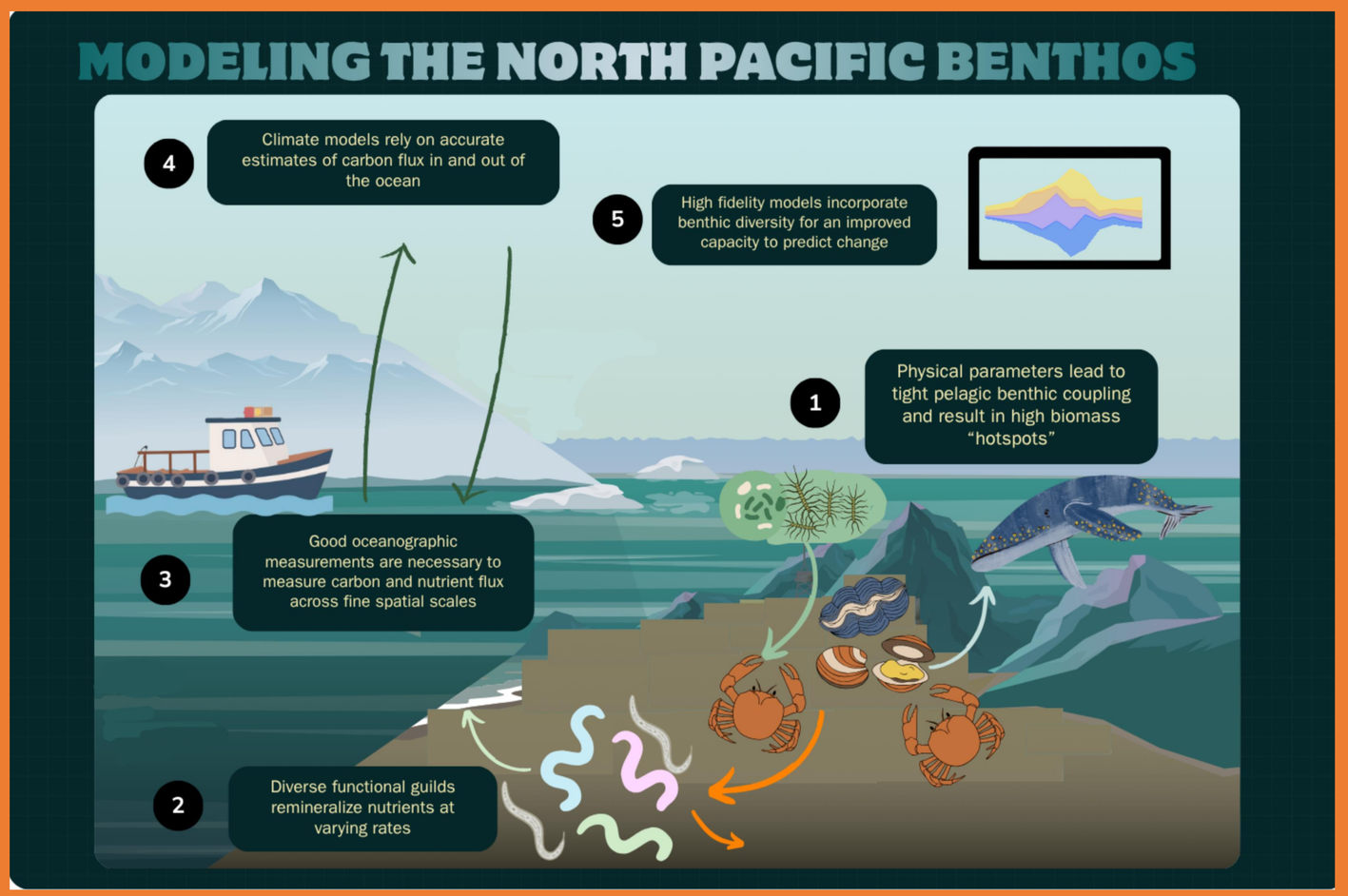
Integrating fine-scale benthic processes into ESMs is essential for improving projections of regional and global climate changes.

