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Sediment Biogeochemistry Model Intercomparison Project (SedBGC_MIP): motivation and guidance for its experimental design

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Abstract:

Benthic biogeochemical models are critical for understanding and predicting seafloor processes that regulate ocean chemistry, carbon sequestration, benthic habitat conditions, and climate feedbacks. However, current sediment models have limited predictive capabilities with widely variable complexity, structure, and underlying assumptions, highlighting a lack of consensus on essential process representations. To address this issue, this paper introduces the Sediment Biogeochemistry Model Intercomparison Project (SedBGC_MIP), a community-driven initiative aimed at systematically comparing existing benthic models against available observational constraints to refine key parameterizations and assess structural uncertainties. We review the state of sediment biogeochemical modeling, highlighting discrepancies in the representation of carbon cycling, burial, and redox remineralization processes across different model complexities. Through case studies, we demonstrate how varying model structures and ecosystem dynamics create uncertainty in global predicted biogeochemical feedbacks. We outline the objectives of SedBGC_MIP, including the need for standardized benchmarking, observational datasets, and cross-disciplinary collaboration to improve model skill and integration into Earth System Models. Ultimately, SedBGC_MIP aims to advance our ability to simulate benthic processes with greater accuracy, enhancing projections of ocean biogeochemistry under climate change scenarios with new capacity to address emerging living marine resource and geoengineering applications.

1. INTRODUCTION

Benthic biogeochemical models are essential for holistic understanding of the Earth system and predicting the emergent behavior through their representation of biogeochemical processes within the seafloor and at the water-sediment interface. These processes play a critical role in determining the chemical state and reservoirs of the ocean (*e.g.,* pH/alkalinity, carbon and nutrient inventories) that regulate the ocean's feedback on climate. Benthic models integrate our state-of-the-art knowledge of these complex systems to investigate relationships between their state and functioning, upscale sparse observations in time and space, and study their response to and interactions with environmental change. Critically, they inform further observational and empirical research needs that recursively drive model development and improvement. While many benthic biogeochemical models have been developed over the last two decades (Burdige and Gieskes, 1983; Rabouille and Gaillard, 1991; Boudreau, 1996; Van Cappellen and Wang, 1996; Soetaert et al., 1996; Archer et al., 2002; Munhoven, 2007; Couture et al., 2010; Paraska et al., 2014; Yakushev et al., 2017; Hülse et al., 2018; Lessin et al., 2018; Munhoven, 2021; Sulpis et al. 2022), they differ in their complexity, structure and context for which they were developed. Furthermore, there is little consensus on how these models must be structured and what processes need to be included to simulate carbon dynamics and sequestration in the benthos at global scales. Most formulations in current models rely heavily on empirical relationships resulting in low prognostic capacity.

The limitations inherent in current sediment biogeochemical models pose challenges to advancing our understanding of processes responsible for benthic carbon cycling. Given the tight coupling between the different biogeochemical cycles in the sediment, a complete understanding of the dynamics and fate of carbon requires consideration of nitrogen, phosphorus, oxygen, silica, metals (Fe and Mn), sulfur, and the ecological interactions mediated by benthic biota (Burdige 2012). In addition, climate change-induced variation of environmental forcings necessitates flexibility currently not found in simulating benthic biogeochemical cycling, necessitating new data and models to explain and predict these changes (Bianchi et al., 2021). Furthermore, significant regional heterogeneity in carbon remineralization and burial - from the coast to the continental shelf to the deep ocean - is critical for balancing the sediment global carbon budget (Regnier et al., 2022). Thus, progress in understanding the ultimate fate of seafloor carbon requires overcoming some of these representational limitations in current state-of-the-art benthic biogeochemical models.

Consider the problem posed by simulating seafloor processes globally within an Earth Systems model (ESM). Coupled carbon-climate ESMs were originally designed to simulate global temperature, including carbon at large scales. Initially, simplistic representation of benthic fluxes was sufficient as computational limitations outweighed the need to refine the models mechanistically. As computing power and resolution has increased, ESMs and regional models are now being used for a wider variety of applications (*e.g.,* coastal applications, carbon sequestration scenarios) (Mathis et al., 2022). Some biogeochemical formulations are also being applied regionally in highly variable coastal systems (Deutsch et al., 2021; Drenkard et al., 2024; Ross et al., 2023), where the global simplifications have not been evaluated nor designed. However, there is an overall lack of agreement regarding the level of complexity necessary to address these regional questions, and whether we are able to address them with the existing tools given the low amount of observations and prognostic capacity to constrain the processes currently oversimplified in the models.

As biogeochemical processes are tied to specific space and time scales, representing the space-time continuum within an ESM presents compelling challenges and opportunities for sediment modelers and observationalists/experimentalists. Customarily, biogeochemical processes within sediments are often treated in only the vertical dimension as most processes are assumed to be controlled by vertical diffusion in porous, non-permeable sediments, and lateral advection is often ignored (Froelich et al., 1979). Thus, sediment biogeochemical models are generally either vertically resolved when considered in local or regional process studies (Boudreau, 1996; Rabouille and Gaillard, 1991; Soetaert et al., 1996; Brady et al. 2013) or vertically integrated, particularly when embedded in ESMs (Soetaert et al., 2000).

Furthermore, many sediment biogeochemical models are developed with steady-state assumptions to simplify the complex processes involved in sediment diagenesis and allow for a more straightforward and tractable mathematical representation of the system (Berner, 1980; DiToro, 2001). Steady state reaction transport models have been used in various ocean settings including coastal, shelf and deep seas to untangle complex biogeochemical cycles in sediments (Bohlen et al., 2011; Rakshit et al., 2025; Soetaert et al., 1996). This steady state assumption, although challenged in temperate and polar regions by many observations of particle dynamics in the water column (e.g., Lochte and Turley, 1988), might be consistent with the timescale of carbon cycling in the seafloor in the deep ocean or on the continental

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shelf (<~ 200m), and thus important for understanding the long-term carbon cycle and the role of the ocean in regulating atmospheric CO_2 levels (Kölling et al., 2019). However, in the coastal ocean, these steady-state assumptions might not be valid and simulating benthic biogeochemical dynamics under the influence of coastal constraints poses a different challenge to sediment modeling. For example, seasonality in organic matter (OM) flux, temperature and/or bottom water oxygen have been shown to be important to water column chemistry (Burdige, 2006; Fennel and Testa, 2019; Glud, 2008; Morse and Eldridge, 2007; Siedlecki et al., 2015). In addition, event-driven processes such as flash floods, storms or resuspension events can drive increased oxygen depletion (Cathalot et al., 2010; Moriarty et al., 2021; Tiano et al., 2024) or alter the distribution of porewater profiles of dissolved inorganic carbon (DIC) and sulphate (SO_4) (Ferreira et al., 2024).

