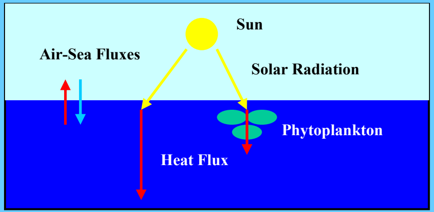

Bio-Optical Impact of Phytoplankton on Ocean Physics and Air-Sea Fluxes

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Introduction

The presence of phytoplankton modifies the penetration of solar radiation through the water column (see panel above) and affects the physical properties of the upper ocean [7,8,9], triggering feedbacks on biogeochemical processes.

Air-sea CO_2 and O_2 fluxes are modified by both direct changes in the physical structure of the upper ocean (temperature, stratification, and sea-ice) and indirect changes in the pelagic ecosystem (primary production and biogenic calcification). We model this mechanism and quantify the impact by using a global Ocean Biogeochemical General Circulation Model.

Highlights:

This study reveals that phytoplankton, the main driver of the biological pump, can also impact the solubility pump in the ocean. This forces us to **revisit the concept of solubility versus biological pump**, considering them **strictly linked together** in a new way and **mutually interacting by feedbacks** shown here.

Modelling

The **Model** used for this study is composed by 3 components [7]:

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 [4]. OPA has 10 m resolution in top 100 m meter.

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 and oxygen cycle and co-limitation by light, Fe, Si and PO_4 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 the daily NCEP forcing, for the period 1990-2000 analyzing the model diagnostics of the last year. We used this model with 3 different parameterizations for light penetration:

I) *Dead Ocean* (*DO*) simulation : Optical model representing only physical properties [10], 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$_{TOT}$* (*GO$_{TOT}$*) simulation : We use a bio-optical model for explicit representation of visible light attenuation by total algal biomass as used in the previous studies [7,9,11] shown in [8], 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 ($1/\xi$) is computed as function of total chlorophyll concentration ([Chl]) that is the sum of the [Chl] of the three phytoplankton species of DGOM:

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

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

III) *Green Ocean$_{PFT}$* (*GO$_{PFT}$*) simulation: In this simulation we implement in the equation (2) the new formulation of K computed by using for phytoplankton type (j) represented in DGOM, both the corresponding specific pigment absorption coefficient $(a)_j$ and their relative biomass $[Chl]_j$:

$$K_{(\lambda)} = kw_{(\lambda)} + \sum_j a_{(\lambda)j} * [Chl]_j \quad (4)$$

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Results

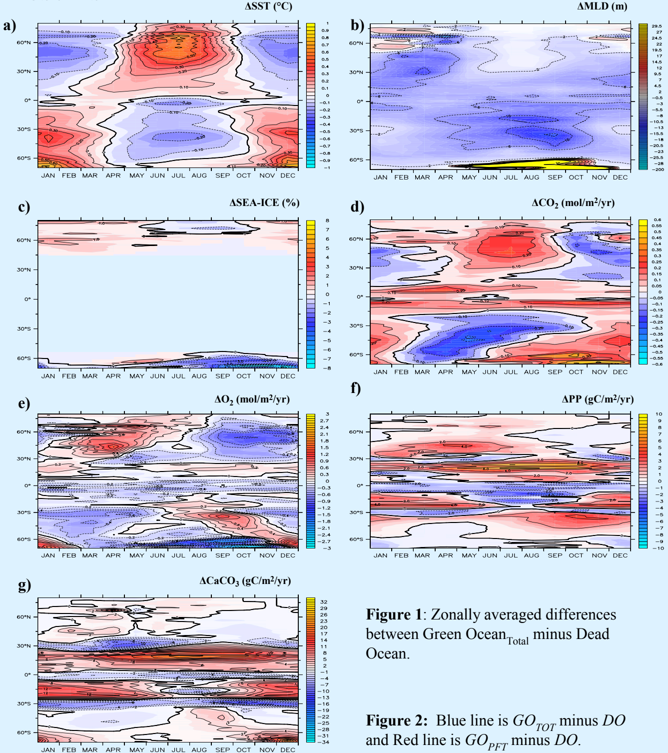
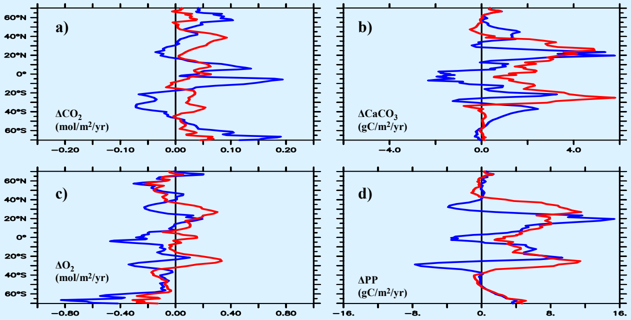


