Pathways of Organic Carbon Export and Sequestration by the Biological Pump

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The biological pump is a set of biological processes that lead to depletion of DIC at the surface and accumulation in the deep ocean. One of the 3 main “carbon pumps” in the ocean, along with the solubility and CaCO₃ pumps.

The biological pump is associated with the fixation of organic carbon at the surface and its respiration back to DIC at depth. Also known as the “soft tissue pump” (Volk and Hoffert, 1985).

Carbon export is the vertical flux of organic carbon past a fixed depth horizon (typically the base of the euphotic zone). Expressed as a rate (e.g. GtC yr⁻¹).

Carbon sequestration is the buildup of respired DIC (biogenic DIC) below the euphotic zone. Expressed as an inventory (GtC).

The sequestration time refers to the time it takes for biogenic DIC to resurface in the euphotic zone. Expressed as a timescale (yr).
Pathways of Carbon Export and Sequestration

The mixing pump is driven by large-scale subduction, eddy pumping, and seasonal mixed layer deepening/shoaling.

The migrant pump is driven by the vertical migrations of animals (zooplankton and fish).

The gravitational pump is driven by the sinking of detrital matter such as phytoplankton aggregates, animal feces, and carcasses.

How well do current ocean biogeochemical models (OBMs) represent these processes?

- The **mixing pump** is at least partially captured by all models. The C$_{org}$ pools most important for the mixing pump are non-sinking pools such as DOC (labile to semi-refractory pools) and suspended POC. Most OBMs represent at least one pool (semi-labile) of DOC and a few represent other pools as well. Some (but not most) models have a suspended POC pool, which is roughly equivalent to a labile DOC pool. Eddy pumping is incompletely represented in models due to their coarse resolution and parameterized mixing.

- The **migrant pump** is represented in only a few models (e.g. PISCES; Aumont et al., 2021) but will likely be standard in next-generation models. Most models do not represent higher trophic levels such as mesopelagic fish, which are potentially large contributors to the migrant pump (Pinti et al., 2023).

- The **gravitational pump** is represented in all models. The simplest representation is with a single sinking particulate organic carbon (POC) pool, possibly with or without variations in sinking speed with depth or seawater viscosity. More complex models represent multiple (two) sinking POC pools with different sizes and sinking speeds. Bacterial respiration of POC is generally parameterized as a function of temperature and oxygen. Some models include ballast minerals (CaCO$_3$, SiO$_2$, or lithogenic minerals) that act to increase the sinking speed of POC and/or protect it from bacterial degradation.
Many previous models focused on one particular pathway, and typically assessed carbon export at one or more depths. Less work has been done assessing all pathways in combination, and fewer estimates of carbon sequestration by pathway. Nowicki et al. (2022) present a food-web ecosystem model embedded in a data-constrained biological pump model (DeVries and Weber, 2017). This model provides carbon export and sequestration estimates for all biological pump pathways, as discussed in the following slides.

### Previous Model and Data-based Estimates

<table>
<thead>
<tr>
<th>Pump component</th>
<th>Approach</th>
<th>Export (GtC/yr)</th>
<th>Sequestration (GtC)</th>
<th>Sequestration time (yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravitational pump</strong></td>
<td>$^{234}$Th-calibrated relationship between export and SST</td>
<td>4.0(±2.2) at 100 m</td>
<td></td>
<td></td>
<td>Henson et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>SST- and NPP-relationship calibrated to summary of global observations</td>
<td>6.9</td>
<td></td>
<td></td>
<td>Laws et al. (2011)</td>
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<td></td>
<td>Food web model</td>
<td>5.9(±1.2)</td>
<td></td>
<td></td>
<td>Siegel et al. (2014)</td>
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<td></td>
<td>Compilation of Earth System Models</td>
<td>4.9-8.1</td>
<td></td>
<td></td>
<td>Bopp et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Compilation of OBMs</td>
<td>6.0(±1.2) at 100 m</td>
<td></td>
<td></td>
<td>Doney et al. (2024)</td>
</tr>
<tr>
<td><strong>Mixing pump</strong></td>
<td>Model of DOC transport</td>
<td>1.9</td>
<td></td>
<td></td>
<td>Hansell et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>ANN map of DOC and ocean circulation model</td>
<td>2.3(±1.2) at 75 m</td>
<td></td>
<td></td>
<td>Roshan et al. (2017)</td>
</tr>
<tr>
<td><strong>Migrant pump</strong></td>
<td>Food web model with migrants</td>
<td>0.7</td>
<td></td>
<td></td>
<td>Archibald et al. (2019)</td>
</tr>
<tr>
<td></td>
<td>OBM coupled to upper trophic levels model</td>
<td>1.05(±0.15)</td>
<td></td>
<td></td>
<td>Aumont et al. (2018)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>O2 budget and circulation</td>
<td></td>
<td>1,300(±200)</td>
<td>300-600</td>
<td>Carter et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>Literature summary</td>
<td></td>
<td>11(±6)</td>
<td>2,000(±1,000)</td>
<td>Boyd et al. (2019)</td>
</tr>
</tbody>
</table>
A Data-Assimilated Biological Pump Model

(Top left): The satellite-driven implicit ecosystem (SIMPLE) model of DeVries and Weber (2017) was updated by Nowicki et al. (2022) to explicitly represent zooplankton and their migrations.

