

- DeRosa, M., Gambacorta, A. and Gliozzi, A., 1986. Structure, biosynthesis, and physicochemical properties of archaeobacterial lipids. *Microbiol. Rev.* 50: 70-80.
- Eglinton T. I. and Eglinton G., 2008. Molecular proxies for paleoclimatology. *Earth and Planetary Science Letters* 275: 1-16.
- Guckert J. B., Antworth C. B., Nichols P. D., and White D. C., 1985. Phospholipid ester-linked fatty acid profiles as reproducible assays for changes in prokaryotic community structure of estuarine sediments. *FEMS Microbiol. Ecol.* 31: 147-158.
- Hopmans EC, Weijers JWH, Schefuss E, et al., 2004. A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. *Earth. Planet. Sci. Lett.* 224:107-116.
- Ingalls AE, Shah SR, Hansman RL, Aluwihare LI, Santos GM, Druffel ERM, Pearson A., 2006. Quantifying archaeal community autotrophy in the mesopelagic ocean using natural radiocarbon. *Proc Natl Acad Sci USA* 103: 6442-6447.
- Lipp, J.S., Morono, Y., Inagaki, F., Hinrichs, K.-U., 2008. Significant contribution of Archaea to extant biomass in marine subsurface sediments. *Nature* 454: 991-994.
- Prahl, F. G., Muehlhausen, L. A. and Zahnle, D. L., 1988. Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions. *Geochim. Cosmochim. Acta* 52: 2303-2310.
- Schouten S, Hopmans EC, Schefuss E, Sinninghe Damsté JS., 2002. Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? *Earth. Planet. Sci. Lett.* 204: 265-274.
- Sinninghe Damsté JS, Hopmans EC, Schouten S, van Duin ACT, Geenevasen JAJ., 2002. Crenarchaeol: the characteristic glycerol dibiphytanyl glycerol tetraether membrane lipid of cosmopolitan pelagic Crenarchaeota. *J. Lipid Res.* 43:1641-1651.
- Villanueva L., Navarrete A., Urmeneta J., Geyer R., White D.C., Guerrero R., 2007. Monitoring diel variations of physiological status and bacterial diversity in an estuarine microbial mat: An integrated biomarker analysis. *Microb. Ecol.* 54: 523-531.
- White, D.C., Davis, W.M., Nickels, J.S., King, J.D., and Bobbie, R.J., 1979. Determination of the sedimentary microbial biomass by extractable lipid phosphate. *Oecologia* 40: 51-62.

1.2.2 Ocean Biological Pump sensitivities and implications for climate change impacts

A. Romanou

Columbia University and NASA-GISS, New York

ar2235@columbia.edu

The ocean is one of the principal reservoirs of CO₂, a greenhouse gas, and therefore plays a crucial role in regulating Earth's climate. Currently, the ocean sequesters about a third of anthropogenic CO₂ emissions, mitigating the human impact on climate. At the same time, the deeper ocean represents the largest carbon pool in the Earth System and processes that describe the transfer of carbon from the surface of the ocean to depth are intimately linked to the effectiveness of carbon sequestration.

The ocean biological pump (OBP), which involves several biogeochemical processes, is a major pathway for transfer of carbon from the surface mixed layer into the ocean interior. About 75% of the carbon vertical gradient is due to the carbon pump with only 25% attributed to the solubility pump. However, the relative importance and role of the two pumps is poorly constrained (Gruber and Sarmiento 2002; Passow and Carlson 2012). OBP is further divided to the organic carbon pump (soft tissue pump) and the carbonate pump, with the former exporting about 10 times more carbon than the latter through processes like remineralization (Sarmiento et al 2004).

Major uncertainties about OBP, and hence in the carbon uptake and sequestration, stem from uncertainties in processes involved in OBP such as particulate organic/inorganic carbon sinking/settling, remineralization, microbial degradation of DOC and uptake/growth rate changes of the ocean biology. The deep ocean is a major sink of atmospheric CO₂ in scales of hundreds to thousands of years, but how the export efficiency (i.e. the fraction of total carbon fixation at the surface that is transported at depth) is affected by climate change remains largely undetermined. These processes affect the ocean chemistry (alkalinity, pH, DIC, particulate and dissolved organic carbon) as well as the ecology (biodiversity, functional groups and their interactions) in the ocean. It is important to have a rigorous, quantitative understanding of the uncertainties involved in the observational measurements, the models and the projections of future changes.

Uncertainties in carbon export

The large uncertainty in the estimates of carbon export (Table 2) is partially explained by the different methodologies (experimental, analytical, numerical), the specific sites of measurements/analysis, the interpolation techniques and the numerical approaches that were used in each study. Mainly however, these discrepancies in global carbon export flux underscore the lack of observational constraints and hence the incomplete understanding of deep processes involved in OBP.

