Modeling the biological carbon pump

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Introduction

Context: atmospheric CO_2 controls our climate, and is itself controlled by a plethora of factors. Our understanding of past, current and future CO_2 levels hinges on our ability to quantify all CO_2 sources and sinks.

Focus: the *biological carbon pump*: biota-controlled transport of CO_2 from the atmosphere to the ocean deep. Near the ocean surface, plankton builds organic carbon from CO_2. Part of this carbon sinks, passes a diffusion barrier, and is locked in the ocean deep.

Aim: to understand the global influence of the biological carbon pump. We employ mathematical models that combine geophysical, biological and mathematical expertise. Our focus is on *informed simplification*: we model biological and physical processes on their relevant (small) scales, then seek well-founded parameterizations to feed global climate models.

We study the biological carbon pump in a 1D model of the marine water column, focusing on the main controls of the carbon pump:

- Marine ecosystems
- Turbulence
- Marine snow

Figure 1 illustrates the interplay of these processes.

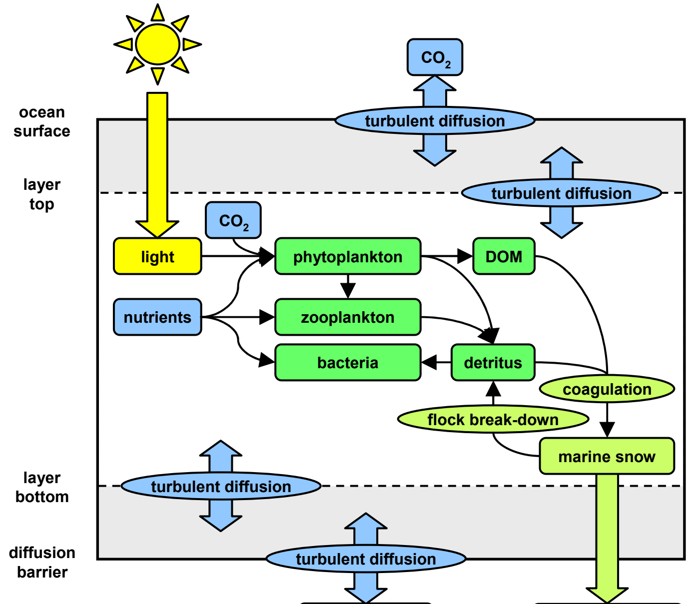

Fig. 1. The biological carbon pump in the marine water column.

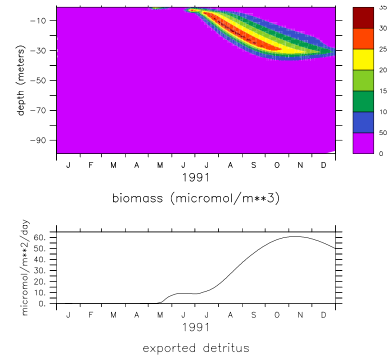

Fig. 2. Simulation of a marine water column on the northern hemisphere. Shown are the concentration of biomass (top), and the amount of detritus sinking out of the system (bottom).
Biomass is governed by stratification of the water column, deepening of the nutricline, and the onset of winter storms, respectively.
The simulation was performed with GOTM-BIO [2], and a DEB-based mixotrophic population model. Detritus sinks (50 m/day), other state variables neither sink nor float.

Scaling up

Sophisticated models bring complexity. A first attempt to model the top of the water column might lead to:

- >3 trait distributions, >10 cells each, to describe biodiversity.
- >200 size classes to describe marine snow.
- >75 layers in the vertical to describe turbulence.

This would imply >90,000 variables to describe the ocean's upper layer. This sharply contrasts with the number of <10 additional variables that 3D global climate models typically can accommodate.

Approach: To assemble distributions/grids in mathematically simple models that retain all behavior of interest.

For instance, we may:

- replace ecosystem trait distributions by (adaptive) average trait values.
- replace marine snow size distribution by time-dependent average flock size (and average sinking speed).
- replace vertical grid by vertically-averaged behavior, using average turbulent diffusion and average light intensity.

Marine ecosystems

Phytoplankton converts CO_2 to biomass. The fate of fixed organic carbon depends on many factors, as phytoplankton stands at the base of an elaborate food web (figure 1).

Important processes:

- *Photosynthesis*: phytoplankton fixes CO_2 in the presence of light and nutrients.
- *Predation*: zooplankton predates on phytoplankton.
- *Death* of organisms results in formation of detritus.
- *Remineralization*: bacteria consume detritus, and partly transform it into the original nutrients.

How modeled?

The Dynamic Energy Budget theory (DEB) [1] is a consistent, quantitative approach to biological modeling. We will develop a DEB-based population model that supports any relevant biological activity through quantifiable *traits*. Investment in traits brings benefits (typically an increase in food supply), but also costs in growth and maintenance of biomass.
We assume *infinite biodiversity*: every possible combination of traits can be found in the marine ecosystem. This implies continuous distributions of all traits. We propose to initialize the model in the ocean spring with uniform trait distributions and low biomass. Evolution of trait combinations then represents the rise and fall of species and functional groups.

Turbulence

'Turbulence': unstable, variably-sized, undirected eddies.

Produced by:

- *Buoyancy*: unstable gradients in density form by cooling and evaporation of surface water.
- *Shear*: flow velocity gradients are created by wind, waves and tides.

Turbulence is high in autumn and winter, when storms shear and cool the surface. In summer, heating of the surface creates a stable density gradient: the water is stratified and non-turbulent.

Effects

Turbulence mixes everything across the water column. As such, it:

- stimulates biological productivity by supplying nutrients.
- reduces phytoplankton productivity by decreasing the average light intensity experienced by phytoplankton.

How modeled?

Many empirical models parameterize turbulence. We use the General Ocean Turbulence Model (GOTM) [2], which can simulate turbulence in a water column with a variety of models.

Marine snow

'Marine snow': variably-sized particles of mostly detritus.

Larger particles form when small particles meet and stick together. Particles meet due to:

- *(Turbulent) shear*: differences in traveling speed cause particles to meet.
- *Brownian motion*: small particles 'diffuse' towards one another.
- *Differential sedimentation*: differences in sinking rates cause particles in the same column to meet.

Particle formation is partly controlled by the presence of sticky dissolved organic matter (DOM), excreted by nutrient-limited phytoplankton. Also, large particles can break down due to shear stress in environments with high turbulence.

Effects

Coagulation increases the average particle size, and therewith the average sinking rate. Doing so, it:

- exports organic carbon to the deep.
- decreases percentage of remineralization, indirectly affecting future nutrient supply.

How modeled?

We discretize the particle size distribution, and parameterize the processes creating and destroying particles [3].

References

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More info

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For more information:
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