Beyond these fundamental research considerations, the integration of more complex benthic models into ESMs is currently limited due to several factors including: 1) computational efficiency, which limits their spatial and computational resolution, and ability to incorporate complex biogeochemical and ecosystem components; 2) low vertical and spatial resolution in regions where benthic-pelagic coupling is prominent, e.g. coastal ocean and bottom water layer of the deep sea; and 3) reliance on steady state assumptions while non-steady state models are needed to disentangle dynamic processes (e.g., climate change, extreme events) especially along the coast and river-dominated ocean margins (Rhone-RioMAR programme, Toussaint et al., 2014). The limitation of current ESMs to represent coastal processes, including the flow and diagenetic alteration of carbon along the land-ocean-benthos continuum and exchange processes with the open ocean, has driven different initiatives (Ward et al., 2020) within the oceanographic community to better resolve biogeochemical coastal sediment processes in the context of large-scale ESM simulations. Bridging the spatial gap and integrating appropriate temporal dynamics while maintaining the necessary processes that represent benthic fluxes and interactions in contemporary ESMs is an ongoing area of research, and will require a cross-disciplinary approach involving modeling groups and empirical scientists with a common shared objective toward understanding and predicting the benthic marine environment (Lessin et al., 2018). Currently, there is very little consensus on how benthic processes should be parameterized, with clear examples reviewed recently identifying how CMIP models differ in this regard for carbon and alkalinity cycling (Planchat et al., 2023).

The Benthic Ecosystem and Carbon Synthesis working group (BECS), funded by the U.S. Ocean Carbon and Biogeochemistry Program (US-OCB), organized a series of discussions centered around understanding the carbon cycle and ecosystems within the land-to-ocean aquatic continuum with the goal of improving observation and simulation of carbon inventories and cycling in the benthos, and their representation in ocean and climate models. We developed an action plan to fast-track inclusion of this vital environment into ESMs and regional models. We first summarized progress made by the biogeochemical modeling community to simulate sediment biogeochemical dynamics with increasing levels of spatial and process resolution. The end result was a hierarchy of models built for different purposes and applications. Next, we discussed the importance of observations and identified a suite of variables essential for moving the community toward consensus. To advance this field further, we propose a formal sediment biogeochemistry model intercomparison project (SedBGC_MIP), focused on achieving a better understanding of the processes responsible for carbon sequestration, burial, and residence time. This includes

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assessment of the sensitivity of benthic carbon dynamics to model complexity, refinement of structural uncertainty, guidance on what mechanisms are necessary to represent for various applications, and recommendations for how to simulate those processes. Finally, we conclude with our vision of how these new tools could improve our understanding and prognostic capacity around the benthos and global carbon cycles.

2. CURRENT MODELING APPROACHES

ESMs designed to simulate global climate and the associated carbon cycling most commonly implement benthic processes under steady state assumptions to close global carbon budgets. To describe the complexity of benthic models, we split the categorization into biogeochemical and ecosystem complexity depicted in Figure 1. In the most simple, *low geochemical - low ecosystem (Low-Low)* complexity category, most organic and inorganic material that settles to the seafloor is instantly respired or induces an empirically derived flux that returns components to the overlying water column, with little or no ecosystem representation (Figure 1a,d). Some examples of models that employ this strategy are described in detail in Table 1 and include the benthic components of the Carbon, Ocean Biogeochemistry And Lower Trophics (COBALT) model (Stock et al., 2020) and the UVic Model of Ocean Biogeochemistry and Isotopes (MOBI) model (Somes et al., 2021). While these models were designed for and perform well in representing benthic-pelagic exchange on long timescales (e.g., Dunne et al., 2007, 2012), their utility for investigating process-level questions regarding the benthos, particularly at seasonal to interannual timescales, is limited. These models also do not prognostically track benthic material such as carbon and other metabolic products within the sediment, thus limiting their ability to represent feedback processes, hysteresis, or long-term storage of carbon. Specifically, they lack any interaction with bottom water currents or benthic ecosystem dynamics aside from an occasional consideration of bioturbation with an empirically derived diffusive flux associated with this process, making them unable to respond to variability of the internal benthic processes or bottom boundary conditions.

There are a number of models with *high geochemical* but *low ecosystem (High-Low)* complexity (Figure 1a,f), which include vertically resolved sediment biogeochemical processes (FESDIA; Nmor et al., 2022; RADI; Sulpis et al., 2022). Some even include representation of diffusive boundary layer dynamics and material exchange across the sediment-water interface, carbonate chemistry (Sulpis et al., 2022) and coupling with sediment transport capturing dynamic processes such as resuspension and erosion (HydroBioSed; Moriarty et al., 2017). However, many of these models have a limited representation of the benthic ecosystem, specifically the biota that inhabits this region, and rely heavily on parameterizations to describe ecological interaction on reactive transport processes in the sediment (e.g., biological mixing). Some other models could be characterized as medium biogeochemical, low ecosystem, where there are only two vertical layers (*i.e.,* aerobic, anaerobic), but multiple POC reactivity pools, a wide range of solutes and state variables (N, C, P, Si, sulfur), and dynamically-simulated aerobic layer depths (Di Toro 2001; applied within Khangaonkar et al. 2018; Zhao et al. 2012; Wang et al. 2020). In our review, we found that a wide variety of models exist in the *High-Low* category (Table 1) that can be employed to investigate the cycling of various types of organic carbon (e.g., POC and DOC), redox processes within the sediment, as well as resuspension/erosion events in varying degrees. While these models are more computationally expensive, they allow for the analysis of complex feedbacks

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and dynamics in the sediment but are not commonly applied in global ESMs. However, advances in the field of benthic biogeochemical modeling have resulted in an increased utilization of these types of models in regional contexts. For example, HydroBioSed has been used to explore the role of resuspension of sediments in the persistence of hypoxia in the Gulf of Mexico (Moriarty et al., 2018). Despite these advances, these models are still limited in their ability to investigate benthic ecosystem dynamics and their interactions with sediment biogeochemistry, especially during abrupt events on short and intermediate timescale (De Borger et al., 2021), as well as the impact of climate change on benthic macrofauna mediation of elemental cycles (Bianchi et al., 2021).

A more complex suite of models (*medium geochemical, high ecosystem; Medium-High*, Figure 1c,e) enables analysis of a range of biogeochemical feedbacks within the benthic ecosystem. In addition to the description of the geochemistry of solid and solute species in the sediment as found in medium complexity models, these high complexity sediment models include biota functional groups (e.g., aerobic and anaerobic bacteria, meiofauna and macrozoobenthos) interacting with and affecting biogeochemistry (e.g., ERSEM, Butenschön et al., 2016). Although increased complexity is inevitably associated with increased uncertainty and associated observational requirements, these models allow the exploration of questions regarding the role of conservation and sustainability measures alongside those of long-term carbon storage and sequestration. Such questions are increasingly addressed to the modeling community to inform impact assessments and marine spatial planning.