Zoë Bolling

University of Alaska Fairbanks

zmbolling@alaska.edu

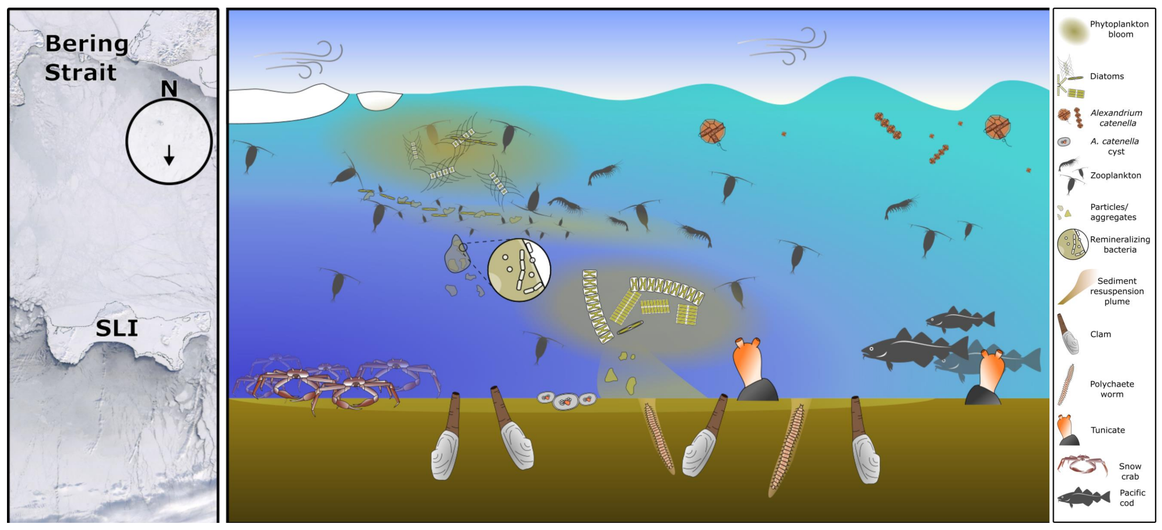
Sarah Mincks' Benthic Ecology Lab



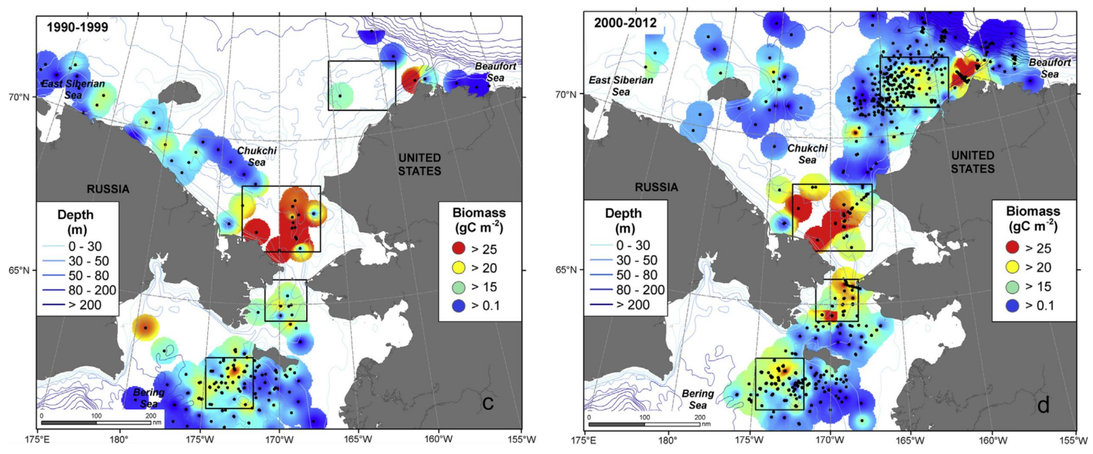
Sea floor sediments regulate carbon remineralization, oxygen consumption, and nutrient regeneration. These processes are often simplified or omitted in large-scale models. Better predictions require more targeted data collection in the field and integration into ESM's.