Figure 1: Zonally averaged differences between Green Ocean$_{Total}$ minus Dead Ocean.

Figure 2: Blue line is *GO$_{TOT}$* minus *DO* and Red line is *GO$_{PFT}$* minus *DO*. Data are zonally and annually averaged.



Impact on Upper Ocean Physics

- **Sea Surface Temperature (SST) seasonal cycle is amplified by up to ~ 1.2 °C**, (Fig.1a) with spring/summer warming at mid/high latitudes, following the evolution of the bloom polewards. The relative winter SST cooling is due to heat trapping caused by phytoplankton presence and by subsequent winter convective mixing of cooler subsurface layers.
- **Mixed Layer Depth shoals by up to -10 m** (Fig. 1b) following the polewards migration of spring bloom. This is due to the heat trapping by phytoplankton by closer to the surface. In the polar regions the ice reduction promotes mixing and a deepening of the following winter mixed layer.
- **Sea-Ice is reduced in boreal (-1 %) and austral (-4 %) summer** (Fig.1c) because of the relative SST warming. In winter relative SST cooling induces relative sea-ice accretion by ~ 2 % but with greater effect in the Northern Hemisphere.

Impact on Pelagic Ecosystem

- **Primary production increases at mid and high latitudes by up to ~20 gC/m²/yr and ~ 2 gC/m²/yr** (Fig. 1f) respectively. The increase in stratification reduces light limitation at high latitudes and decreases nutrient supply at mid-latitudes enhancing coccolithophores productivity which is favoured in both cases.
- **Biogenic Calcification, carried out by coccolithophores, increases at mid and high latitudes by up to ~ 10 gC/m²/yr and ~4 gC/m²/yr** , respectively, and follows the same patterns observed in changes in primary production (Fig.1g). Decrease in light limitation at high latitudes and decrease in nutrient supply in the subtropical gyres favours coccolithophores calcification activity.

Impact on CO_2 and O_2 Air-Sea Fluxes

Air-Sea Fluxes are impacted both by **direct physical effects and** by **feedbacks on pelagic ecosystem**.

- **CO_2 and O_2 flux seasonal cycles are amplified by 0.6 and 1.2 mol/m²/yr, respectively at high latitudes** of both hemispheres (Fig. 1d & 1e). The amplification is mainly driven by the SST cycle amplification.
- **Relative CO_2 outgassing and O_2 ingassing at mid-latitudes, both by up to 0.2 mol/m²/yr**, are caused by a relative increase in both biogenic calcification and primary production respectively, and both due coccolithophores relative increase.
- **In the Southern Ocean (south of 60° S) CO_2 shows relative outgassing (by up to 3.0 mol/m²/yr) and O_2 relative ingassing (by up to 0.6 mol/m²/yr)** because the reduction of sea-ice strongly enhances vertical mixing which disrupts pre-set vertical gradient and induces disequilibration and consequent fluxes.

Air-Sea fluxes sensitivity to bio-optical parameterizations

By implementing the **ecosystem composition as further factor modulating light penetration** (equation 4), it shows that air-sea fluxes seem quite sensitive to the bio-optical model implemented in the two *Green Ocean* cases. Preliminary results presented here (Fig. 2) shows that in the case of *GO$_{PFT}$* the feedbacks with pelagic ecosystem are more important in driving air-sea fluxes than in *GO$_{TOT}$* . In fact, in the subtropical gyres of both hemispheres the increase both in calcification (Fig. 2b) and in primary production (Fig. 2d) drive a greater (when compared to the case between *GO$_{TOT}$* and *DO*) relative outgassing of CO_2 (Fig. 2a) and O_2 (Fig. 2c), by up to 0.1 and 0.4 mol/m²/yr, respectively.

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