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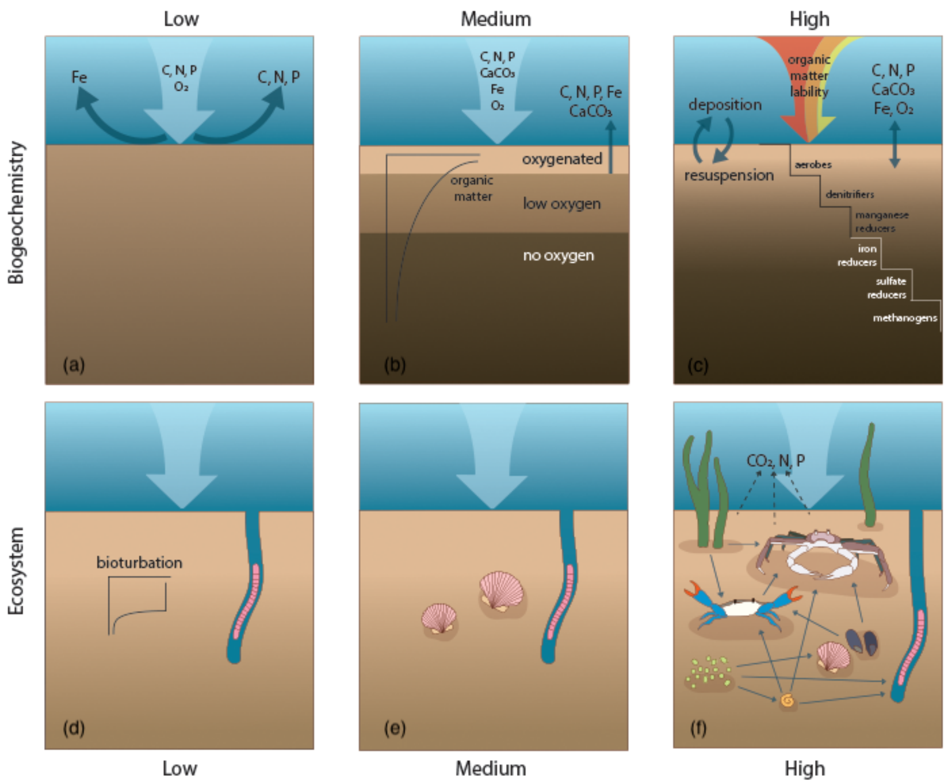

Figure 1: Cartoon illustrating the conceptual framework for our model complexity categories implemented in Table 1. The top row indicates the three complexity levels we consider for the biogeochemistry: (a) Low geochemical, (b) Medium geochemical, (c) High geochemical. The benthic ecosystem: (d) Low ecosystem, (e) Medium ecosystem, (f) High ecosystem. In all cases the organic material delivered to the benthos from the overlying water column is depicted as a light blue arrow. In the most complex biogeochemical case, this material has specific lability as indicated by the different color composition of the arrow. Feedbacks between the benthos and the overlying water column are depicted as dark blue arrows. The degree to which within-sediment resolution is considered is highlighted with color (uniform, coarse layers, or fine gradations). Specific examples of existing models in these categories can be found in Table 1. Illustration by Anne Gutherman (NOAA/GFDL).

3. CASE STUDIES HIGHLIGHTING THE UNCERTAINTIES TO FOCUS ON IN A MIP

The parameterization of benthic models, including the depiction of ecosystem components, can impact the biogeochemistry of the overlying water column and carbon residence time in the benthos. In the following sections, we use several case studies to highlight the importance of benthic system representation in marine ecosystem models and their implication on the dynamics of the overlying water column and carbon cycling. These examples highlight key process level uncertainties and their potential impacts on the global carbon cycle. One urgent need for the

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SedBGC_MIP is that the systematic evaluation of benthic models may improve the skill of the growing suite of coastal regional ocean-biogeochemical models used to investigate climate impacts on fisheries, as shown by the first case study. The second case study compares a detailed benthic model with a low complexity model to highlight current knowledge gaps in benthic processes related to carbon turnover in surface sediments. While both models focus on the change in benthic POC mineralization and DIC production in bottom waters, they result in very different stocks and pathways due to differences in process resolution and formulations, highlighting areas where our understanding needs improvement. Finally, understanding burial efficiencies and carbon turnover times in surface sediments of the global ocean is important for carbon uptake in the surface ocean with implications for marine Carbon Dioxide Removal (mCDR) applications in particular. All of these case studies help underscore the need for a SedBGC_MIP to improve models for benthic carbon cycling.

3a. *Uncertainty in benthic-pelagic feedbacks lead to impacts on water column nutrients in the Eastern Bering Sea*

Benthic processes strongly impact the pelagic ecosystem in shallow coastal regions. One such ecosystem is the Eastern Bering Sea, a wide continental shelf environment with high productivity that supports fisheries, sea birds, and marine mammals. A recent comparison of biogeochemical models in the Eastern Bering Sea found that the structural resolution of benthic processes was the primary control on the amount of total nitrogen retained on the shelf and the amount of ammonium retained below the seasonally stratified mixed layer (Kearney et al., *in review*; Fig. 2). The three biogeochemical models explored in this study included the low-medium complexity BEST_NPZ (Gibson and Spitz, 2011; Kearney et al., 2020), one with an empirical approach (low-low complexity, COBALT; Stock et al., 2014, 2020), and one without a benthic model (Banas et al., 2016). While the bottom boundary was a net nitrogen sink across the shelf in all three models, the strength of that net sink differed by a factor of 2.75 across the three (with net sinks of 0.33, 0.12, and 0.17 mmol N m^{-2} d^{-1} for the Banas, BEST_NPZ, and COBALT models, respectively) and the differing repartitioning of material at the sea floor boundary (Fig. 2) led to ammonium retention that spanned an order of magnitude across the models (0.132, 2.267, and 0.312 Tg N as ammonium, respectively, across the shelf region). The resulting difference in available macronutrient concentration led to high inter-model variability in the magnitude and timing of phytoplankton blooms, particularly with respect to late summer to early fall ammonium-driven production. This had cascading impacts on the rest of the food web with respect to phytoplankton and zooplankton biomass, community composition, and relative distribution across the distinct stratification regimes of the Bering Sea shelf (Kearney et al., *in review*). The biogeochemical framework used in Kearney et al. (*in review*) was designed in part to simulate climate impacts on the ecosystem of commercial and subsistence fisheries that have considerable economic and cultural importance in this region. These often-overlooked benthic processes can impact metrics of interest to research on living marine resources. Kearney et al. (*in review*) also demonstrated the poor ability of any of those simple benthic models to fully capture the observed nutrient environment of the shelf. The model with an explicit but simple and poorly-constrained benthic module led to an ammonium-rich, over productive ecosystem while the other options failed to produce or retain the observed amount of ammonium.

