Bio-Optical Impact of Phytoplankton on Ocean Physics and Carbon Cycle

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Introduction

The presence of phytoplankton modifies the penetration of solar radiation and affects the physical properties of the upper ocean [7,8,10].
Direct changes in the **physical structure** of the upper ocean (temperature, stratification, circulation and sea-ice cover) and **indirect changes in the pelagic ecosystem,** can modify both of the physical and the biological ocean carbon pump. We model this mechanism and quantify the preliminary results of the impact on Ocean Carbon Cycle using a global Ocean General Circulation Model coupled to an ocean biogeochemistry model (See description in the Modelling section).

Impact on Ocean Carbon Cycle

I) PRIMARY PRODUCTION (+ 0.6 PgC yr^{-1}): PP increases in the sub-tropical gyres because of the increased lateral supply of nutrients from tropics to sub-tropics caused by the enhanced equatorial upwelling.

II) EXPORT PRODUTION (-0.3 PgC yr^{-1}): Higher stratification and the consequent higher rate of remineralization of organic matter in the upper ocean are thought to affect the organic carbon exported toward the ocean interior.

III) AIR-SEA CO2 FLUX (-0.1 PgC yr^{-1}): Warmer Sea Surface Temperature, reduced vertical mixing at mid and high latitudes, increased equatorial upwelling, and enhanced summer sea-ice melting act together and reduce the ocean CO_2 absorption.

Modelling

The **Model** used for this study is composed by 3 components:
1) OPA 8.1: A fully prognostic ocean general circulation model [5] with global variable mesh (2 ° longitude by 0.5 ° - 1.5 ° latitude from equator to poles) [4], Gent and McWilliams parameterization for implicit eddy-mixing [2] and 1.5 Turbulent Kinetic Energy model for vertical mixing [3].
2) DYNAMIC GREEN OCEAN MODEL: An ocean biogeochemistry model with 3 phytoplankton types (diatoms, coccolithophores and nanophytoplankton), 2 zooplankton groups (meso and micro) , full ocean carbon cycle and co-limitation by light, Fe, Si and PO4 based on the PISCES model [1].
3) LIM: A sea-ice model with explicit thermodynamics and prognostically computed sea-ice cover [3].
We run the model, using NCEP forcing, for the period 1990-2000 analyzing the model diagnostics of the last year. We used this model with two different parameterization for light penetration:

I) *Dead Ocean* simulation : Optical model with physical properties of pure seawater only [9], as follows:

$$I_{(z)} = I_o * [R * e^{(-z/\xi_1)} + (1-R) * e^{(-z/\xi_2)}] \quad (1)$$

Where R = 0.58, ξ_1= 0.35 m, ξ_2 =23 m, corresponding to **Type I** waters (open ocean waters).
I_o is the surface irradiance and z is depth.
II) *Green Ocean* simulation : We use a bio-optical model for explicit representation of visible light attenuation by algal biomass as used in the previous studies [7,8,10], as follows:

$$I_{(z)} = I_0 * [R*(e^{-z/\xi_1}) + I_{VIS\ (z-1)} *(e^{-(kr*\Delta z)}/2 + e^{-(kg*\Delta z)}/2)] \quad (2)$$

The visible light is split in two averaged bands, red and blue/green and k_r and k_g are the respective light attenuation coefficients. We include the *self shading* effect for the visible light.
The light attenuation coefficient k is computed as function of the chlorophyll concentration ([Chl]) which is the sum of the [Chl] of the three phytoplankton species of DGOM:

$$K_{(\lambda)} = kw_{(\lambda)} + \chi_{(\lambda)} * [Chl_{tot}]^{l_{(\lambda)}} \quad (3)$$

$K_{(\lambda)}$, $kw_{(\lambda)}$, $\chi_{(\lambda)}$, $l_{(\lambda)}$ are respectively, the light extinction, the pure seawater absorption, pigment absorption and exponential coefficient for a single wavelength (λ).