The seafloor is not a boundary condition or a black box. We must include benthic processes in ecosystem models.

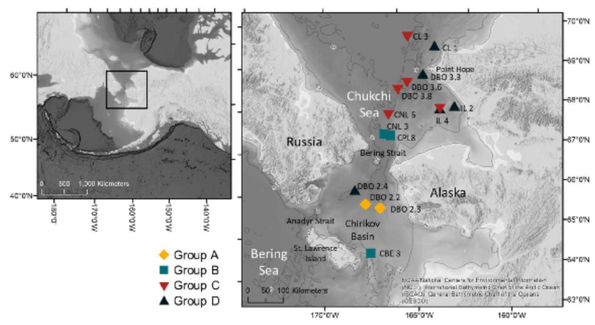
1 Seasonal sea-ice dynamics, shifting atmospheric wind patterns, converging water masses, and water column stratification drive extreme spatial heterogeneity and tight pelagic-benthic coupling across the North Pacific.

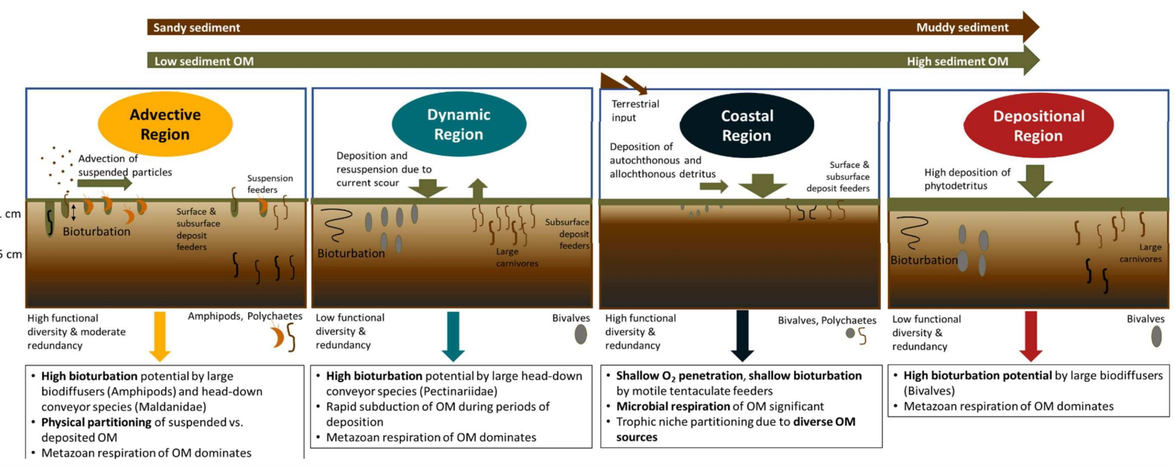


2 Physical drivers support persistent macro-benthic "hotspots" defined by high biomass and diverse community assemblages, leading to spatially variable carbon flux, oxygen demand, and remineralization rates.

