Effect of including accurate turbulent layers on phytoplankton vertical distribution and export through a 1D model for mid-latitude, open ocean settings

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Physical model (GOTM):

-Reference conditions: heat and momentum fluxes from station PAPA (1961-1986) (50ºN, 145ºE)

-Future conditions: increasing wind intensity (30%) and present atmospheric temperature (6.5%).

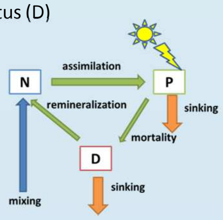
Biogeochemical Model:

Nutrients (N)-Phytoplankton (P)-Detritus (D)

$$\frac{\partial N}{\partial t} = -(Light_f * Nutrient_f * g_{max}) * P + r * D$$

$$\frac{\partial P}{\partial t} = (Light_f * Nutrient_f * g_{max} - mort) * P$$

$$\frac{\partial D}{\partial t} = +mort * P - r * D$$



Coupled model:

$$\frac{\partial C}{\partial t} = reaction - \frac{\partial}{\partial z}(w_p * C) - \frac{\partial}{\partial z}\left(-K_v \frac{\partial C}{\partial z}\right)$$

- Stratification

$$N^2 = -(g/\rho)\frac{\partial \rho}{\partial z}$$

- Diffusivity coefficient

$$K_v = \frac{0.25\varepsilon}{N^2}$$

- Relationship ε-sinking rate (Ruiz et al.,2004)

$$w_p = -(1944 * e^{(0.83*\log \varepsilon)})$$

Simulations:

A) Constant values of K_v and w_p

B) Vertical profile of K_v and constant w_p : Reference and future conditions (Fig.2)

C) Vertical profile of K_v and w_p : Reference and future conditions (Fig.2)

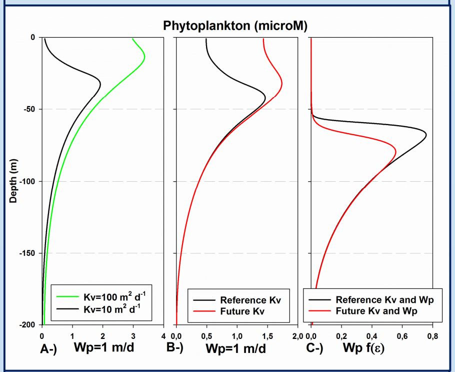
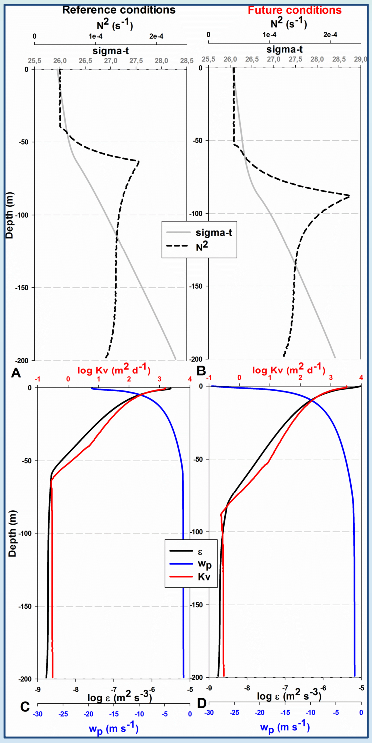


Figure 3. *Vertical distribution of Phytoplankton biomass using different physical structure of the water column (note the different scales in x-axes).*

A-Classical simulations using oversimplified physical structure of the water column. In contraposition with averaged recent global measurement in the mixing layer (10^2-10^3 m^2 d^{-1}) (Fernández-Castro et al., 2014).

B-Realistic K_v profile and classical sinking rates estimated in laminar flow. Future conditions would produce an increase of phytoplankton production and biomass.

C-Phytoplankton cells sink fast high-turbulence zones and more slowly in low-turbulence regions. Accumulations of cells in the at the base of the turbulent layer. This pattern is consistent with the recent findings by Macías et al. (2013) in a collection of field data. Decrease of biomass and productivity under future conditions.