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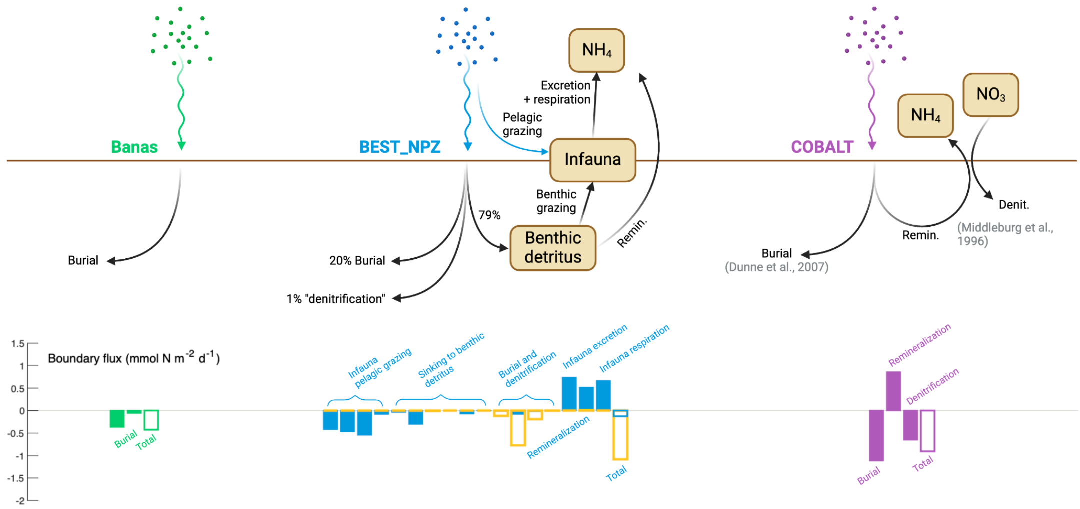

Figure 2: Schematic of bottom boundary processes in the Kearney et al. (*in review*) biogeochemical model intercomparison. The models included one with no benthic representation (Banas, left), one with a two-box benthic model (low-medium complexity, BEST_NPZ, center), and one with an empirical approach (low-low complexity, COBALT, right). In the lower bar graph, solid bars indicate the mean annual flux of material across the boundary (positive from benthic to pelagic) for each process that moves material in or out of the water column; the rightmost white bar in each set depicts the sum of the individual processes for the total net nitrogen flux. Gold-outlined bars in the BEST_NPZ plot indicate the fluxes in a minimal benthos variant simulation, where the 79% of sinking-to-benthic-detritus and pelagic-grazing-by-infauna fluxes are removed; the difference between these bars and the default blue bars indicate the influence of the benthic model on the net benthic-pelagic exchange. Figure reproduced from Kearney et al. (*in review*).

3b. *The complexity of carbon fluxes in the sediments from the English Channel (Western Channel Observatory)*

The choice of benthic model complexity and process resolution can also considerably impact the stocks and fluxes within the benthic system itself, and the type of information that can be derived, which is particularly relevant for decision-making related to e.g. demersal fisheries, offshore structure installations or designation of marine protected areas. Here, we illustrate these differences by applying two benthic models of contrasting complexity within identical water-column settings (Lessin, 2025). One of these models is the standard ERSEM benthic model (*Medium-High*), briefly described in Table 1 (Butenschön et al., 2016). The second model applied is a considerably simpler, so-called 'benthic returns' model (*Low-Low*) which only includes two types of particulate and one type of dissolved organic matter, subject to first-order remineralization. This latter model is comparable to those typically used within ESMs, while the former was developed specifically for shelf sea applications.

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For this experiment, a 1D (water-column) model representing Station L4 (50º15.00’N, 4º13.02’W) of the Western Channel Observatory was implemented. Model forcing and the pelagic system, as provided by ERSEM pelagic modules for biogeochemistry and the General Ocean Turbulence Model (GOTM) for physics, were kept identical; only the benthic models differed. Both simulations were run for a 10-year period and, carbon stocks and fluxes averaged over the last year of simulations were compared (Figure 3).

The *Medium-High* category benthic model (left) revealed the prominent role of benthic biota in organic matter transformation, with meiofauna, despite its relatively low biomass, acting both as the major consumer of semi-labile POC and the main contributor to carbon remineralization. It also highlighted a close coupling between semi-labile POC and suspension feeders, where the latter effectively consume freshly deposited organic matter and, via excretion, moderate biological activity in the deeper sediments. Additionally, respiration and remineralization fluxes contributed to the pore water DIC pool, which is exchanged with its pelagic counterpart via diffusion. None of these intricate dynamics could be resolved in the *Low-Low* ‘benthic returns’ model (right), where semi-labile POC is converted directly into pelagic DIC, as the main purpose of this model formulation is to return inorganic nutrients back to the water column. Therefore, this simple approach has very limited utility in advancing understanding of benthic system functioning and controls on carbon transformations within sediments and across the benthic-pelagic boundary, and is insufficient to characterize shifts in fluxes due to impacts of climate change or human activities, such as trawling, on the benthic communities.

While a more complex model provides a more detailed picture of the benthic dynamics, it brings about considerable additional sources of uncertainty as it requires additional knowledge for the parameterizations and rates of numerous processes not represented in the simpler model that can have significant implications for the outcomes, such as diet compositions, vertical distributions of living organisms and affinity of bacteria to different types of POC (Lessin et al., 2019). This uncertainty is reflected in the different modeled standing stocks of benthic POC in the two simulations, as first-order POC remineralization constants of the simple model cannot directly translate to the multiple biota-mediated remineralization pathways represented in the more complex model. These differences in process representation and resultant uncertainties highlight the need for a structured approach to model comparison that would identify the level of complexity appropriate for different applications, quantify uncertainties across model structures, and establish benchmarks for evaluating when increasing model complexity delivers improvements in the quality of outputs.

