The Role of Iron and Community Structure in a Global Ocean Ecosystem and Carbon Cycle Model

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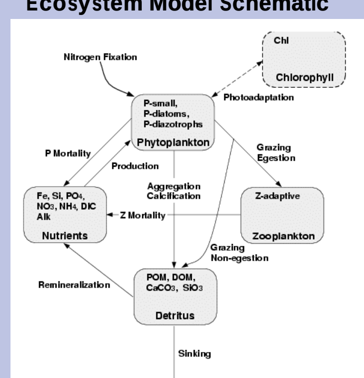
Abstract

Over the last decade, JGOFS and related field studies have dramatically altered our basic conceptualization of ocean biogeochemistry, highlighting the importance of (among other things) trace-metal limitation, community structure, and planktonic "geochemical functional groups" (e.g., diatoms, nitrogen fixers, calcifiers). These plankton groups provide important links between ocean carbon and the biogeochemical cycles of other key species (e.g., macro- and micro-nutrients, alkalinity, silica). To better quantify the role of marine ecosystem dynamics on the global ocean carbon cycle, we have developed a new global, three-dimensional coupled ecobiogeochemistry model under the framework of the CCSM-Ocean model. Community structure is determined prognostically by a balance of temperature, light, and multi-nutrient limitation (Fe, P, N, Si) as well as zooplankton grazing. The ecological components are linked with full carbonate system chemistry and an iron biogeochemical cycle. We present results from global simulations, focusing on model-data evaluation against standard metrics (local time-series stations; SeaWiFS ocean color and primary productivity; export production; and air-sea CO_2 flux) as well as the impact of iron limitation and upper ocean iron cycling. Upper ocean simulations initialized with climatological nutrient fields show significant skill in replicating observed spatial and seasonal biological patterns. The incorporation of a dynamic iron cycle is critical for this success, modulating both total ecosystem rates and community structure.

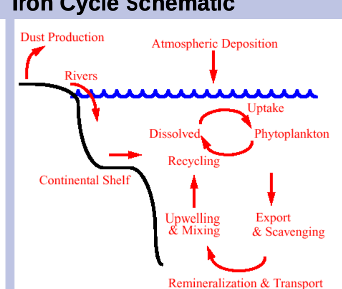
Model Description

The global ocean circulation is from a quasi-equilibrium solution of the NCAR/LANL Community Climate System Model (CCSM) 2.0 ocean model. The upper ocean ecosystem is adapted from Moore et al. (2002a;b) and includes nitrogen (N), phosphorus (P), iron (Fe), and silicon (Si), four phytoplankton functional groups (pico-/nano-plankton, diazotrophs, diatoms and coccolithophores), one class of zooplankton, dissolved organic matter and sinking particulate detritus. The ecosystem is coupled with a full depth carbon biogeochemistry model (Doney et al., 2003) modified to include a dynamic iron cycle (atmospheric deposition, continental shelf source, scavenging).

