Eos

Our Evolving Understanding of Biological Carbon Export

The array of processes and organisms that make up the biological carbon pump has immense influence on Earth's carbon cycle and climate. But there's still much to learn about how the pump works.

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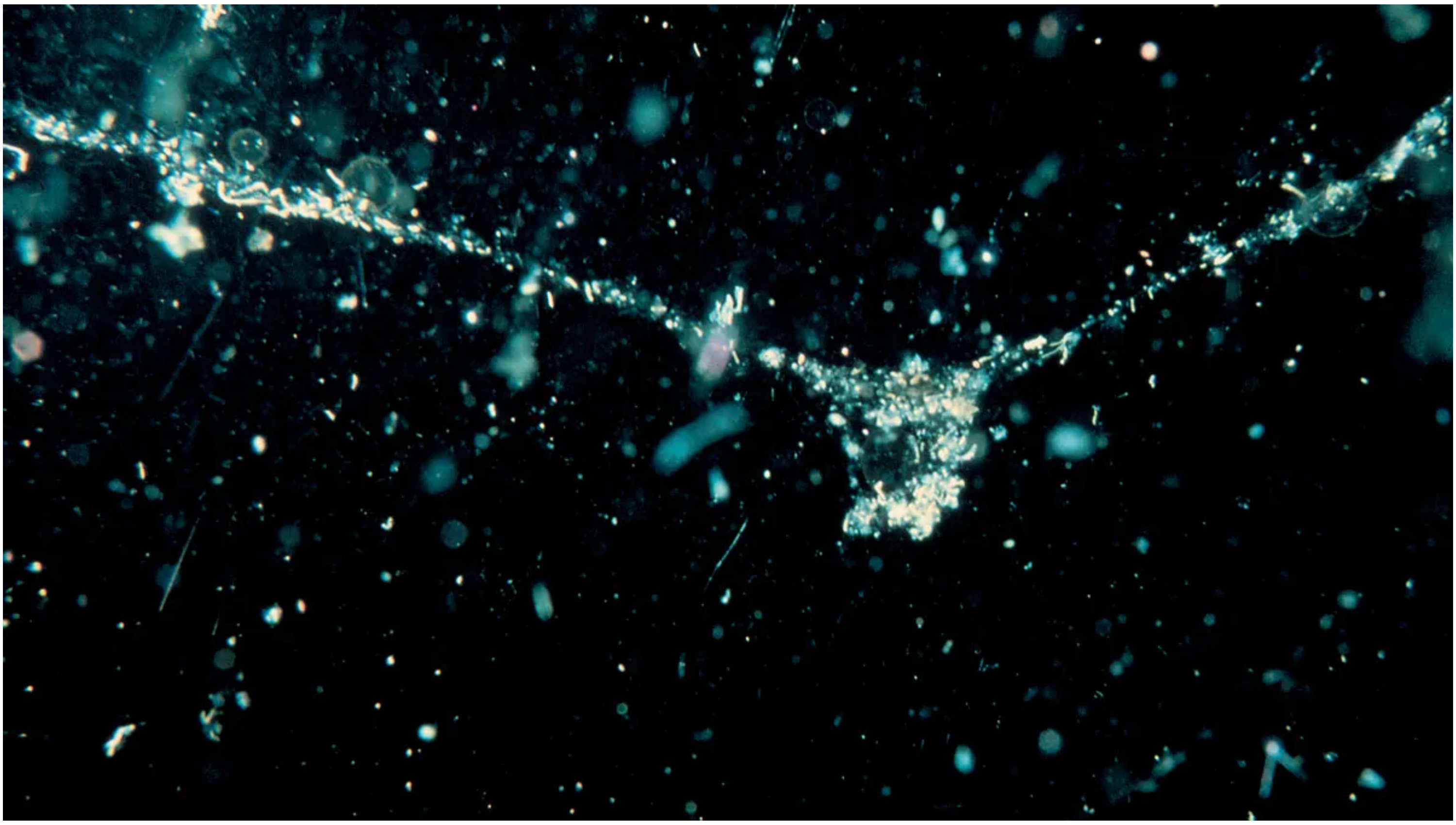

"Marine snow," ubiquitous across the open ocean, comprises tiny (~millimeter-long) bits of organic detritus that accumulate and break down as they descend through the water column. This image shows marine snow within the photic, or epipelagic, zone, 55 meters below the sea surface in Monterey Bay, California. Credit: © Woods Hole Oceanographic Institution, S. Honjo

Since long before humans began fundamentally changing the Earth system, the ocean has been absorbing and releasing carbon, **cycling it** and other elements globally including from the water's surface down to the seafloor. More recently, since industrialization started in the mid-18th century, the ocean has **absorbed at least one quarter** of anthropogenic **carbon dioxide (CO_2) emissions**, helping mitigate the impacts of climate change.