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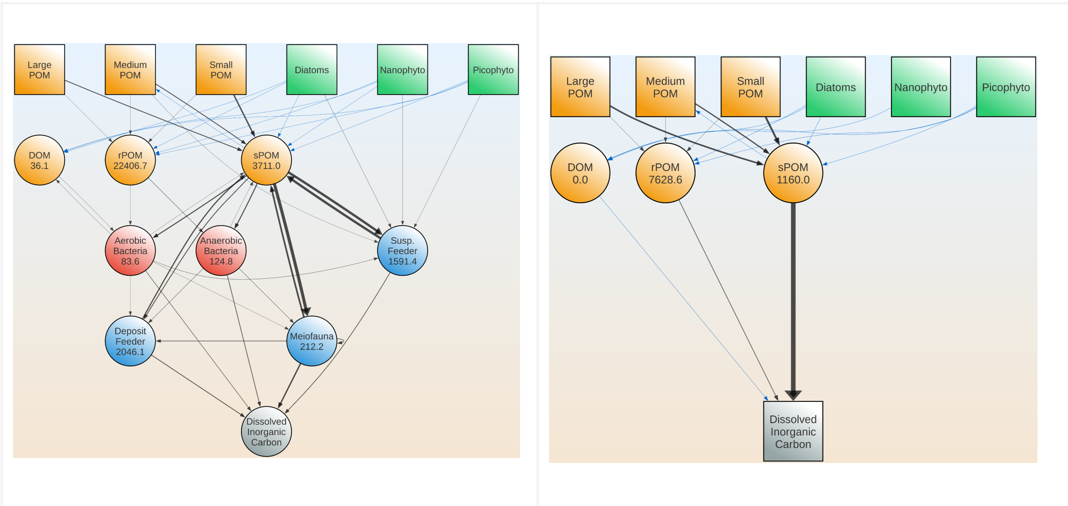

Figure 3. Comparison of annual average carbon fluxes in two variants of ERSEM benthic model (Lessin 2025): standard (left) and simplified (right) applied to Station L4 of the Western Channel Observatory. Gray arrow thickness: relative magnitude of carbon flux. Thin blue arrows: fluxes that were not realized. Boxes: pelagic (water column) variables, circles: benthic (seafloor) variables, indicating average carbon stock (mg C/m²). rPOM refers to the refractory, while sPOM to the semi-labile POM pools. Note that in the standard model, respiration contributes DIC to the benthic pore water pool, while in the simplified model, it contributes directly to the pelagic pool.

3c. A case study of the role of benthic fluxes on net primary production (NPP) and surface CO_2 fluxes

To understand the potential influence of sediment on global ocean biogeochemistry, we used the COBALT model (*Low-Low*) to perform a series of model experiments (Rakshit & Luo, 2025). The standard COBALT model (Stock et al., 2020) (control run) has a reflective sediment boundary, where a fraction of the deposited organic matter (OM) is instantly remineralized into equivalent DIC and nutrients and returned to the bottom water, while consuming the equivalent oxygen from the bottom water. The remainder of the OM is permanently buried following Dunne et al. (2007). The standard COBALT model is also equipped with empirical relationships to represent benthic denitrification (Middelburg et al., 1996) and benthic dissolved iron release to the bottom water (Dale et al., 2015).

Here, we explore two model experiments, one where the ocean bottom acts as complete burial sink, and the other where it acts as a mirror. In the first, "*allburial*" case, all the OM reaching the seafloor is completely buried, providing no benthic feedback to the bottom water. In the second, "*noburial*" case, OM reaching the seafloor is completely reflected, *i.e.* regenerated DIC, nutrients, and dissolved iron are returned to the bottom water, and the equivalent oxygen is consumed. In both cases, benthic denitrification and dissolved iron fluxes are excluded. We compared the experimental simulations with the "*control*" which was the base run detailed in (Stock et al. 2020).

We ran the GFDL MOM6-SIS2-COBALTv2 model to perform the above experiments and control simulations for 60 years starting in 1948 with CORE II interannual forcing (Large and Yeager, 2009) at a ½ degree nominal resolution.

The mean of the last 20 years of simulation is reported in the following results. To understand the influence of benthic feedback on the ocean biogeochemistry, we specifically looked at three metrics, namely depth integrated dissolved inorganic nitrogen (int DIN), net primary production (NPP) and surface CO_2 flux.

The integrated DIN in the *allburial* case was generally lower than the *control,* while the *noburial* case was higher. These effects were most prominent in regions with shallower depths, such as coastal and shelf seas, as greater OM concentrations reach the seafloor compared to abyssal depths. These results are expected because in the *allburial* case, the nutrients contained in the OM leave the model system (via burial), while in the *noburial* case, all the nutrients in the deposited OM return to the water column. Consequently, the NPP in the *allburial* case is lower when compared to the *control* run, while the *noburial* case had higher NPP. These differences are likely due to the nutrient availability described by the DIN metric. Interestingly, the NPP was lower than the *control* in the Southern Ocean for both the experiments. The Southern Ocean is a high nutrient low chlorophyll (HNLC) region where primary production is iron limited. Unlike the *control* case, the model experiments did not include empirical benthic dissolved iron efflux (Dale et al., 2015). This indicates that benthic dissolved iron release is a major source of dissolved iron in the ocean and plays a crucial role in controlling the NPP. This effect is more prominent in the Southern Ocean where the other sources of iron (e.g. dust deposition, river runoff) are minimal.

Interestingly, the oceanic sink of CO_2 was larger in the *allburial* case and lower in the *noburial* case compared to the *control*. These results show that even though the *allburial* case had lower NPP, it led to greater uptake of atmospheric CO_2. In other words, burying OM in sediment acts as a significant mechanism of C-sequestration that has the potential to increase new CO_2 net uptake by the surface ocean, but at the expense of NPP, which is reduced because of lower nutrient availability. However, we do not yet understand how efficient burial should be, part of the central focus of the questions raised here.

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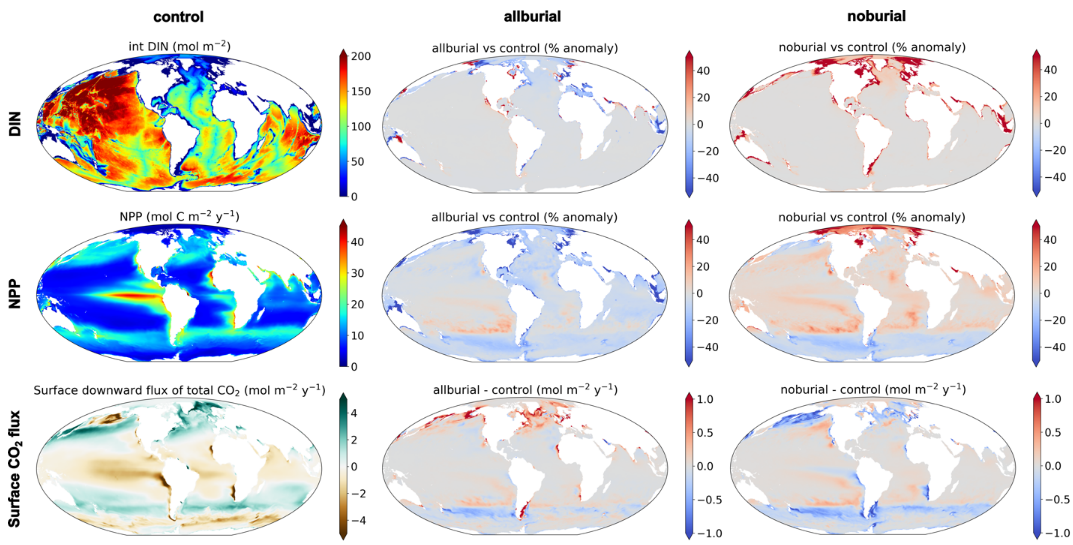

Figure 4: Model experiments with COBALT in an ESM (Rakshit & Luo, 2025). The "*control*" indicates the standard model run. The "*allburial*" and "*noburial*" cases are two experiments designed to better understand the biogeochemical influence of organic matter burial on several water column metrics: dissolved inorganic nitrogen (int DIN), net primary production (NPP) and surface CO_2 flux. The model experiments are shown as anomalies compared to the control run.