Ecosystem Model Schematic



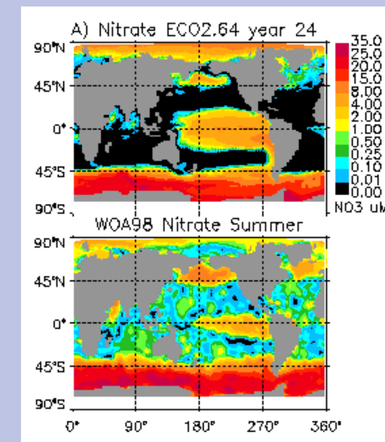
Iron Cycle Schematic

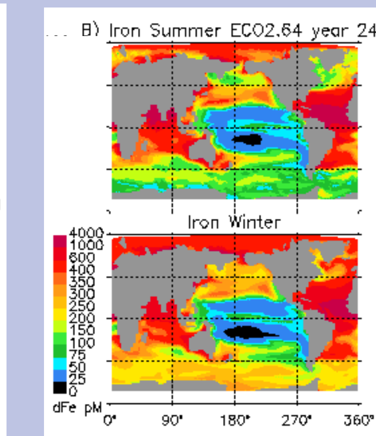


Model-Data Evaluation

Nutrients

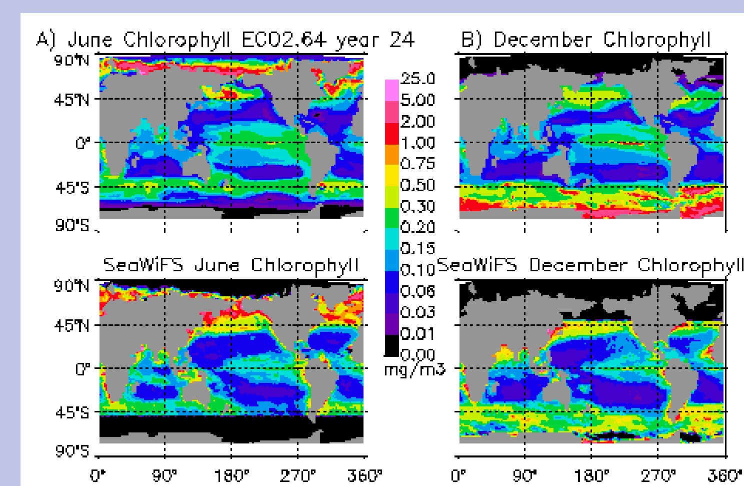
The simulation captures the large-scale seasonal patterns of nutrients, biomass and productivity and in particular the high-nitrate, low-chlorophyll (HNLC) conditions in the Southern Ocean and equatorial and subarctic Pacific Ocean. The HNLC region in the equatorial Pacific is much larger in the model than in the observations, largely due to the excessive nutrient upwelling. Surface phosphate concentrations (not shown) are strongly depleted in the North Atlantic gyre by nitrogen fixation. The model surface iron fields are broadly similar to the limited observational data base, with values >1.0 nM under the North Africa and the Arabian Peninsula dust plumes falling to 0.025-0.150 nM in HNLC regions.





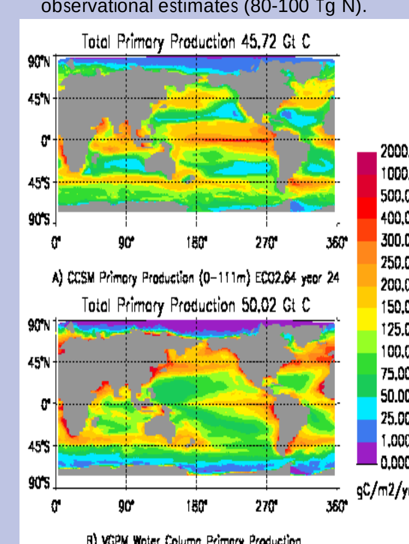
Ocean Color

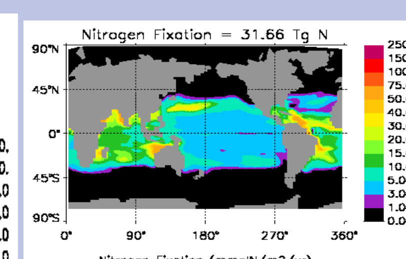
Model surface chlorophyll concentrations for June and December are in good qualitative agreement with SeaWiFS satellite estimates, showing the expected large-scale latitudinal and seasonal patterns, regional seasonal blooms, and moderate HNLC levels. The model overpredicts summer chlorophyll along the Antarctic coast, underpredicts eastern boundary upwelling regions, and has a somewhat too large equatorial Pacific zone of moderate chlorophyll is again too large.



Primary Production and N_2 Fixation

The spatial patterns and total magnitude of primary production also compare well with SeaWiFS estimates, with somewhat higher model production in the equatorial upwelling zones and Southern Ocean and lower production in coastal waters and the North Atlantic relative. Nitrogen fixation patterns are similar to observed, but the total annual rate (32 Tg N) is low because of iron/phosphate limitations relative to the Moore et al. result (62 Tg N) or observational estimates (80-100 Tg N).