The dominant conduit for transporting carbon from the ocean surface to depth is the biological carbon pump (BCP). Biologically mediated removal of carbon from the ocean surface creates a vertical gradient in carbon concentration in the water column, which enhances the ocean's capacity to absorb additional atmospheric CO_2. Consequently, the

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BCP is one of the most important determinants of oceanic absorption of atmospheric CO_2 over geologic timescales and, accordingly, an important determinant of global temperatures. **Estimates have suggested** that the present-day atmospheric CO_2 concentration would be 50% higher in the absence of the BCP.

The impacts of accumulating anthropogenic CO_2 on Earth's climate make the BCP a **foundational target of oceanographic research**. Changes in the functioning of the BCP have direct implications for climate feedbacks, amplifying or mitigating global warming. Goals to implement or accelerate nature-based solutions and **marine carbon dioxide removal** (mCDR) interventions, some of which propose to stimulate the BCP to draw more carbon from the atmosphere, add urgency to better understand the BCP.

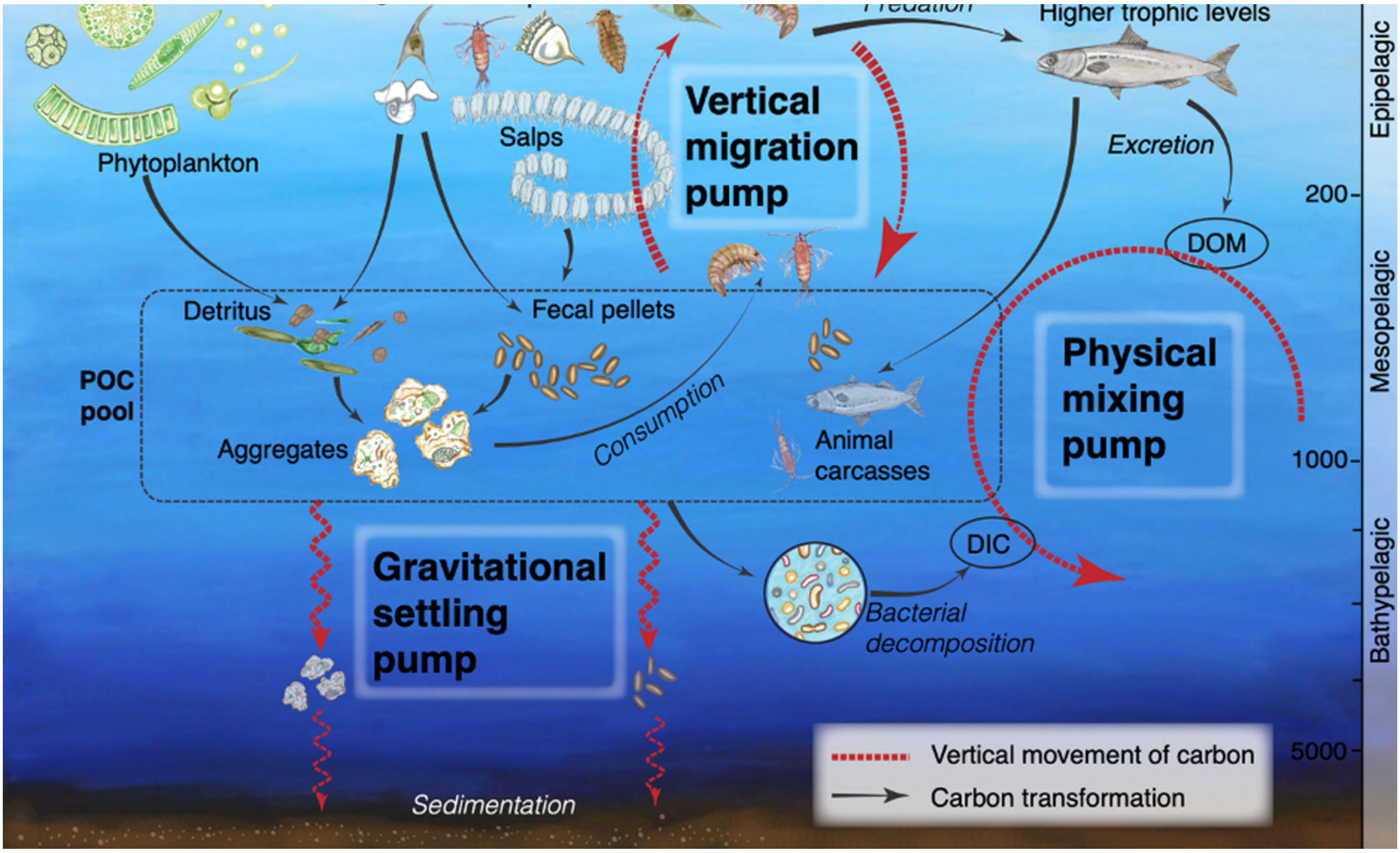
During a session at the **2022 Ocean Carbon and Biogeochemistry** (OCB) summer workshop, participants identified critical elements of a future BCP research agenda, which we outline here.