Furthermore, carbon export varies significantly over different time scales. On interannual through decadal time scales, export can change by 0.23-30%, whereas for scales longer than that it may only change within 1-5%. Such variability may also be responsible for the discrepancies in carbon export estimates from observational expeditions that take place at different times of the year, in different years and at different locations.

Table 2. Carbon export estimates from different published studies. Although significant progress has been made, there is still large uncertainty in the amount of carbon that is transported away from the euphotic zone. We need to understand the source of the uncertainties and reduce them.

Table 2. Carbon export estimates from different published studies. Although significant progress has been made, there is still large uncertainty in the amount of carbon that is transported away from the euphotic zone. We need to understand the source of the uncertainties and reduce them.

Source	Export (PgC/yr)
Eppley and Peterson 1979	3.4-4.7
Martin et al 1987	6
Falkowski et al 1998	16
Laws et al 2000	11-20
Schlitzer 2002	10
Denman 2003	25
Sabine et al 2004	8
Dunne et al 2005/2007	8-11
Lutz et al 2007	5.7
Henson 2011/2012	5

Because of the large uncertainty range of observational estimates of carbon export, modeling OBP can lead to precarious conclusions. Models use a wide range of parameterizations to describe the fundamental processes involved in OBP, the sensitivity of which, in the parameter space, should be known for each model and always appraised against the observational uncertainties.

Several studies have highlighted the large regional variability of the carbon export (Laws et al 2000; Lutz et al 2007; Henson et al 2011). The largest rates were observed in the upwelling region off Peru, the Ross Sea, the North Atlantic bloom region and the Subtropical Convergence Zones (35° S-45° S) in the Southern Ocean where mode waters form.

Lowest estimates were obtained off Bermuda in the North Atlantic subtropical gyre, at HOT (the site of Hawaii Ocean Time-Series), and in the Eastern Equatorial Pacific during El Niño when upwelling of deep nutrients and primary production in the euphotic layer are reduced. Very low export estimates are given for the Arctic Ocean. Beyond the qualitative agreement though, these studies often disagree quantitatively.

Physics vs. biogeochemistry

The sensitivity of OBP to parameterizations of the recycling of particulate organic carbon in the unforced climate (preindustrial conditions) has been explored in Romanou et al (2013a; 2013b) and was presented at IMBIZO III. Twin control climate simulations were performed using two ocean models coupled to the same atmosphere, land and ice models. The two ocean models (the Russell ocean model and the Hybrid Coordinate Ocean Model, HYCOM) use different vertical coordinate systems, and therefore represent two distinct classes of ocean physics formulation. The Russell model uses a z-like coordinate system, whereas HYCOM uses a hybrid coordinate system in which the vertical grid follows the isobaths in the upper ocean and the isopycnals at depth. Both variants of the GISS climate model were then coupled to the NASA Ocean Biogeochemical Model (NOBM; Gregg and Casey 2007) shown in Fig. 4, which is a functional type based model of chlorophyll and the carbon cycle in the ocean.

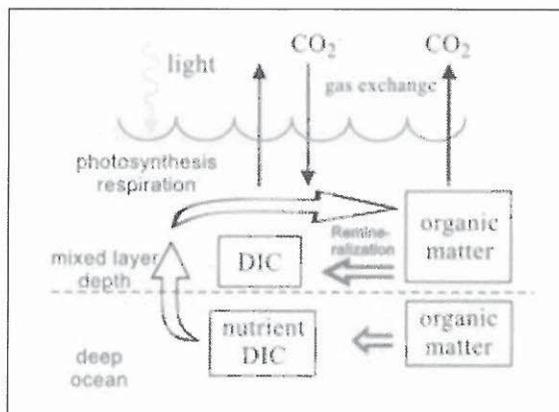


Figure 4. Schematic diagram of the NASA Ocean Biogeochemical Model (NOBM). NOBM includes four functional phytoplankton groups, one heterotrophic group, four nutrients, three detrital pools, DIC and DOC.

Model results showed that the air-sea CO₂ flux, the primary production as well as the carbon export are sensitive to ocean model differences due to the different formulations of physical processes such as ventilation, mixing, eddy stirring and vertical advection. However, it was also found that biogeochemical parameterizations such as the treatment of the remineralization affect the

model OBP as much as those physical parameterizations. Furthermore, OBP is found to be more sensitive to biological parameterizations in the subtropical front regions of both hemisphere oceans, whereas the oligotrophic subtropical gyres are more sensitive to changes that affect stratification. The Southern Ocean subtropical zone emerged as a key region where the sensitivity to remineralization was robust (of the same order of magnitude in both models).