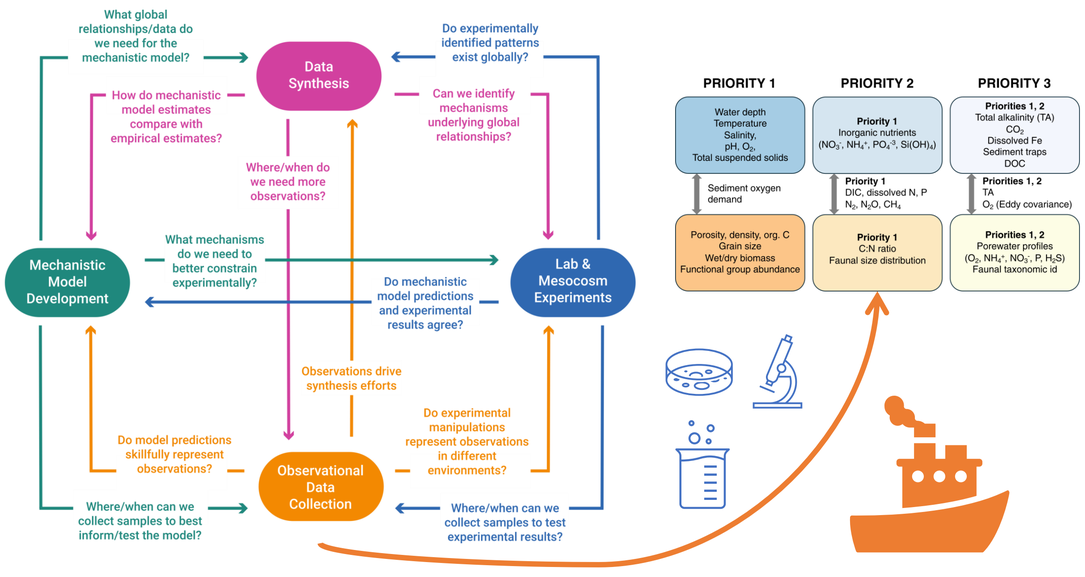


3 Functional guilds within community assemblages provides a proxy measurement for organic matter flux and nutrient cycling, as different guilds respire and remineralize nutrients at heterogeneous rates.





4 Future research should measure variables prioritized through working groups, conduct *in situ* and *ex situ* experiments to quantify changing process rates, and utilize new technologies to expand *in situ* sampling to better parameterize biogeochemical cycles in the benthos.



Abstract

Current Earth System Models and climate prediction frameworks do not characterize benthic processes with consistency or fidelity. Although sediments regulate carbon remineralization, oxygen consumption, and nutrient regeneration, these processes are often simplified or omitted in large-scale models. Addressing this limitation requires clearer conceptual integration of benthic heterogeneity and pelagic–benthic coupling into predictive models. The Pacific Arctic benthic ecosystem serves as a primary example of these modeling challenges. Seasonal sea-ice dynamics, shifting atmospheric wind patterns, converging water masses, and water column stratification drive extreme spatial heterogeneity and tight pelagic-benthic coupling across the region. These physical drivers support persistent macrobenthic "hotspots" defined by high biomass and diverse community assemblages, leading to spatially variable carbon flux, oxygen demand, and remineralization rates. These hotspots also differ in resuspension rates, bioturbation, and nutrient cycling in the water column, which creates a dynamic sediment-pelagic boundary. At finer scales, identifying functional guilds within community assemblages provides a proxy measurement for organic matter flux and nutrient cycling, as different guilds respire and remineralize nutrients at heterogeneous. Incorporating functional diversity into benthic parameterizations may therefore improve representation of sediment biogeochemistry in next-generation models. Future research should measure variables prioritized through working groups, conduct *in situ* and *ex situ* experiments to quantify changing process rates, and utilize new technologies to expand in situ sampling to better parameterize biogeochemical cycles in the benthos.

Figures

1. Conceptual model showing ecosystem effects of stratified conditions typical of colder, heavier-ice. Panel shows prevailing ice conditions during a cold (2012) winter in late February/early March (NASA Worldview); dial and arrow indicate wind direction and magnitude. Colder conditions allows for particle accumulation at the density stratified interface, concentrating zooplankton grazers, and allowing for two distinct phytoplankton bloom communities to form above and below the pycnocline.