The Complexities of Observing Small Things

Annually, the BCP is responsible for removing about 10 petagrams (10 trillion kilograms) of carbon from the sunlit, or epipelagic, zone (0- to 200-meter depth) of the ocean [***Nowicki et al.***, 2022]. Coincidentally, this amount is roughly equal to the **total annual average emission of anthropogenic carbon** during the present decade. Ultimately, a large fraction of carbon absorbed by the surface ocean returns to the atmosphere through respiration while only a small fraction (sometimes <1%) of this 10 petagrams makes its way to the deep ocean for long-term sequestration. At intermediary, or mesopelagic, ocean depth (200–1,000 meters), the BCP feeds essential carbon (and other nutrients) to mesopelagic food webs that not only modulate the amount of carbon exported to the deep ocean but also support important commercial fisheries.

The BCP's effects on Earth's ecosystems and climate are global in scale. The BCP is a composite of numerous interacting biogeochemical and physical processes—some poorly known—that operate over a range of spatial and temporal scales. Three main mechanisms transport biological carbon through the ocean: passive gravitational sinking of particles, active vertical migration of zooplankton and fish, and physical advection and diffusion of particulate or dissolved carbon (Figure 1; reviewed by ***Siegel et al.*** [2023]).

Fig. 1. The biological carbon pump involves many biological players, from microscopic plankton to large fish, and physical processes that transform carbon into different forms and transport it through the water column. POC = particulate organic carbon; DOM = dissolved organic matter; DIC = dissolved inorganic carbon. Credit: Kristen Krumhardt



Decades of research have yielded major advances in our knowledge of the BCP. However, observing processes that simultaneously occur on spatial and temporal scales spanning orders of magnitude presents major challenges for research. Limitations, such as the difficulty of observing microscopic processes across a global scale and the continued discovery of diverse organisms with previously unknown ecological and physiological capacities, constrain our **understanding of even the dominant processes** that drive the BCP, causing significant uncertainties in estimates of the rates of carbon flux. These uncertainties propagate into models that, depending on how they're parameterized, variably project either enhanced or decreased strength of the BCP under future climate change scenarios. Such discrepancy in even the directionality—the enhancement or reduction of flux processes—has obvious ramifications for our ability to predict the effects of future CO_2 emissions on global climate.

A further hindrance is that the mechanistic relationships between climate drivers and the biological, physical, and chemical components of the BCP are too poorly understood at present to predict effects of ocean warming, stratification, acidification, expansion of oxygen minimum zones, or limitations of nutrient delivery on these components. By extension, climate-related changes in the efficiency and magnitude of **carbon export to the deep ocean** are unclear.

New Knowledge Means Advances—And New Uncertainties

Speakers at the 2022 OCB workshop laid the groundwork for group discussions by describing recent advances in BCP research and understanding. Their presentations highlighted substantial contributions to carbon export from organisms previously overlooked, such as pelagic (open-water) fishes [***Saba et al.***, 2021] and single-celled herbivores [***Larsson et al.***, 2022; ***McNair et al.***, 2021], as well as nuanced advances in our understanding of how known carbon conduits, such as zooplankton and **salp fecal pellets** and carcasses, contribute to the BCP [***Steinberg*** *et al.*, 2023]. Together these biological actors and processes that remineralize or redistribute carbon vertically are critical but uncertain contributors to long-term carbon sequestration.

Speakers also described the important lines of evidence that the paleoceanographic record provides on how the BCP has functioned over time, particularly because ocean temperature can affect the supply of organic carbon to the seafloor [*Boscolo-Galazzo et al.*, 2021]. And emergent **environmental DNA** tools were discussed, because they offer new approaches to identifying sources of carbon to the BCP from the epipelagic layer [*Durkin et al.*, 2022] down to the seabed [*Cordier et al.*, 2022].

Ultimately, these observed processes and carbon sources must all be integrated into models to simulate the behaviors and responses of the BCP across the ocean system skillfully. Several studies featured during workshop discussions emphasized potential missing components from model representations of the BCP, including characterizations of various organism groups, how these groups stimulate the BCP [*Laufkötter et al.*, 2016; *Luo et al.*, 2022], and the ways that these organisms affect and are affected by climate change [*Henson et al.*, 2022].