(Top right): The parameters of the model were adjusted in an iterative process to best capture observations of phytoplankton, zooplankton, and biogeochemical tracers (bottom left). Results of 124 different models were used to quantify and characterize the carbon export and sequestration by the mixing, migrant, and gravitational pumps.
Gravitational Pump

The gravitational pump includes sinking phytoplankton aggregates and zooplankton fecal pellets. Fish are not represented in the model, and their export is likely subsumed under zooplankton fecal pellets.

Gravitational export is about 7 GtC/yr, roughly 20% phytoplankton aggregates and 80% zooplankton fecal pellets.

Carbon sequestration by the gravitational pump is roughly 1000 GtC, with a sequestration time of roughly 150 years.

Zooplankton fecal pellets dominate carbon export in the low latitudes. Phytoplankton aggregates are important for carbon export in the high latitudes and high-productivity coastal regions.
Mixing Pump

Mixing pump export is around 2 GtC/yr. Carbon sequestration by the mixing pump is roughly 100 GtC, for a sequestration time of about 50 years, the shortest of all the pumps.

*N.B. the model does not include the seasonal mixed layer pump, since the circulation is steady-state. Eddy subduction pump is not explicitly resolved, but thought to be small (Resplandy et al., 2019).

The mixing pump includes the large-scale subduction of semi-labile and semi-refractory DOC. Labile DOC/suspended POC is represented but not included due to its short sequestration time (<5 years).

The mixing pump is most important in regions where mode/intermediate/deep waters are formed such as the western edges of subtropical gyres (subtropical mode waters), the Antarctic convergence (Antarctic intermediate water) and the subpolar North Atlantic.
The migrant pump includes the daily migrations of zooplankton. Seasonal migrations, as well as daily migrations of fish, are not represented in the model.

Migrant pump export is around 1 GtC/yr. Carbon sequestration by the mixing pump is roughly 150 GtC, for a sequestration time of about 150 years. The sequestration time is determined mainly by the mean migration depth which is around 300-400 m.

The migrant pump is most important in high-productivity regions of the subpolar and coastal oceans. These regions support large populations of “large zooplankton” which undergo diel vertical migration in the model. This pattern contrasts with inferences from satellite LIDAR observations which appear to show that the subtropical gyres support the largest populations of migrating organisms (Behrenfeld et al., 2019).
Depth Distribution of Respiration and Sequestration

(a) Respiration injects exported C$_{org}$ into the water column as DIC. The respiration rate decreases exponentially with depth.

(b) The sequestration time of respired DIC (biogenic DIC) increases with depth and is largest in the Pacific Ocean.

(c) The resulting carbon sequestration peaks in the mesopelagic zone at ~200-400 m. 50% of carbon sequestration is due to respiration above 1000 m depth, and 50% to respiration below 1000 m depth.

See also Legendre et al. (2023), Nat. Geo.
Role of air-sea disequilibrium

Air-sea CO₂ disequilibrium can enhance the storage of biogenic carbon because slow air-sea CO₂ equilibration prevents upwelled biogenic DIC from escaping to the atmosphere. This effect is sometimes called the disequilibrium pump.

Air-sea CO₂ disequilibrium has the following effects:

- It increases the total carbon sequestered by the biological pump by about 35% (450 GtC)
- It increases the sequestration time of biogenic carbon by around 70 years on (spatial) average
- It enhances carbon sequestration most effectively in the Atlantic and Southern Oceans
- It reduces carbon sequestration in deep-water formation regions such as the Labrador and Greenland Seas and in Antarctic marginal seas.

Nowicki et al. (2024, GBC) coupled an interactive atmosphere to the biological pump model of Nowicki et al. (2022) to investigate the effects of air-sea disequilibrium on carbon sequestration by the biological pump. Simulations were run with realistic and instantaneous gas exchange. The disequilibrium effect was determined by taking the difference between the two simulations.
## Summary

<table>
<thead>
<tr>
<th>Pump component</th>
<th>Export (GtC/yr)</th>
<th>Sequestration (GtC)</th>
<th>Sequestration time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational pump</td>
<td>7.3(±1)</td>
<td>1040(±90)</td>
<td>142(±15)</td>
</tr>
<tr>
<td>Mixing pump</td>
<td>1.9(±0.6)</td>
<td>102(±8)</td>
<td>54(±12)</td>
</tr>
<tr>
<td>Migrant pump</td>
<td>1.0(±0.6)</td>
<td>150(±100)</td>
<td>150(±100)</td>
</tr>
<tr>
<td>Disequilibrium pump</td>
<td>—</td>
<td>460(±10%)</td>
<td>45(±10%)</td>
</tr>
<tr>
<td>Total</td>
<td>10.2(±1)</td>
<td>1753(±30%)</td>
<td>172(±30%)</td>
</tr>
</tbody>
</table>

- Numbers based on Nowicki et al. (2022, 2024)
- Uncertainties are approximately 2σ

Significant caveats of this model:
- Coarse resolution and does not resolve seasonality or interannual variability
- Higher trophic levels are not represented

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### Thank You

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