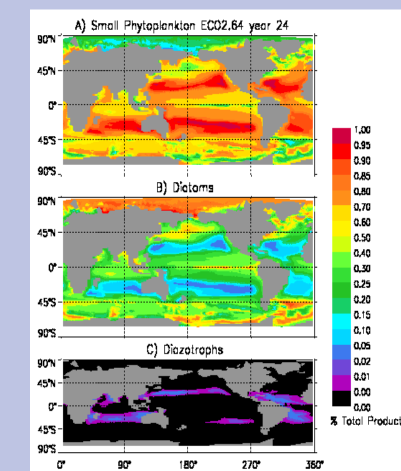


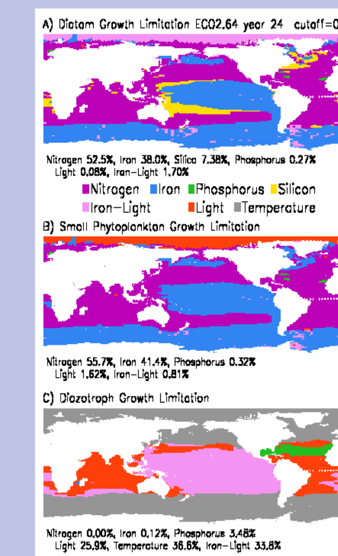


Biogeochemical Dynamics

Community Structure and Nutrient Limitation

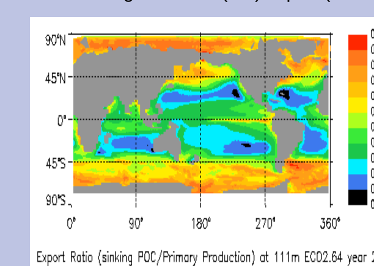
Pico/nano plankton dominate production in the oligotrophic subtropical gyres; diatoms contribute roughly 15-50% in the tropics and mid-latitude Southern ocean, increasing in bloom regions. Diazotrophs are only a small component of total production but are key for subtropical new production. The model simulates extensive areas of iron limitation for diatoms and picoplankton in the equatorial Pacific and Southern Ocean with nitrogen and silicon limitations elsewhere. Diazotrophs are iron-light co-limited in the Pacific, phosphorus limited in the North Atlantic (modest nitrogen fixation leading to phosphate drawdown and export), and temperature limited, by construction, at high latitudes.

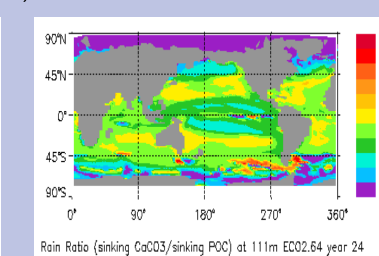




Export Fluxes

Annual particulate organic export at the base of the euphotic zone (111m) is 5.6 PgC, on the lower end of observational estimates, with spatial patterns driven largely by blooms of diatoms and coccolithophores. Export ratios range from >4% in oligotrophic gyres to >25% in bloom regions. The simulated total $CaCO_3$ export (0.51 PgC) and rain ratio (sinking $CaCO_3$/ sinking POC) is comparable to the calcification estimate (~0.7 PgC), with elevated values in the North Atlantic, coastal and equatorial upwelling zones, and Patagonian shelf. Global model biogenic silica (bSi) export (not shown) is 0.67×10^{14} mol Si.





Future Work

The global 3-D coupled eco-biogeochemistry model incorporates multiple limiting nutrients, explicit phytoplankton geochemical functional groups, and variable elemental stoichiometry. Future work will focus on examining the ecosystem response to interannual climate variability, improving understand of the mechanisms governing surface and subsurface iron cycling, and exploring the coupling of the upper ocean ecosystem with subsurface nutrient and inorganic carbon fields on longer centennial to millennial time-scales.

References

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