCAR re-analyzed forcing:

$$\psi_{CC} = \psi_{NCEP} + \Psi_{IPSL_{30}} \qquad (1)$$

We retain the interannual variability of ψ_{NCEP}, and prevent double counting variability by using the smoothed $\Psi_{IPSL_{30}}$ as done by *Manizza* [2006] and *Vallina et al.* [2007]. For both DGOMs, we carry out two simulations. In the control simulation we use the atmospheric forcing of 1948–2004 period (but with projected 2005–2061 atmospheric [CO$_2$]) whereas in the climate change simulation we apply the

atmospheric forcing of the 2005–2061 period (both for CO$_2$ and climate).

3. Results and Discussion

3.1. Ocean Physical Response to Climate Change

[10] Anthropogenic climate change impacts the main physical properties of the upper ocean. The sea surface temperature increases (by up to 2°C), mixed layer mostly shoals (by up to 10 meter) between 60°N and 60°S and the extension of sea-ice reduces (by up to 15%) in the polar oceans (see auxiliary material).[1] These changes are also comparable to previous studies carried out with coupled climate models, though with some differences in spatial distribution and magnitude of the responses [*Sarmiento et al.*, 1998; *Friedlingstein et al.*, 2001; *Flato*, 2004; *Steinacher et al.*, 2010]. All these physical changes influence the metabolism of planktonic organisms through the change

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043360.
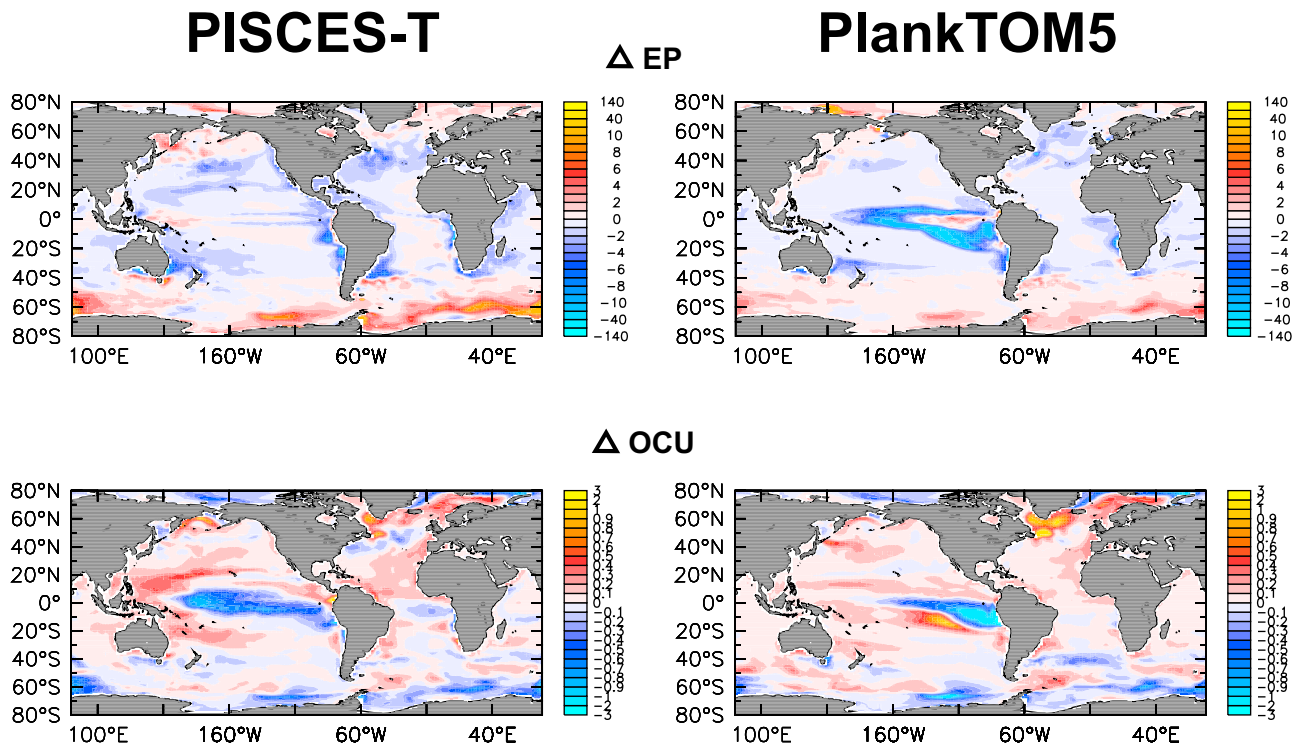
PISCES-T

