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RECEIVED 30 September 2025
REVISED 15 October 2025
ACCEPTED 20 October 2025
PUBLISHED 11 November 2025

CITATION
Pedrosa-Pàmies R, Conte MH, Honda M and
Herndl GJ (2025) Editorial: The oceanic
particle flux and its cycling within the deep
water column, volume II.
Front. Earth Sci. 13:1716510.
doi: 10.3389/feart.2025.1716510

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Editorial: The oceanic particle flux and its cycling within the deep water column, volume II

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KEYWORDS

particle flux, biological pump, export efficiency, mineral ballasting, element cycling, deep ocean

Editorial on the Research Topic

The oceanic particle flux and its cycling within the deep water column, volume II

Introduction

The vertical export of biogenic and lithogenic particles from the euphotic zone to the deep ocean constitutes a primary vector for the transfer of carbon, nitrogen, silica, and associated trace elements, thereby regulating the functioning of ocean's biogeochemical cycles and contributing to long-term carbon sequestration. While the "classical" biological pump emphasizes primary productivity and gravitational settling of organic matter (Volk and Hoffert, 1985), decades of research have revealed the high complexity of the particle flux in the ocean, in which particle export efficiency and fate are influenced by ecosystem composition, episodic forcing, mineral ballasting, and chemical transformations during descent (Armstrong et al., 2002; Klaas and Archer, 2002; Buesseler and Boyd, 2009; Guidi et al., 2016; Boyd et al., 2019; Conte et al., 2025; Pedrosa-Pàmies et al.).

The six articles compiled in this Research Topic provide a multi-faceted exploration of these processes, spanning geochemical tracers, long-term sediment trap records, mesopelagic nitrogen cycling, episodic dust deposition events, Arctic climate controls, and ecosystem shifts in a coastal sea. Together, they illustrate both the complexity and diversity of particle flux dynamics across the ocean, while highlighting Research Topic that advance our conceptual understanding of the biological pump.

Geochemical tracers of export production

Mayfield et al. provided a time-series study of barium cycling in the Gulf of Aqaba, integrating measurements of dissolved, particulate, and sedimentary Ba isotopes. Their analysis reveals consistent isotopic offsets between seawater (+0.55‰), sinking particles (+0.09‰), and sediments (+0.34‰). These results refine our understanding of barite

formation and fractionation, a key development because marine barite has long been used as a proxy for past export production (Paytan and Griffith, 2007). By constraining isotopic fractionation across the water column and into sediments, this work strengthens the application of barium isotopes in paleoceanography and deepens our mechanistic grasp of Ba cycling in marginal seas.

Long-term perspectives on carbon sequestration

Lampitt et al. compiled 3 decades of organic carbon flux data (1989–2018) at the Porcupine Abyssal Plain Sustained Observatory (PAP-SO) and estimate an average sequestration rate of $\sim 1.9 \text{ g C m}^{-2} \text{ yr}^{-1}$ at 3,000 m depth, with striking interannual variability ($\text{CV} \approx 73\%$). Variability in flux was not well predicted by net primary production or winter mixing, but instead correlated with the abundance of protozoan taxa such as Radiolaria and Foraminifera. This finding emphasizes the importance of plankton community structure, rather than bulk productivity alone, in determining carbon transfer to the deep ocean. The study highlights how long time-series records provide critical perspectives on ecological controls of the biological carbon pump.

Pathways of nitrogen export

Mino et al. investigated mesopelagic nitrogen dynamics in the western North Pacific by applying an isotopic mass-balance framework at two contrasting sites: the subarctic station K2 and the subtropical station S1. The study revealed that non-gravitational pathways, namely, the mixed-layer pump and the fragmentation of sinking aggregates, contributed substantially to particulate nitrogen (PN) export, together accounting for approximately 20% of the total flux at both locations. The relative contribution of mixing-driven transport *versus* fragmentation was elevated at K2 as compared with S1, reflecting the influence of regional hydrography and ecosystem structure on mesopelagic nitrogen transfer. These findings highlight the importance of transformation processes within the water column in modulating export efficiency, challenging the long-standing view that passive gravitational settling of intact particles is the dominant pathway. By quantifying the role of mesopelagic processing, this study expands our understanding of nitrogen budgets across oceanic regimes and underscores the need to incorporate fragmentation and mixing into predictive models of biogeochemical cycling.

