

Simulated changes in the particulate carbon export efficiency due to diel vertical migration of zooplankton in the North Atlantic

Thomas Gorgues⁺, Olivier Aumont[§], Laurent Memery^{*}

⁺Laboratoire d'Océanographie Physique et Spatiale (LOPS), UBO/CNRS/IRD/Ifremer, Institut Universitaire Européen de la Mer (IUEM), Technopole Brest Iroise, 29280, Plouzané, France.

[§]Laboratoire d'Océanographie et de Climatologie: Experimentation et Approches Numeriques, IPSL, 4 Place Jussieu, 75005, Paris, France.

^{*}Laboratoire des Sciences de l'Environnement Marin (LEMAR), UBO/CNRS/IRD/Ifremer, Institut Universitaire Européen de la Mer (IUEM), Technopole Brest Iroise, 29280, Plouzané, France.

Model description

In this study, we use the state-of-the-art “Nucleus for European Modelling of the Ocean » (NEMO) modelling framework [Madec *et al.*, 2008]. A configuration simulating the North Atlantic region from 20°S to 80°N with 64 vertical z-levels has been set up with a horizontal resolution of $\frac{1}{4}^\circ$ of a degree. The numerical simulations have been run for the 1995-2005 time-period and the atmospheric fields used to force the model are issued from the Drakkar Forcing Set 5 fields (DFS5, Dussin *et al.*, [2014]) for wind, air temperature and humidity, precipitation, shortwave and longwave radiations. Only the last five years have been used for our diagnostics. North and South ocean boundaries are closed with a classical Newtonian damping term for temperature and salinity towards monthly climatologies from the World Ocean Atlas 2005 (WOA05) [Antonov *et al.*, 2006; Locarnini, 2006].

The ocean dynamical component of NEMO is then coupled with the PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies) biogeochemical model [Aumont *et al.*, 2015]. PISCES simulates the lower trophic levels of marine ecosystems (phytoplankton, microzooplankton and mesozooplankton) and the biogeochemical cycles of carbon and the main nutrients (P, N, Fe and Si). Four prognostic variables (tracers) including two phytoplankton compartments (diatoms and nanophytoplankton), two zooplankton size classes (micro-zooplankton and mesozooplankton) and a description of the carbonate chemistry are considered in PISCES. The model is based on a mixed Monod–Quota formalism, with a fixed stoichiometry of C/N/P and an iron variable quota. Thus, phytoplankton growth rates are predicted simultaneously using the Monod approach for N, P and Si and the quota approach for Fe. Our regional simulation uses the World Ocean Atlas 2005 (WOA05) climatologies for initialization and damping near the ocean North and South boundaries for phosphate,

nitrate and silicate [Garcia *et al.*, 2006]. Iron has been derived from a model climatology employed by Aumont and Bopp [2006].

Diurnal Vertical Migration model parameterization

As mentioned in the main part of this manuscript, the DVM is set in the model to be performed solely by some of the mesozooplankton. Indeed, mesozooplankton, representing in the model the 200 to 2000 μm size class, is the only compartment encompassing heterotrophic organisms able to swim fast enough to vertically migrate twice a day.

In our set-up, we have chosen to not explicitly model the migrating zooplankton but rather to parameterize the effect of migration. This method allows to avoid computationally expensive explicit simulation of the mesozooplankton migration.

Migration Depth

To parameterize the DVM, we first need to compute the depth of the diurnal vertical migration (Z_{DVM}). The latter is computed using the parameterization published by Bianchi *et al.*, [2013a] using oxygen and temperature gradients (ΔO_2 in mmol.m^{-3} and ΔT in $^{\circ}\text{C}$) between the surface (0 to 25m) and the upper mesopelagic zone (150 to 500m), surface chlorophyll (Chl in mg.m^{-3}) and the mixed layer depth (mld):

$$Z_{\text{DVM}} = 398 - 0.56 \cdot \Delta\text{O}_2 - 115 \cdot \text{Log}_{10}(\text{Chl}) + 0.36 \cdot \text{mld} - 2.4 \cdot \Delta T$$

(Eq. 1)

The resulting estimation of Z_{DVM} for our modeling exercise is displayed on figure 2c of the manuscript, which shows a good agreement with the Z_{DVM} based on acoustic data displayed in Bianchi *et al.*, [2013a]'s figure 2.