△ EP

PlankTOM5

△ OCU

Figure 2. Change in (top) EP and (bottom) OCU for (left) PISCES-T and (right) PlankTOM5 between climate change and control run as average of the last five years. Negative differences in sea-to-air CO_2 flux indicate an increase in OCU caused by climate change.

in water temperature and the availability of both light and nutrients.

3.2. Ecosystem Response and Biogeochemical Dynamics

[11] In these DGOMs, climate change causes global reductions in primary production, EP, and OCU comparable to previous studies by *Friedlingstein et al.* [2001, 2006] and *Steinacher et al.* [2010] (see also auxiliary material). For each DGOM, we calculate the relative contribution of PFTs to total carbon content (RCC) for each PFT at the surface of the ocean as follows:

$$RCC = \frac{C_{PFT}}{C_{TOTAL}} \cdot 100 \qquad (2)$$

and we show the difference between the climate change and the control run. The differences in the two DGOMs (Figure 1) show similar general spatial patterns but evident ecosystem re-arrangements occur in two specific regions: (1) the Equatorial Pacific Ocean and (2) the Southern Ocean.

[12] In the Equatorial Pacific Ocean, PISCES-T does not show any major shift in RCC of the two PFTs (Figure 1, left). However, in PlankTOM5 the modified ecological niche is taken over by the calcifiers that have a better affinity for more stratified waters and almost totally outcompete the other two PFTs. The change in EP (Figure 2, top) is directly influenced by the response of ecosystem dynamics to physical change. In PlankTOM5 the EP reduces by up to 30 gC m^{-2} a^{-1} whereas in PISCES-T the change is not notable. This difference is due to the decrease in mesozooplankton biomass in PlankTOM5 (Figure 1, bottom) due to the decrease of silicifiers, their preferred food source.

Mesozooplankton fecal pellets production is one of the major routes for producing fast sinking particles. There is only a limited effect from increased calcifiers on increased sinking speed due to the ballasting by biogenic calcite because over much of the low latitudes the sinking speed is already at its maximum of 150 meter day^{-1}. In both DGOMs the CO_2 outgassing of the Equatorial Pacific Ocean decreases in a future climate (by 11.3 and 54 TgC a^{-1}, for PISCES-T and PlankTOM5, respectively), due to the reduced upwelling of carbon-rich waters (Figure 2, bottom). However, the reduction in outgassing is less in PlankTOM5 (29.5 TgC a^{-1}) than in PISCES-T (54 TgC a^{-1}) because of the greater reduction in EP driven by the ecosystem response.

[13] In the Southern Ocean (south of 40°S) where sea-ice cover evidently reduced silicifiers increase their RCC by up to 60% in both DGOMs (Figure 1, top), although in PISCES-T they compete for resources with only one competitor (mixed-phytoplankton) whereas in PlankTOM5 they compete with two PFTs. The increase in RCC silicifiers is mainly due to the increase in vertical nutrient supply caused by the wind-driven mixing in more ice-free zones. However, the increase in diatoms RCC is partially larger in PlankTOM5 than in PISCES-T and this feature directly reflects on the increase in EP (91.7 TgC a^{-1} in PISCES-T and 85.7 TgC a^{-1} in PlankTOM5) (Figure 2, top). Again, the different response in EP (91.7 and 85.7 TgC a^{-1} for PISCES-T and PlankTOM5, respectively) directly translates in a different enhancement of OCU that is larger in PISCES-T (43.6 TgC a^{-1}) than in PlankTOM5 (20 TgC a^{-1}) (Figure 2, bottom).