4. MODEL INTERCOMPARISON PROPOSAL – SedBGC_MIP

As discussed above, there is a need for further development of the benthic processes within biogeochemical models, to improve our understanding of ecological and biogeochemical processes in the ocean. A first step to facilitate this development is a systematic characterization and comparison of current benthic models with particular attention to their ability to capture relevant biogeochemical/ecological processes specific to answer societally relevant research questions. Our proposed approach entails concerted efforts to curate, benchmark, and assess model performance in a formal and holistic manner in the form of model benchmark analysis. This proposed intercomparison effort follows the structure of a community-driven model intercomparison project and associated activities. This initiative - similar to other attempts like the coupled model intercomparison project (CMIP; Eyring et al., 2016), its ocean carbon cycle equivalent (OCMIP; Doney et al., 2004), the fish and marine ecosystem model intercomparison project (Fish-MIP; Tittensor et al., 2018), the iron model intercomparison project (FeMIP; Tagliabue et al., 2016), the carbon dioxide removal model intercomparison project (CDRMIP; Keller et al., 2018), and other groups within the Inter-sectoral Impact Model Intercomparison Project (ISIMIP; (Frieler et al., 2017) can benefit the benthic modeling community by increasing the understanding of how current models compare both in their fidelity to observations and structures, parameters, and spatiotemporal dynamics.

The goal of a Sediment Biogeochemical Model Intercomparison Project (SedBGC_MIP) is to identify and improve the key model parameterizations and formulations to upscale and extrapolate site-specific models to the resolution of current ESMs. Such model intercomparison facilitates the community recommendation for targeted observational

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campaigns and process studies to improve understanding of various benthic processes across the global seafloor and provides a path for achieving consensus and reducing model structural uncertainty. Quantifying performance of benthic models would promote confidence in their predictions of the future of marine ecosystem dynamics and the ocean carbon budget and identify areas for further improvement in our understanding of benthic processes.

This model intercomparison (MIP) would be developed based on our current suite of models with a need for refinement. It would utilize and identify observational data sets for evaluation and include a gap analysis to inform future observational efforts. A sediment model intercomparison would focus on the following questions:

- How much structural variability and uncertainty is present across the benthic models? Is model skill related to structure?
- Are there systematic model biases in sediment total organic carbon (TOC) stock and other related processes (*e.g.,* surface and burial flux, mineralization/oxygen consumption rates) and where do they originate? Do these differ in coastal and deep seafloor environments?
- What are the consequences of model biases on sediment organic carbon storage and cycling? Are the effects of these biases systematic across models and how can they be reduced?

Model assessment can constrain uncertainty in model ensembles, provide support for model projections, and spur model development. Model intercomparisons create ensembles of simulations used to quantify model variability and uncertainty and can be used to perform sensitivity analyses in a systematic way. The heterogeneity of structure and parameterization across biogeochemical and ecological models of the benthos suggests a high potential for large structural uncertainty or potentially a lack of a unified mechanistic understanding of their dynamics. Many of these models were likely generated for other reasons - not focused on carbon dynamics in particular. This heterogeneity could be a strength, such that an ensemble of diverse models would span a greater number of relevant processes and better represent future states than any one model, something an intercomparison could inform. Finally, the results of the initial MIP will most certainly help inform observational needs moving forward, as such a close collaboration with observational communities is essential throughout this iterative process.

4.1.1. THE IMPORTANCE OF OBSERVATIONS

Observational and experimental datasets are required to improve our understanding of benthic processes, implement model assessment, and enhance performance of benthic sediment models. To be successful, reference observations to ground-truth simulated output will need to be established via collation of existing as well as new data sets. Some syntheses of benthic observations exist for some relevant variables including sediment oxygen demand (Jorgensen et al. 2022), sulfate and sulfate reduction (Jorgensen et al. 2024), but new observational products will be required. In the proposed community-driven model intercomparison, the focal variables capture or relate to key biogeochemical processes thought to be important for benthic carbon dynamics, and will be agreed upon by MIP participants, but a preliminary list was identified here. The modeling community present at the BECS workshop identified a set of common key observations that are used to force sediment models, are key output variables from the models for

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evaluation, and/or that facilitate the comparison of important sediment processes (Table 2). These datasets are especially useful because often models can be calibrated to mimic the observational dataset for empirical reasons without mechanistic justification or be calibrated to fit specific locations or quantities that might not extrapolate to other locations. Further, a select list of model diagnostics was chosen by the BECS workshop attendees as a starting point: benthic O_2 flux, nutrient fluxes, organic carbon content of the surface sediments, $CaCO_3$ content of the surface sediments, total carbon remineralization rate, and benthic primary production rate. None of the listed variables are currently available from the CMIP6 diagnostic list, but some of them could be provided as they are provided at other ocean depths. Some variables were recently formally requested as part of the public call for diagnostic variables from CMIP7 (e.g. nutrient fluxed -N, P, Fe, Si; organic carbon content of the bottom waters, organic detritus concentration and sinking flux of POC, CaCO3 in the bottom waters). Additional variables, which will be requested in the future as part of this MIP, will be entirely new variables to CMIP. This initial set was based on the feasibility of collection or availability of the observations as well as the utility of the results for multiple comparisons of model diagnostics. For the models with more complex ecosystem components, benthic biomass and community structure alongside species and community-specific metabolic rates are also critical diagnostics.

