

ON THE SENSITIVITY OF OCEAN BIOGEOCHEMISTRY AND AIR-SEA CO₂ FLUX TO CLIMATE DRIVEN VARIATIONS IN MINERAL DUST DEPOSITION

J. K. Moore¹, S. C. Doney², K. Lindsay³, and N. Mahowald³

¹*University of California, Irvine, Department of Earth System Science, Irvine, CA 92697-3100;
jkmoore@uci.edu*

²*Woods Hole Oceanographic Institution, Department of Marine Chemistry and Geochemistry, MS #25,
Woods Hole, MA 02543-1543; sdoney@whoi.edu*

³*National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000;
klindsay@ucar.edu, mahowald@ucar.edu*

ABSTRACT

A coupled Biogeochemistry-Ecosystem-Circulation (BEC) ocean model is used to examine the sensitivity of ocean biogeochemical cycling and air-sea CO₂ exchange to variations in mineral dust deposition from the atmosphere. Mineral dust deposition estimates from four different climate regimes are used to force the ocean model. Our estimated climate-induced changes in dust deposition to the oceans significantly modify phytoplankton community composition, and global-scale rates of nitrogen fixation, export production, and air-sea CO₂ flux. Dust driven variations in air-sea CO₂ exchange exceeding 1 PgC/yr are of similar magnitude to present net oceanic anthropogenic uptake. Dust deposition directly modifies rates of export production and CO₂ flux over large regions where iron is the primary growth-limiting nutrient. Dust deposition also indirectly influences these rates by modifying the rates of nitrogen fixation in the tropics and subtropics where nitrogen is the primary limiting nutrient. Initially the direct pathway dominates the ocean biogeochemical response to dust variations, but over multi-decadal timescales the indirect response may be equally important. Our predicted decrease in mineral dust deposition over the next century would significantly slow oceanic uptake of CO₂ and act as a positive feedback mechanism for the ongoing global warming.

Mineral dust deposition is the main external source of the critical micro-nutrient iron, which limits phytoplankton growth rates over some 30-40% of the world ocean in the iron-limited High Nitrate, Low Chlorophyll (HNLC) regions concentrated in the subarctic and equatorial Pacific, and Southern Ocean. In subtropical and tropical regions, where nitrogen is typically the growth-limiting nutrient for the phytoplankton community, the nitrogen-fixing diazotrophs may be limited by iron. Rates of N-fixation modified by mineral dust deposition can then influence primary and export production by the rest of the phytoplankton community. We refer to this dust-nitrogen fixation-carbon linkage as the indirect pathway for dust to influence air-sea CO₂ exchange.

A coupled Biogeochemistry-Ecosystem-Circulation (BEC) model [Moore *et al.*, 2004] is used to examine the sensitivity of ocean biogeochemistry and air-sea CO₂ exchange to climate-driven changes in mineral dust deposition to the oceans. The BEC model runs within the NCAR Community Climate System Model (CCSM3) ocean physics model, and includes multiple potentially growth-limiting nutrients (N, P, Fe, and Si) and explicit iron cycling in the oceans with sources from mineral dust and continental shelves. The BEC model also includes four functional groups of phytoplankton: diatoms, diazotrophs, coccolithophores, and picoplankton. Thus, as dust deposition varies, the model is able to capture the ecosystem shifts observed in the iron-fertilization experiments, and changes in nitrogen fixation rates and the resulting changes in phytoplankton community composition and export production [Moore *et al.*, 2004].

Estimates of dust deposition generated under four climate regimes (Current era, Pre-industrial era, a Future climate with atmospheric CO₂ concentrations at double pre-industrial levels, and the climate of the Last Glacial Maximum (LGM)) are used to drive the BEC ocean model. Terrestrial dust sources, entrainment, atmospheric transport and deposition to the ocean surface are calculated within equilibrium CCSM3 climate simulations using equilibrium vegetation distributions (Mahowald et al, in prep); no land use or water use sources are assumed in these simulations. The Pre-industrial and LGM dust deposition simulations increase the total dust flux to the oceans by factors of 1.6 and 4.2, respectively, relative to Current, while the Future simulation results in a decrease in ocean dust deposition of 63%, relative to Current, with much of the decrease located in the Southern Hemisphere. The ocean model was forced with the Current dust deposition for 160 years beginning with climatological nutrient distributions, and then forced for an additional 40 years with each of the four dust deposition estimates. The only forcing that varied between these simulations was dust deposition. Winds and other climate forcings were from a late 20th century climatology and atmospheric CO₂ concentrations were set everywhere at 278 ppm for all simulations.

In the final 40 years of the Current climate simulation nitrogen fixation and export production were steady at 75 TgN/yr and 5.5 PgC/yr. The simulation exhibits a small but steady net ocean uptake of 0.24 PgC of CO₂ per year reflecting the fact that the simulated ocean carbon cycle is in slight disequilibrium with the prescribed atmospheric CO₂. Under the Pre-industrial and LGM dust depositions, there were large increases in nitrogen fixation, sinking particulate organic carbon (POC) export, and in the ocean uptake of atmospheric CO₂. Sinking POC at 103 m initially increased by more than 2 PgC/yr under the LGM dust deposition, driving an increase in the uptake of CO₂ from the atmosphere by more than 1 PgC/yr of CO₂. The difference in CO₂ uptake between the Current and LGM simulations declined over the simulation but was still ~ 0.6 PgC/yr after 40 years. The decreases in dust deposition in the Future climate simulation led to greatly reduced rates of nitrogen fixation and export production, driving a change in net air-sea CO₂ flux greater than 0.5 PgC/yr of CO₂. The net air-sea CO₂ flux anomaly peaked at +0.59 PgC/yr of CO₂ (year 20), declining to +0.52 PgC/yr (year 40).

These changes in ocean biogeochemical cycling were driven by changes in the phytoplankton community composition and in degree of nutrient stress. Under the Pre-industrial and LGM dust forcing, diatom production and export increased dramatically in the HNLC regions. In both simulations, export production and ocean CO₂ uptake decline over several decades after an initial rapid increase. This occurs in part because nutrients other than iron become depleted, limiting phytoplankton growth rates in some HNLC regions. By the end of the simulations the percentage of the world ocean where iron is limiting diatom growth rates has declined from 33% with the Current dust forcing to 25% with Pre-industrial dust and 13% with the LGM dust. The iron-limited regions in both simulations were concentrated in the Southern Ocean. Diatom and diazotroph production were reduced significantly under the Future dust forcing, with the community shifted towards the smaller picophytoplankton. The global area where iron limits diatom growth increased to 59%, including the entire South Pacific. While the most dramatic changes in biogeochemical fluxes were seen in the HNLC areas in response to the direct iron pathway, significant differences in export production and air-sea CO₂ flux also occurred within the subtropical gyres in response to the indirect nitrogen fixation pathway. Even small changes in export production and air-sea CO₂ flux in these regions can have a global impact as they account for a large fraction of open ocean area. Initially the direct pathway dominates the ocean biogeochemical response to dust variations, but over multi-decadal timescales the indirect response may be equally important.

REFERENCE

Moore, J. K., S. C. Doney, and K. Lindsay, Upper ocean ecosystem dynamics and iron cycling in a global three-dimensional model, *Global Biogeochem. Cycles*, 18, GB4028, doi:10.1029/2004GB002220, 2004.