Episodic forcing by atmospheric dust

Kim et al. present sediment trap observations from the Northwest Pacific during 2017–2018, documenting episodic pulses of sinking particle flux coinciding with high dust deposition events. These flux increases were largely decoupled from surface chlorophyll variability, demonstrating that atmospheric dust deposition can stimulate particle export through both nutrient fertilization and mineral ballasting. With biogenic particles accounting for $\sim 82\%$ of flux, the study shows how dust can act as a powerful driver of export flux, independent of local productivity. These findings highlight the

importance of external, episodic forcing in particle cycling, raising critical questions about how changing dust regimes under future climate conditions will reshape deep carbon flux.

Climate modulation of flux in the arctic

Salter et al. investigate interannual variability in mesopelagic and bathypelagic particle fluxes in the Fram Strait between 2000 and 2013, a period marked by pronounced shifts in sea-ice extent and meltwater dynamics. Despite increasing surface chlorophyll concentrations, deep carbon export efficiency declined, driven by reduced diatom-derived biogenic silica fluxes and a greater contribution from lithogenic and ice-rafted particles. This apparent decoupling between surface productivity and export underscores the role of sea-ice dynamics and meltwater in shaping the Arctic particle cycling. The study emphasizes that in polar systems, climate-driven changes in ice cover may diminish export efficiency even in the face of enhanced surface productivity, with profound implications for carbon sequestration in polar oceans.

Ecosystem shifts in the Baltic Sea

Beltran-Perez et al. present a 22-year sediment trap record (1999–2020) from the Gotland Basin in the Baltic Sea, a marginal basin strongly influenced by eutrophication and seasonal stratification. The study shows clear seasonal maxima in spring, summer, and autumn, with isotopic shifts in exported organic matter linked to transitions between diatom- and cyanobacteria-dominated communities. These results demonstrate how community composition can shape both the magnitude and geochemical composition, providing insights relevant to eutrophic systems worldwide. Additionally, the study establishes a valuable baseline for understanding how future ecological changes in coastal and marginal seas will influence carbon and nutrient cycling.

Emerging Research Topic and future research

Collectively, the six contributions to this Research Topic reinforce several emerging themes. First, community composition exerts a significant control over particle flux processes, from protozoan mediation in the open Atlantic to phytoplankton succession in the Baltic. Second, non-classical pathways, including physical mixing, fragmentation, dust deposition, and ice rafting, provide additional controls of export flux that are often independent of or decoupled from surface production. Third, regional and climatic drivers, ranging from atmospheric forcing to sea-ice dynamics, fundamentally shape export efficiency and flux composition. Finally, isotopic tracers such as barium, carbon, and nitrogen are valuable tools to trace particle sources and transformations, bridging contemporary process studies and paleoceanographic reconstructions.

This compilation thus advances our understanding of the biological pump as a highly dynamic and complex system, rather

than a linear function of surface productivity. By integrating ecological, physical, and chemical perspectives across a range of environments, these studies point toward a future where predictive models of ocean carbon cycling must incorporate community-specific processes, episodic forcing, and climate-driven variability. Such efforts will be indispensable for projecting the ocean's role in regulating the global carbon cycle under conditions of rapid environmental change.

Author contributions

RP-P: Writing – original draft, Writing – review and editing. MC: Writing – review and editing. MH: Writing – review and editing. GH: Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The handling editor TE declared a past co-authorship with the authors RP-P and MC.

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