Known Unknowns: A Road Map for New Research

Rates of particulate sinking and carbon remineralization as well as the residence times of BCP-exported carbon in the deep ocean—on regional to global scales—remain significant unknowns. Our understanding of carbon sequestration timescales is still in its infancy, and studies that design observing systems capable of tracking the fate of carbon and that can quantify the BCP carbon residence time are needed. In this vein, a better grasp of BCP processes is critical in determining the rates and magnitudes of carbon fluxes required to **quantify and validate the effectiveness of different mCDR initiatives** as these mitigation approaches advance. The downstream effects of mCDR on ocean ecosystem function, organisms that contribute to the BCP, and the resulting export efficiency represent additional major unknowns.

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The sensitivities of organic carbon generation, particle size, and remineralization in the BCP to climate-associated changes, such as ocean warming, have not been studied in situ and are therefore not parameterized within models. Other challenges to improving models include better constraining key transfer processes of carbon, including respiration, production, and consumption; extrapolating species- or site-specific experiments to the global domain; and growing data sets that can be used to improve validation. The role of regional variability in global models, including in region-specific rates, is also largely unconstrained.

Moreover, investigations connecting domains, such as through coastal-to-open-ocean transport measurements, are needed to quantify how coastal processes contribute to global carbon export and sequestration. Intercomparisons between models and observations must identify whether a single modeling framework adequately represents the BCP or whether unique processes require individual representation. Such intercomparisons will be foundational to assessing and improving model performance and directing observational efforts.

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Meaningful connections between process-level, mechanistic-focused studies and larger-scale observational programs will be central to establishing statistical relationships and large-scale mass balances to connect disparate observational approaches. New global observational capabilities—including from the autonomous Biogeochemical-Argo (**BGC-Argo**) float network and NASA's Plankton, Aerosol, Cloud, Ocean Ecosystem (**PACE**) mission—can feed data-assimilative models global-scale information on features such as phytoplankton community composition as well as unparalleled observations of in situ ocean biogeochemistry from the surface to 2,000-meter depth.

Emerging approaches for characterizing the composition of biological particles via environmental DNA sequencing offer new ways to investigate major players associated with particulate carbon export. Pairing results from emerging tools with new global-scale observing systems such as PACE and BGC-Argo may pave the way toward an operational system for monitoring the BCP. Such an operational system will span vast temporal and spatial scales and overcome historical observational limitations on our capacity to quantify carbon export on a routine basis.

In addition, we now know that many processes contributing to the BCP are ephemeral, and determining those processes' contributions (both their frequency and magnitude) to carbon export is particularly challenging. For example, the influences of episodic and ephemeral biological events like **jelly-falls and salp blooms** on BCP function are poorly quantified, although some studies have demonstrated their importance [e.g., ***Steinberg et al.***, 2023]. Partnering with the global BGC-Argo array to modify the timescales over which some floats profile the water column (normally 10 days) to capture ephemeral BGC processes (~1-day timescales) can help fill this observational gap and feed data-assimilative models.

Data management will lay the groundwork for developing an operational system capable of routinely and effectively ingesting data. Synthesizing, consolidating, and cross-validating data are essential for observation-model intercomparisons, which require accessible, well-managed data and data products created in consultation with the modeling community.

Another key factor in improving BCP understanding involves supporting and investing in the next generation of BCP researchers, who reflect diverse perspectives and backgrounds and who bring distinct skill sets and experiences to the table, from at-sea observational work to molecular work to working with large, complex data sets. To take a step in this direction, invited speakers at the OCB meeting reflected gender balance and representation of both senior scientists who have spent their careers advancing BCP frontiers and early-career researchers who are pushing the research agenda forward with new perspectives and approaches.

Collectively Envisioning a Complex Future

Community discussions at the OCB workshop highlighted the complexity of the BCP. Ongoing studies of mechanistic relationships are bringing to light existing strengths and opportunities of both models and empirical studies, as well as needed research targets and infrastructure. The importance of the BCP in the global carbon cycle makes it essential that we capitalize on opportunities to discover thus far unknown processes and better quantify known ones.

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Our knowledge of the BCP fundamentally dictates our capacity to understand and estimate carbon fluxes globally and to predict how these fluxes will affect climate, and vice versa. As potential implementations of mCDR advance, the oceanographic and climate science communities also face an urgent need to better understand these approaches to minimize their environmental harm, maximize their effectiveness, and ultimately contribute to enhancing climate change resilience.

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