Simulating Arctic Benthic Organic Carbon in E3SM

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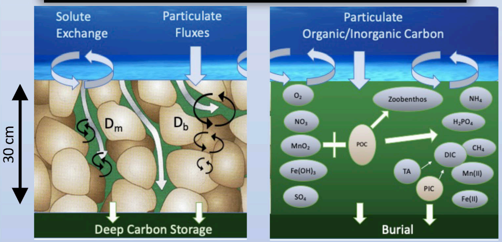
Ocean Sediments & the Marine Ecosystem

The Arctic marine ecosystem supports a very high biomass, abundance and diversity of benthic (bottom ocean sediment) organisms that play a key role in the Arctic food web. This is due to the high export rates of ocean and sea ice primary production particularly in shelf and coastal regions. Dramatic changes in recent decades in the Arctic physical climate are bringing equally dramatic changes in Arctic ecosystem structure and functioning. The recent declines in sea ice extent and persistence, for example, have direct consequences on ice algal production and export to the benthos, and for marine mammals that use sea ice as a platform for accessing those rich benthic coastal feeding-zones.

In order to better understand the linkages between climate, pelagic primary production, and the Arctic marine ecosystem, we present research from the ecosystem project InteRFACE (Integrated Research for Arctic Coastal Environments, PI Joel Rowland) – an equilibrium modeling study of ocean benthic organic carbon content in the Arctic coastal-shelf waters using E3SM.v2 (Energy Exascale Earth System Model version 2) plus a new *benthic biogeochemistry submodule.* We find that in some regions, those of high benthic organic carbon content, the equilibrium concentration is highly correlated with the sinking POC (particulate organic carbon) flux normalized by the total burial rate. This strong relationship allows us to explore how Arctic benthic carbon may respond in the future to changes in land-derived fluxes of POC and lithogenic material or with changes to the pelagically-derived POC fluxes.

The Benthic BGC Submodule

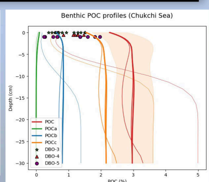


Above: Schematic of diagenetic processes included in the E3SM benthic biogeochemical submodule. The current submodule does not yet explicitly resolve the zoobenthos. Our model is based on the 1-D diagenetic model of Reed et al. 2011 [6] with inorganic carbon modifications from Krumins et al. 2013 [7].

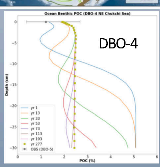
Spinning Up Benthic Carbon: Equilibration

Right: *DBO – Distributed Biological Observatory* https://www.pmel.noaa.gov/dbo/

A change detection array instituted in 2010 focusing on region "hot spots" -- locations of high productivity, biodiversity and rates of biological change.

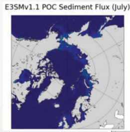


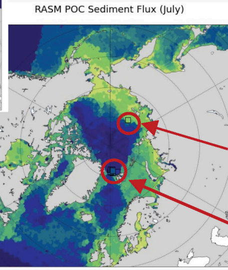
Above: Mean and standard deviation (shading) for total POC (%) in the Chukchi Sea shelf sediments. POCa = labile POC, POCb = semi-labile. POCc = refractory POC. Symbols indicate observations from DBO-3,4 and 5. Colored line progressions from thin to thick indicate profiles every 50 years of spin-up.

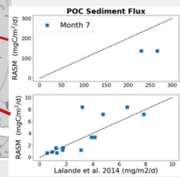


Lower Right: *Upper benthos % organic carbon from DBO-4 compared with equilibrium concentrations from a 280-year spin-up with climatological forcing of POC flux (RASM), lithogenic flux (CASCADE OBS + RASM), and bottom ocean BGC (E3SMv1.1).*

Particulate Organic Carbon Flux



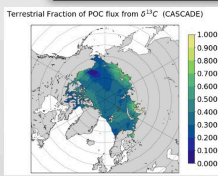




Left: *An updated climatology incorporates POC sediment fluxes from a RASM high resolution historical simulation [4] show better agreement with observations [2] (below).*

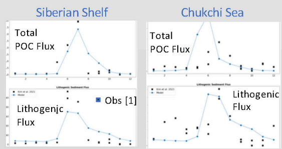
Above: *E3SMv1.1 2000-2009 climatology of ocean bottom BGC [3] forced the benthic submodule. However low primary production biases led to unrealistic POC benthic fluxes.*