[14] It is worth to note that the reduction in OCU is different in the magnitude for the two DGOMs (Figure 3, top
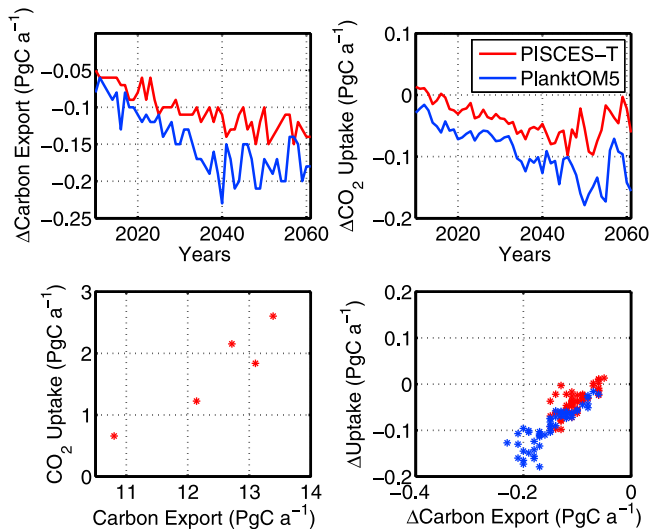
Figure 3. (Time-varying difference in annually averaged (top left) EP and (top right) OCU driven by climate change for both (red line) PISCES-T and (blue line) PlankTOM5. Relationship (bottom left) between EP and OCU calculated by PISCES-T by modifying the degradation rate of particulate organic carbon. Relationship (bottom right) between changes in both EP and OCU induced by climate change for (red) PISCES-T and (blue) PlankTOM5. Values of climate simulations shown here are selected from 2010 to 2061 to avoid the 2005–2009 spin-up period whose data are not used the analysis shown here.

right) although the climate-driven trend is similar. In fact, in PISCES-T the reduction in OCU induced by climate change is always smaller than 0.1 PgC a^{-1} whereas in PlankTOM5 this difference is up to 0.18 PgC a^{-1} although the applied physical forcing is identical. This trend in OCU mostly reflects the same as shown by EP (Figure 3, top left) in both models highlighting the importance of the marine ecosystem representation for the OCU in a future climate.

[15] In both models a reduction in EP would mostly translate into a reduction in OCU at comparable timescales (Figure 3, bottom right). In PISCES-T, 79 ± 9% of the change in EP is reflected in a change in the sea-to-air flux, while in PlankTOM5 the slope was very similar at 85 ± 6%. Presumably, the other ~20% is dissipated due to change in concentration gradient of dissolved inorganic carbon between the surface and the deep ocean. In these simulations, the OCU response driven by the biological EP is the sum of several responses, including changes in ocean physics and chemistry. To isolate the sensitivity of the OCU to changes in biogeochemical cycling, we additionally carried out five sensitivity simulations of 10 years each (with PISCES-T only) in which we varied EP modifying the degradation rate of particulate organic matter (Figure 3, bottom left). The slope was again very similar to 70 ± 15%. These results confirmed the direct OCU response to EP changes. Since the sensitivity simulations were all performed in the same physical setting and the applied climate change the same for two DGOMs, this response is shown to be mostly independent of changes in ocean circulation, and to have the same slope for different drivers of the biological changes.

These simulations show that these results can be comparable to the potential response of the marine ecosystem to climate change.

[16] The strong link between EP and OCU in our results is also confirmed by other studies where EP was modified either by changing either the aeolian dust flux [*Moore et al.*, 2006] or by enhancing the nutrients supply in the coastal regions [*Giraud et al.*, 2008].

4. Conclusions

[17] In this study we have shown that a more complete representation of the ecological complexity in DGOMs can lead to different responses of both PFTs distributions and EP to climate change, with direct consequences for OCU at regional scale. A future warmer climate could produce an expansion of the permanently stratified ocean regions [*Sarmiento et al.*, 2004] favoring diazotrophs [*Boyd and Doney*, 2002] that are well adapted to such environmental conditions and that are not represented in the models used in this study. Adding more PFTs to these two models might create a further re-arrangement in the ecosystem structure while responding to climate change with potential consequences for EP and OCU at regional scales.

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