For the SedBGC_MIP objectives to be properly realized, observations are critical. There was a clear need identified at the BECS workshop for a suite of sustained long-term observations/stations, mesocosm experiments, and process studies (Schultz et al. in review) that would enable a more mechanistic understanding for the *High-High* complexity model structures. Indeed, a minimum of 3-5 years of sustained observations (at one station but ideally at a set of contrasting locations) would reveal patterns in seasonal variability and enable a suite of models to be parameterized and assessed. However, few benthic locations are sites of long-term observing. Examples include the Ocean Observatories Initiative (OOI; Tryon et al., 2001), and NOAA coastal cruises (USA, Frenzel et al., *in prep*) coastal cruise observing sites as well as Mesurho station (France; Rhone-RioMAR programme, Toussaint et al., 2014), but these sampling programs are focused on the coastal ocean. Unfortunately, only a few observing stations (e.g., Station M (Smith et al., 2018) are equipped with similar monitoring breadth on the deep seafloor and historically have been used to suggest the system is largely steady without much seasonal variation (Smith et al. 1996). This discrepancy in benthic data density between coastal locations and open ocean deep seafloor sites should stimulate further collaborative efforts to cover this data gap in the future.

4.1.2. VISION FOR CONSISTENT BENCHMARKS AND PROTOCOLS

The next step for a SedBGC_MIP would be to create a protocol for intercomparison experiments. In existing MIP protocols, individual models are forced by the same environmental drivers at a specified spatiotemporal scale and then one or several outputs of the individual models are compared, again at the same spatiotemporal scale. This requires identifying common forcing variables and common outputs across models. Standardization of model forcing in a centralized manner will ensure that all participating models operate from common baseline conditions. Forcing variables provided by the same source such that they are internally consistent (*e.g.,* particulate organic matter deposition/seafloor flux, primary production, phytoplankton biomass, chlorophyll from the same pelagic BGC model),

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but the specific forcing each model structure requires will differ. Similarly, model output variables will differ depending on the model structure but can be processed into equivalent diagnostic metrics. These model outputs are often concentrations (*e.g.,* total particulate organic carbon, total benthic consumer biomass) and fluxes or rates (*e.g.,* oxygen flux, remineralization rate). Thus, to start a MIP, there will be a trial and error phase as a set of forcings is proposed and iterated upon as different modeling centers provide feedback on their model forcing requirements. As part of that process, participating models must be thoroughly reviewed and synthesized to determine potential inputs and outputs and then select scenarios. In some cases, at the global scale, these reviews exist (*e.g.*, Seferian et al. 2016; Seferian et al. 2020; Planchat et al. 2023) and thus can be analyzed with benthic processes in mind, but the coastal/regional models have not been included in these reviews. This process is improved by understanding the region where each model was developed/parameterized/applied, its purpose (what questions does it seek to answer), and its strengths and weaknesses.

MIPs often start with a set of standard tests for benchmarking the participating models. The benthic modeling community can adopt this framework for model assessment, which would be useful to the benthic modeling and observation communities alike, as the observational community can better understand critical observations for modeling. Model benchmarking can take the form of evaluating models against a common set of data, which can be either observational or experimental in nature. The goal is not to define which is the "best" model, but to advance understanding of the capabilities of our models and allow model developers to identify areas for improvement. Furthermore, model intercomparisons can enable a community to establish minimal standards for model performance for certain applications, which can be especially useful for achieving the near-term goal of improving the representation of benthic biogeochemistry in current ESMs.

Essentially, any such benchmark should focus on the central variables and fluxes identified by the community of end users as the most important for a model to capture, or variables that demonstrate whether a model accurately captures a critical process. At a minimum (to support the model level *Low-Low* as described in section 2 and Figure 2), these model outputs should include: benthic oxygen (O_2) flux, carbon depositional flux, burial flux, and the sediment diffusive fluxes of nutrients (e.g., nitrate (NO_3), ammonium (NH_4), and phosphate (PO_4)). These output variables of benthic sediment models are essential for water-column carbon cycling and biogeochemical processes represented in ESMs (e.g., Figure 4). Further forcing and output variables might be desired depending on the problems/questions being addressed, which may require a higher level of model complexity (model levels *Medium* and *High*). To avoid these issues, there must be agreed-upon skill metrics that allow multiple models to be statistically compared while also allowing individual model performance to be tracked over time.

Finally, current benthic models are developed with a focal spatial scale for their respective application (see Table 1) ranging from 0D global benthic models with vertically integrated biogeochemistry to 1D vertically resolved and coupled benthic-pelagic models for local/regional modeling. How these models are compared will be critical for a successful SedBGC_MIP. Moreso, many benthic models are not coupled to a pelagic model. Those not coupled are written in a variety of programming languages that may be incompatible with the pelagic models, presenting a

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challenge for examining two-way pelagic-benthic dynamics. However, unifying frameworks are available (FABM, Bruggeman and Bolding, 2014), that could allow for multiple benthic models to be forced by the same pelagic regional or global model forcing. A successful benthic-focused MIP can borrow from lessons learned in other adjacent domains where similar issues/solutions exist.

5. THE FUTURE OF BENTHIC MODELING

The ultimate goal of the BECS community is to simulate benthic processes responsible for the cycling of carbon at the seafloor more realistically with prognostic capabilities rather than diagnostically as they mainly are now. In reality, benthic components and/or species functions regulate surface sedimentary organic carbon cycling, and the cumulative effect of these drivers on biogeochemical processes and their feedback into the overlying water column is at an early stage of understanding relative to the pelagic BGC community. Prognostic/predictive in this context refers to more ambitious biogeochemical and ecological forecasting of benthic processes rather than just fitting a specific dataset. Forecasting could even include data assimilative models in the benthic environment that could be capable of tracking the carbon inventories of surface sediments in real time. This near-term iterative forecasting coupled with synthesizing new and existing data can lead to rapid exploration of competing hypotheses regarding carbon transformation on the seafloor as well as potential feedback processes emerging from pelagic-benthic coupling and temporal lags in sediment-water interactions. This would include the development of models capable of simulating the diverse spatial and temporal dynamics that occur on the seafloor. As previously stated in Section #4 (on observations), the availability of data for evaluation and the development of process-level understanding is critical to further model development, as we can only begin to simulate future changes in benthic fauna and biogeochemical properties if we can reliably simulate the current state with convincingly robust process representation - including past changes (Ehrnsten et al., 2020). In this regard, increased collaboration between observational and modeling communities cannot be overstated.

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TABLES:

Table 1: Examples of models with different simulation strategies to represent benthic processes. Coupled ocean and pelagic biogeochemical models are referred to as “3D pelagic models”.