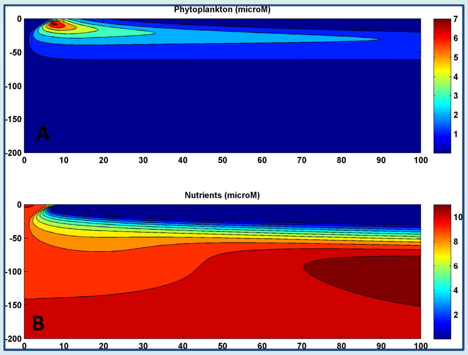


Figure 2 **.** Example of simulation B: Time evolution of phytoplankton (P, mmol N m^{-3}) (A) and nutrients (N, mmol N m^{-3}) (A) in the simulation with the "Reference conditions" (Figure 1 A,C).

Figure 1 **(left).** Reference (A,C) and future (B,D) hydrological conditions simulated with the GOTM. Solid blue line, sedimentation velocity (w_p)(based on Ruiz et al., (2004)).

Parameter	Units	Value	Functions/Equations
g_{max} , phytoplankton maximum growth rate	d^{-1}	2	
m, mortality rate	d^{-1}	0.1	
K ,phytoplankton half saturation constant for nutrient uptake	µM N	0.5	*Nutrient factor*= N/(N+K)
λ_w ,light attenuation coefficient due to the seawater	m^{-1}	0.04	*Irradiance*= $I(z)=I_0\ e(-\lambda_w-\lambda_{Chla}P)z$
λ_{Chla} , absorption coefficient due to phytoplankton	$(mmol\ N)^{-1}\ m^2$	0.07	
I_{opt} ,Optimal irradiance	W m^{-2}	100	*Light factor*= $I(z)/I_{opt}\ e(1-I/I_{opt})$

Water column physical structure: Future conditions (Fig. 1 B,D)

-Increase of stratification (3-20%) (Sarmiento et al. ;2004)

-Enhanced active turbulent layer: higher ε values and thicker layer

-Biological implications

-Enhancement of turbulent layers could favor the dominance of diatoms (*e.g.* Peters 2008)

-Increase in nutrient input (diffusion terms) could alter the dominance of coccolitophorids *vs.* diatoms in stratified regions (Cermeño et al. 2008)

-Decrease in biological production and deeper Deep Biomass Maximum (Fig. 3C)

-Species more adapted to lower levels of Irradiance

Implications to Biogeochemical cycles:

-Increase in particulate fluxes (enhanced carbon export) could counteract CO_2 rise via Biological Carbon Pump (Fig. 4 A)

-Decrease in phytoplankton production and particulate fluxes (Fig. 4 B) are considered as a positive feedback mechanism for global warming (e.g. Cermeño et al. 2008)

Conclusion:

This very simple model has demonstrated that turbulence-plankton interactions are non-trivial drivers of pelagic plankton distributions and dynamics. These interactions should be cleared up and included in current prediction models to better evaluate the potential effect of climate change on the world's pelagic ocean ecosystems.

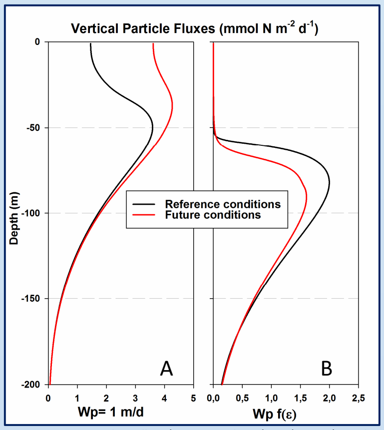


Figure 4. Particulate flux (computed as (*P+D*) x w_p) at the end of the simulation:

A) Vertical profiles of K_v and constant w_p. Future conditions could lead to an increase of the vertical flux or particulate exportation to deep ocean

B) Vertical profiles of K_v and w_p; Future conditions provoke a decrease in biological productivity and particulate fluxes

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