Mesozooplankton

In our set-up, the temporal evolution of the mesozooplankton biomass (M) is computed using the exact same equation than the one used in the PISCES version documented in Aumont *et al.*, [2015]:

$$\begin{aligned} \frac{\partial M}{\partial t} = & e^M (g^M(\text{Phyto}) + g^M(\text{Diat}) + g^M(\text{POC}_s) + g^M(\text{Zoo}) + g_{FF}^M(\text{POC}_s) \\ & + g_{FF}^M(\text{POC}_b)) M - m^M f_M(T) M^2 - r^M f_M(T) \left(\frac{M}{K_M + M} + 3\Delta\text{O}_2 \right) M \end{aligned}$$

(Eq. 2)

where “Phyto”, “Diat” and “Zoo” stand respectively for nanophytoplankton, diatoms and microzooplankton. Grazing by mesozooplankton (g^M on each species (either Phyto, Diat, Zoo) is represented by g^M . $g_{FF}^M(\text{POC}_s)$ and $g_{FF}^M(\text{POC}_b)$ refer to flux feeding [Stemmann *et al.*, 2004] by mesozooplankton on small and big particles (respectively POC_s and POC_b). e^M represents the growth efficiency associated with grazing (detailed in equation 27a and b in Aumont *et al.*, [2015]). The two remaining terms are the linear mortality and the quadratic mortality. The latter is used to account for predation by non-resolved higher trophic levels (please refer to Aumont *et al.*, [2015] for a detailed description of the temperature dependence function f_M or value of the parameters m^M and r^M).

In our set up, this equation is strictly the same for our different simulations (CTL, M30 and M60). Only the differences in concentrations of nanophytoplankton, diatoms, microzooplankton, POC_s and POC_b (used in the Equation 2 to compute the time evolution of mesozooplankton biomass) lead to the differences in mesozooplankton concentrations between CTL, M30 and M60. CTL experiment

corresponds to a PISCES set up that is exactly identical to the version described and used in Aumont et al. [2015]. M30 and M60 include a representation of DVM which is described in the following section.

Parameterization of the migration impacts on carbon, oxygen and nutrients

In M30 and M60, the total mesozooplankton concentration (M) in each grid cell is split between a “non-migrating” (M_{nm}) and a “migrating” (M_m) fraction. Depending on the considered scenario (M30 or M60), 30 or 60% of mesozooplankton is considered to perform DVM (p_m). The time spent daily at depth by the migrating mesozooplankton (L_{day}) also accounts for the geographical and seasonal variability of the daylight duration. Here, we assumed that the migrating mesozooplankton stays at the migration depth for the full duration of the daylight (i.e. migration of mesozooplankton from the surface to Z_{DVM} is assumed instantaneous).

The non-migrating fraction of the mesozooplankton biomass is then computed from the total biomass of mesozooplankton computed with Equation 2 from which we subtracted the migrating fraction. The migrating and non-migrating fraction can then be considered as diagnostically (rather than prognostically) derived from the total mesozooplankton concentration.

$$M_m = M \times p_m \times L_{day} \quad (\text{Eq. 3})$$

$$M_{nm} = M - M_m \quad (\text{Eq. 4})$$

Then, those two mesozooplankton fractions are used, in each grid cell, to compute the time evolution (hereafter named “trends”) of the POC_b, DOC, DIC, nutrients and O₂ concentrations (using the standard PISCES equations of Aumont et al., [2015]) for respectively the migrating and the non-migrating fractions. **Only the non-migrating related trends are used in all grid cells to compute the POC_b, DOC, DIC, nutrients and O₂ concentrations.**

The **migrating related trends** of POC_b, DOC, DIC, nutrients and O₂ concentrations **are, for their part, saved and integrated over the water column**. Then, those integrated trends are **vertically redistributed at the depth of the vertical migration (Z_{DVM})**. As a result, at the migration depth, the concentrations of POC_b, DOC, DIC, nutrients and O₂ are computed using the sum of (i) the local “non-migrating” trends (which is very small at those depth) and (ii) the migrating trends (computed at each z-levels and vertically integrated).