Terrigenous Fluxes



Above: *Estimate of the terrestrial fraction of POC flux derived from gridded observations of the upper benthos POC $\delta^{13}C$ [5]*

Below: *Estimates (blue lines/symbols) of the terrestrial contribution to POC flux and lithogenic fluxes were derived from gridded observations of upper benthos $\delta^{13}C$ from the CASCADE database [5]*

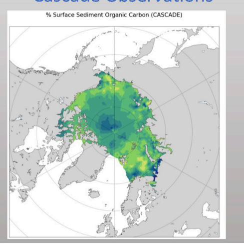


Regional Carbon Validation

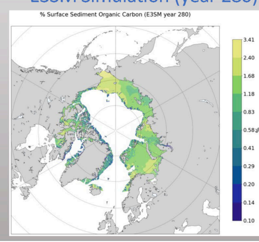
Comparison of equilibrated surface benthic organic carbon with the (Below Left) *gridded dataset (CASCADE).* Overall magnitudes are consistent and encouraging.

Below Right: *Simulated POC is generally overestimated in the Chukchi and coastal Eurasian seas, and slightly underestimated in the Beaufort.*

Cascade Observations



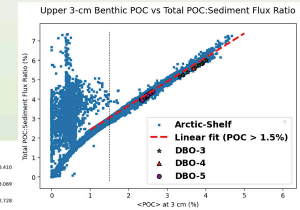
E3SM Simulation (year 280)

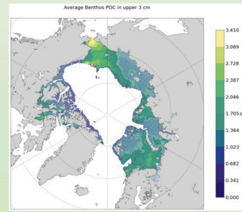


What Controls Benthic POC?

Key Result: *POC content is highly correlated with the ratio of POC ocean-sediment flux to the total mass burial flux in regions where the equilibrium upper benthic particulate organic carbon pool is high (> 1.5% mass ratio).* A highly significant linear fit (P-value < 0.01%) is shown below.

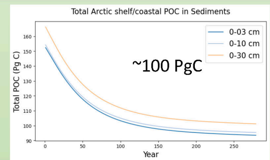
Right: *Scatter plot of grid-cell annual average sediment POC in Arctic-shelf vs the ratio of ocean-sediment POC flux to total mass sedimentary flux. A linear fit for POC > 1.5% is highly significant. Locations DBO-3 to 5 of the Distributed Biological Observatory (DBO) are also indicated as symbols.*





Left: *the spatial pattern of POC content with regions of poor correlation (POC < 1.5%) shown in hatched contours. The linear relationship is robust through-out the Bering and Chukchi Seas, and high production regions in the Barents and Kara Seas.*

Right: *Total modelled POC (PgC) in the upper 30 cm of Arctic coastal and shelf sediments (< 400 m depth). After 280 years of spin-up, total POC is approximately 100 PgC. By comparison, the carbon content of CO_2 in all the atmosphere is currently only 9 times that value.*



Conclusions and Next Steps

- In InteRFACE Phase 1, we have implemented a 30-layer, 35-tracer benthic biogeochemical submodule in MPAS-O (and E3SM.v2) representing the upper 30 cm active benthic layer.
- Modelled POC was tested and validated in Arctic coastal and shelf regions with depths < 400 m using a 280-year spin-up with climatology of pan-Arctic ocean bottom state and biogeochemistry from the E3SMv1.1 historical simulations (2000-2009) [3], RASM historical POC sedimentation fluxes, and estimates of terrestrial POC flux and lithogenic fluxes derived from the CASCADE database [5].
- Modelled upper benthic POC compares favorably with CASCADE and two DBO "hot spot" regions (DBO-4 and DBO-5) while overestimating carbon content in DBO-3.
- Upper benthic organic carbon is not, generally, correlated with bottom ocean POC flux. However, for regions with high benthic POC (> 1.5% by mass), POC content is highly correlated with ocean POC flux normalized by the total burial flux.
- In year-4 of InteRFACE, we are preparing an updated climatology using E3SM.v2 and activating 2-way coupling between MarBL and the benthic BGC to assess how historical changes in ocean-ice primary production have impacted Arctic shelf carbon storage.

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