Results

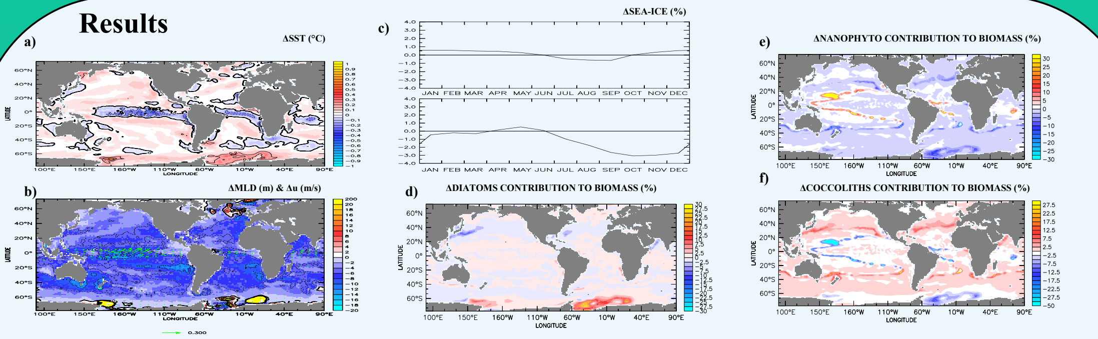

Figure 1 : Annual average of difference between ***Green Ocean*** and ***Dead Ocean*** in (a) Sea Surface Temperature (°C) , (b) Mixed Layer Depth (m) & surface velocity (m/s), (d) Surface relative diatoms biomass (%) , (e) Surface nanophytoplankton relative biomass (%), (f) Surface coccolithophores relative biomass (%) and (c) zonally and meridionally (55 °- 90°) averaged difference of sea-ice cover (%) in the north (top) and southern (bottom) hemisphere.

Impact on Ocean Physics

The inclusion of the biophysical coupling can modify the Sea Surface Temperature, Mixed Layer Depth (MLD), sea-ice cover and , producing feedbacks to pelagic ecosystem which responds to physical modifications:

- **Warming** of SST in both hemispheres (Fig 1a) at mid-latitudes (by + 0.05 °C) and high latitude (by + 0.6 °C). Maximum warming reaches 1.4 °C during *spring blooms* at high latitudes (data not shown here). These data are in agreement with previous global studies [10] which used satellite-derived chlorophyll concentration though.
- **Cooling** of SST is produced in the tropical regions. The cooling is an indirect effect due to the change of the thermal structure, around the equatorial areas (especially in the Pacific), which produces a modification in the local geostrophic circulation as shown by (Figure 1b). The cooling (ca -0.3 °C) is a result of an anomalous upwelling and divergence as shown by the vector plots as also already confirmed by the previous modelling [8] .
- **Mixed Layer Depth** is affected not only in the equatorial area but up to 60° of latitude in both hemispheres (Figure 1b). The shallower MLD (ca –6 m) observed almost globally, as annual average, is related to the greater absorption of light in the upper ocean by phytoplankton and its trapping effect on heat closer to the surface.
- **Melting** of sea-ice is enhanced by the biologically induced SST warming which reduces sea-ice cover during boreal (-1 %) and austral (-3.0 %) summer in the respective hemispheres.

Impact on Pelagic Ecosystem

- **Pelagic Ecosystem** responds, as feedback, to the modifications of the physical properties of the upper ocean. The general increase in stratification, produces a consequent decrease in nutrient supply and increase in light availability, favouring coccolithophores (+2.5 -12.5 %) in spite of nanophytoplankton (- 5-10 %), especially at high latitudes. Diatoms increase their contribution to total biomass in the Southern Ocean (up to +30 %). This feature can be explained by two factors. First, the enhanced melting of sea-ice in summer produces more ice free zones which favours winter convection. The augmented vertical mixing favours the replenishment of iron in the mixed layer for the next growing season. Second, the biologically-induced increased stratification reduces also the light limitation.

Modifications to the both physical and biological carbon pump due to **DIRECT** and **INIDIRECT** effects (triggered by feedbacks) have a profound effect on the Ocean Carbon Cycle (see Section).

These results push us to investigate the other biogeochemical implications which can alter the global ocean carbon cycle via modification of the physical properties of the ocean because of phytoplankton presence. In order to do that we will couple the model used here to an Atmospheric General Circulation Model to investigate how phytoplankton can modify the ocean-atmosphere interaction and Earth's climate.

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