Example: POC_b in the migration scenarios

Let us consider the surface layers of the ocean for either the M30 or M60 scenario. At the first z-level, only the “non-migrating” trends is considered ($\frac{\partial POC_{b_{nm}}}{\partial t} = \frac{\partial POC_b}{\partial t}$). The concentration of the POC_b is computed using the following time-evolution equation:

$$\begin{aligned}
\frac{\partial POC_b_{nm}}{\partial t} = & \sigma^M (g^M(Phyto) + g^M(Diat) + g^M(POC_s) + g^M(Zoo) + g_{FF}^M(POC_s) \\
& + g_{FF}^M(POC_b))M_{nm} + r^M f_M(T) \left(\frac{M_{nm}}{K_M + M_{nm}} \right) M_{nm} + P_{up}^M \\
& + 0.5 R_{CaCO_3} \left(m^P \frac{Phyto}{(Phyto + K_m)} Phyto + \omega^{Phyto} Phyto^2 \right) \\
& + 0.5 \left(m^{Diat} \frac{Diat}{Diat + K_m} Diat + \omega^{Diat} Diat^2 \right) + \varphi + \varphi_2^{DOC} \\
& - g_{FF}^M(POC_b)M_{nm} - \lambda_{POC_s}^* POC_b - w_{POC_b} \partial POC_b / \partial z
\end{aligned}
\tag{Eq. 5}$$

where the first term represents the POC_b produced by the non-assimilated fraction of the mesozooplankton grazing (with σ^M the non-assimilated fraction parameter). The second term represents the POC_b produced by the mesozooplankton mortality. The third term “ P_{up}^M ” refers to the POC_b produced by the quadratic mortality of the mesozooplankton. The latter is mimicking grazing by the non-resolved higher trophic levels (please refer to *Aumont et al.*, [2015] for the detailed formulation of P_{up}^M). The fourth term represents the routing of 50% of the dying calcifiers to the fast sinking big particles due to the calcite being significantly denser than organic matter (with R_{CaCO_3} the proportion of calcifying organisms, m^P the nanophytoplankton mortality rate and ω^{Phyto} the quadratic nanophytoplankton mortality rate). Fifth term is similar to the fourth term as it represents the routing of 50% of the dying diatoms to the fast sinking big particles [*Smetacek*, 1985; *Decho*, 1990] (with m^{Diat} the diatoms mortality and ω^{Diat} the quadratic mortality rate of diatoms,). The sixth and seventh terms are respectively the aggregation of POC_s to POC_b and aggregation of DOC on POC_b. The sink terms are respectively the flux feeding of POC_b by mesozooplankton, the degradation ($\lambda_{POC_s}^*$ being the degradation rate) and the vertical sedimentation of POC_b.

At the migrating depth, the POC_b concentration is computed following:

$$\frac{\partial POC_b}{\partial t} = \frac{\partial POC_b_{nm}}{\partial t} + \sum_{z-levels} \frac{\partial POC_b_m}{\partial t}
\tag{Eq 6}$$

with the time evolution of POC_b_m in each grid cells:

$$\begin{aligned}
\frac{\partial POC_b_m}{\partial t} = & \sigma^M (g^M(Phyto) + g^M(Diat) + g^M(POC_s) + g^M(Zoo) + g_{FF}^M(POC_s) \\
& + g_{FF}^M(POC_b))M_m + r^M f_M(T) \left(\frac{M_m}{K_M + M_m} \right) M_m + P_{up}^M - g_{FF}^M(POC_b)M_m
\end{aligned}
\tag{Eq 7}$$