2. Decadal distribution of macrofaunal benthic biomass in the northern Bering and Chukchi Seas for the time periods:, (c) 1990–1999, (d) 2000–2012. Black boxes identify the four benthic bounding boxes used in our study with >20 g C m2 station biomass that occurred during one or more of the decades in our study region. Specifically, these bounding boxes from south to north are: SLIP (St. Lawrence Island Polynya region) hotspot, Chirikov (Chirikov Basin) hotspot, SECS (Southeast Chukchi Sea) hotspot, and NECS (Northeast Chukchi Sea) hotspot. *Reprinted from*: Grebmeier, J. M. (2015). Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Progress in Oceanography, 136, 92–114. https://doi.org/10.1016/j.pocean.2015.05.006

3. Summary of four benthic eco-regions identified based on spatial patterns in polychaete functional guilds. Regions are arranged from left to right along a gradient of sandy substrate with low OM to muddy substrate with high OM. Upper boxes indicate the nature of particle deposition to the seafloor. Color gradient in lower boxes indicates approximate depth of bioturbation and oxygen penetration. Taxa referenced in lower right corner of each panel indicate biomass dominants for each region. Polychaete functional guild diversity and redundancy levels are listed in the lower left of each panel. Text boxes highlight inferences made regarding differences in ecosystem function among regions, providing a series of testable hypotheses. Advective Region (yellow, Group A): Moderately fast currents transport suspended particles, supporting high abundance of suspension feeders. There was high abundance of small-bodied macrofauna with low biomassdominated by amphipods and polychaetes. There was high abundance of small-bodied polychaetes in the surface layer; biomass maximum at 5-10 cm. Polychaetes were dominated by surface and subsurface deposit feeders and large tube-dwellers. Dynamic Region (blue, Group B): High current speeds scour and resuspend surface sediment, with deposition during periods of less energetic flow. Abundant large-bodied macrofauna with high biomass dominated by bivalves. High surface abundance of small-bodied polychaetes with a biomass maximum at 1-5 cm. Polychaetes dominated by large carnivores and subsurface deposit feeders. Coastal Region (black, Group D): High export flux of local and advected detritus, including terrestrial material. Low abundance and biomass of small-bodied macrofauna, with biomass dominated by bivalves followed by polychaetes. Dominance of small-bodied polychaetes concentrated in surface sediments, dominated by subsurface and surface/subsurface deposit feeders. Depositional Region (red, Group C): Low abundance of large-bodied macrofauna leading to high biomass dominated by bivalves and large-bodied carnivorous and subsurface deposit-feeding polychaetes. Maximum abundance and biomass in deeper sediment layers. Evidence of bioturbation homogenizing sediment conditions. *Reprinted from*: Charrier, B. J., Danielson, S. L., & Mincks, S. L. (2023). Trait-based assessment of polychaete assemblages distinguishes macrofaunal community structure among four distinct benthic eco-regions on a shallow Arctic shelf. *Deep-Sea Research Part II: Topical Studies in Oceanography, 207*, 105240. https://doi.org/10.1016/j.dsr2.2022.105240

4. a) Diagram showing four interlinked key initiatives to improve the understanding of benthic ecosystem and diagenetic dynamics, and benthic-pelagic interactions. Arrows connecting different initiatives highlight the relationship between two individual initiatives. b) Outline of recommended best practices and priority measurements that all researchers can make when deployed in the field. Priority 1 measurements aim to characterize the benthic environment and provide information on oxygen consumption. Priority 2 measurements include measurements from Priority 1 with added information to characterize nutrient dynamics and greenhouse gases, while Priority 3 includes all measurements plus methods that provide higher resolution in time and space but that are more expensive and/or require more expertise and logistical support. *Reprinted from*: Schultz, C., Luo, J. Y., Brady, D. C., Fulweiler, R. W., Long, M. H., Petrik, C. M., et al. (2025). Elucidating the role of marine benthic carbon in a changing world. *Global Biogeochemical Cycles, 39*, e2025GB008643. https://doi.org/10.1029/2025GB008643