Complexity Level (BGC first, ecosystem second)	Model Name / Reference	Model Type	Spatial Extent	Vertical Resolution	Temporal Range	Number of Tracers	Benthic and pelagic exchange	Redox Processes Represented	Ecosystem Processes Represented
Low-Low	Somes et al. 2021 - UVic-MOBI	3D pelagic, vertically integrated benthic model	Global	0D sediment metamodel fluxes	Multimillennial	None	None	Empirical benthic denitrification and iron reduction	None
Low-Low	Stock et al. 2020 - COBALTv2	3D pelagic, vertically integrated benthic model	Global	0D metamodel for calcite; 0D benthic layer for organic matter	Multidecadal to Multimillennial	None	Benthic reflective layer	Empirical benthic denitrification and iron fluxes; Sulfate reduction represented as negative oxygen when nitrate is depleted	None
Low-Medium	Gibson and Spitz, 2011 - BEST_NPZ	1D/3D pelagic with 1D benthic	Bering Sea	1-layer benthic	Multidecadal to Multimillennial	1 solid, 1 infauna	Particulate deposition, Burial, Benthic detrital remineralization	None	Infauna grazing and respiration
Low-Medium	Yool et al. 2017 - BORIS	0D size-resolved benthic biomass model	Global	0D	Multidecadal to Multimillennial	16 size classes of metazoans	None	None	None
Medium-Low	Heinze et al. 1999	Coupled 1-D sediment model	Global	10-layer benthic resolution	O(100) years	6 Sediment Pore Water; 8 Solid Sediment	None	None	Bioturbation represented as a diffusive factor

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Complexity Level (BGC first, ecosystem second)	Model Name / Reference	Model Type	Spatial Extent	Vertical Resolution	Temporal Range	Number of Tracers	Benthic and pelagic exchange	Redox Processes Represented	Ecosystem Processes Represented
Medium-Low	Cerco et al. 2010	3D pelagic with 2D benthic	Regional Seas, Estuaries	2-layer benthic resolution	Seasonal, Annual, Interannual	8 Sediment Porewater, 12 Solid Sediment	Particulate deposition, burial, remineralization, exchange of inorganic nutrients and gases	Anaerobic remineralization; Nitrification; Denitrification; Sulfate Reduction, Methanogenesis, Phosphorus and silica sorption-desorption	Bioturbation represented as a mixing and diffusive factor based on POC
Medium-High	Butenschon et al. 2016 - ERSEM 15.06	Modular 1D/3D benthic + pelagic model	Global and regional seas	3 implicitly resolved redox layers, benthic POM follows an exponential distribution	Annual to Multimillennial	35 benthic variables	POM deposition and resuspension, Diffusive exchange flux of dissolved inorganic nutrients	Aerobic and anaerobic remineralization; Nitrification; Denitrification	Aerobic and anaerobic bacteria; Deposit feeders; Suspension feeders; Meiofauna; Optional benthic predators
High-Low	Moriarty et al. 2017 - HydroBioSed	1D Coupled benthic + pelagic model	Rhone River Subaqueous Delta	1 Active Transport layer 19 high res layers 39 medium res layers 1 repository layer	Daily, Seasonal, Yearly	2 solids; 4 solutes	Age of POM/nutrients in the seabed, Resuspension and redistribution of the OM and nutrients,Incorporated aggregation of detritus, Seabed–water-column diffusion	Oxic and anoxic remineralization; Other oxidants in one process	None
High-Low	Nmor et al. 2022 - FESDIA	1D Sediment Model	Rhone River Mouth, France (river-dominated coastal margins)	100-layer vertical grid increasing geometrically	Daily, Seasonal, Yearly	3 solids; 8 solutes	Diffusive exchange flux of dissolved inorganic nutrients from Benthic to Pelagic	5 redox steps in the primary reaction; 5 in the secondary reaction	Parameterized bioturbation and bioirrigation

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Complexity Level (BGC first, ecosystem second)	Model Name / Reference	Model Type	Spatial Extent	Vertical Resolution	Temporal Range	Number of Tracers	Benthic and pelagic exchange	Redox Processes Represented	Ecosystem Processes Represented
High-Low	Sulpis et al. 2022 RADI	1D Sediment Model	Global application	User-defined	Daily to Multimillenial	8 solids, 11 solutes	Diffusive exchange flux of dissolved inorganic nutrients from Benthic to Pelagic	Organic-matter degradation using O_2, NO_3, MnO_2, $Fe(OH)_3$, SO_4; Methanogenesis; Oxidation of Fe, Mn, H_2S, NH_3	Bioturbation and bioirrigation
High-Low	Ye et al. - FESOM-RECOM-MEDUSA / Munhoven 2021 MEDUSA	3D Coupled benthic + pelagic model	Global	21-layer diagenesis model	?	(MEDUSA)"(must be configured to fit the complexity requirements of a give application"	None	Calcite, opal, and POM reach sediment where remin. + bioturb generate dissolved DIC, DIN, Alk, DSi, and O_2	Bioturbation is represented as a diffusive process

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Table 2: Common and essential variables that could inform and be compared between different models

Model Level/Tier (Linked to the table on model levels of complexity)	**Common input/Forcing (From ESM)**	**Common output/Fluxes (From Sediment models)**	**Possible variables for evaluation**
Low-Low	Bottom water temperature, salinity, O2, and nutrients, Export production/flux of POC	Benthic O2 flux, Burial flux of carbon, Diffusive fluxes of NH4, NO3, PO4, DIC	Benthic O2 flux, Total carbon remineralization rate
Medium-Medium	Bottom water inorganic nutrients, Sinking fluxes of PON and DON, Sediment porosity (Grain size)	Diffusive fluxes of dissolved silicate and metals (e.g., Fe), Oxic layer depth, Nitrification rates, Denitrification rates. Benthic biomass	DIC flux, Total Organic Carbon (TOC) content, Benthic biomass, Porewater profiles
High-High	Bottom water alkalinity, Bottom shear stress,	Diffusive fluxes of Alkalinity, Calcite and Opal concentrations, Benthic community structure	Alkalinity flux, Benthic carbon uptake, Benthic primary production, Community composition, Porewater profiles

Code Availability: The COBALTv2 model was retrieved from Github repository: https://github.com/NOAA-GFDL/ocean_BGC . ERSEM model code is available at https://github.com/pmlmodelling/ersem, FABM framework available at https://github.com/fabm-model/fabm and GOTM source code available at https://github.com/gotm-model/. Source code and supporting data for the Kearney et al. (in review) implementation of ROMS with 3 biogeochemical models can be found at https://github.com/kakearney/supplementary-data-bgcmip.

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Data Availability: No new observations were generated as part of this work. The exact version of the model used in the case study surrounding the results described in Kearney et al. (*in review*), to produce the results used in this paper is archived on Zenodo under DOI (10.5281/zenodo.15015214, Kearney et al. 2025b), as are input data and scripts to run the model and produce the plots for all the simulations presented in this paper (Kearney et al. *in review*) and https://github.com/kakearney/supplementary-data-bgcmip/. The results used in this paper for the case study with ERSEM are archived on Zenodo under DOI link 10.5281/zenodo.15235658 (Lessin 2025). The results used in this paper for the case study with the global model experiment is archived on Zenodo under DOI link 10.5281/zenodo.15224380 (Rakshit & Luo, 2025).

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