Conclusion

Uncertainties in OBP reveal the lack of observational evidence to constrain the many processes involved in it, although significant progress has been made in the last decade. Particular attention must be given to estimates of carbon export and variability at shorter as well as longer time scales. At the same time, in models, the large uncertainty reveals a lack of knowledge on how to best parameterize OBP-related processes. Progress along these lines will improve our understanding of how OBP has changed due to anthropogenic perturbations of the global carbon cycle and how it will change in the future due to the changing climate. Given that many of the OBP uncertainties stem from similar magnitude uncertainties in the biological production in the upper ocean, progress in constraining and parameterizing both OBP and PP needs to be made in parallel.

References

- Denman, K. L., 2003. Modelling planktic ecosystems: Parameterizing complexity. *Prog. Oceanogr.* 57: 429-452.
- Dunne, J., Sarmiento, J., and Gnanadesikan, A., 2007. A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles*, 21, GB4006, doi:10.1029/2006GB002907.
- Eppley, R.W., and Peterson, B.J., 1979. Particulate organic matter flux and planktonic new production in the deep ocean. *Nature* 282(5): 677-680

- Falkowski, P.G., Barber, R.T. and Smetacek, V., 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science* 281(5374): 200-206.
- Gregg, W.W., and Casey, N.W., 2007. Modeling coccolithophores in the global oceans. *Deep-Sea Research II*, 54: 447-477.
- Gruber, N., and Sarmiento, J.L., 2002. Large scale biogeochemical-physical interactions in elemental cycles. In A. R. Robinson, J.J. McCarthy, and B.J. Rothschild, editors, *The Sea*, volume 12. John Wiley and Sons, Inc., New York, N.Y.
- Henson, S.A., Sanders, R., Madsen, E., Morris, P.J., Frédéric Le Moigne and Quartly, G.D., 2011. A reduced estimate of the strength of the ocean's biological carbon pump. *Geophys. Res. Lett.* 38(4): L04606.
- Laws, E.A., Falkowski, P.G., Smith, W.O., Ducklow, H., and McCarthy, J.J., 2000. Temperature effects on export production in the open ocean. *Global Biogeochemical Cycles* 14(4): 1-16.
- Lutz, M.J., Caldeira, K., Dunbar, R.B. and Behrenfeld, M.J., 2007. Seasonal rhythms of net primary production and particulate organic carbon flux to depth describe the efficiency of biological pump in the global ocean. *J. Geophys. Res.* 112(C10): C10011.
- Marra, J., 2009. Net and gross productivity: Weighing in with ¹⁴C. *Aquat. Microb. Ecol.* 56: 123-131.
- Martin, J.H., Knauer, G.A., Karl, D.M. and Broenkow, W.W., 1987. Vertex: Carbon cycling in the northeast Pacific. *Deep-Sea Research II* 34(2): 267-285.
- Passow, U. and Carlson, C.A., 2012. The biological pump in a high CO₂ world. *Mar. Ecol. Prog. Ser.* 470:249-271.
- Romanou, A., Gregg, W.W., and Romanski, J., 2013b (submitted). Carbon cycle sensitivities in modeling biological processes in the NASA GISS climate model. *Biogeosciences*.
- Romanou, A., Gregg, W.W., Romanski, J., Kelley, M., Bleck, R., Healy, R., Nazarenko, L., Russell, G., Schmidt, G.S., Sun, S. and Tausnev, N., 2013. Natural air-sea flux of CO₂ in simulations of the NASA GISS climate model: Sensitivity to the physical ocean model formulation. *Ocean Modelling* dx.doi.org/10.1016/j.ocemod.2013.01.008.
- Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.-H., Kozyr, A., Ono, T. and Rios, A.F., 2004. The oceanic sink for anthropogenic CO₂. *Science* 305: 367-371.
- Sarmiento, J.L., Dunne, J. and Armstrong, R.A., 2004. Do we understand the ocean's biological pump? *U.S. JGOFS News* 12(4): 1-20.
- Schlitzer, R., 2002. Carbon export fluxes in the Southern Ocean: Results from inverse modeling and comparison with satellite-based estimates. *Deep Sea Research Part II: Topical Studies in Oceanography* 49(9-10): 1623-1644.

1.2.3 Ocean iron fertilization experiments: The dawn of a new era in applied ocean sciences?

Victor Shahed Smetacek

Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany

CSIR National Institute of Oceanography, Goa, India

Victor.Smetacek@awi.de

Ocean iron fertilization (OIF) experiments represent a powerful tool to test ecological hypotheses under natural conditions in the open ocean. They are the marine equivalent of whole-lake experiments in limnology, the results of which have changed our understanding of aquatic ecosystem functioning and lake management techniques in fundamental ways. Decades of close observations of lake ecosystems could not reveal the impact of top predators, via trophic cascades, that came to