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Oscillations in Cretaceous ocean productivity and deoxygenation induced by redox-dependent nutrient cycling

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Deoxygenation and productivity of the Late Cretaceous ocean were studied using the UVic earth system model. Simulations were performed at 4 different atmospheric pCO2 values (500 ppm, 1200 ppm, 1800 ppm, 2200 ppm) using a state-of-the-art reconstruction of paleogeography and ocean basin configuration. Consistent with the proxy record, the model predicts low oxygen conditions for the proto North Atlantic and Tethys while most of the Pacific is well ventilated. This pattern is maintained over the entire pCO2 range applied in the modeling when the standing stock of nutrients is conserved. The mean oxygenation state of the Cretaceous ocean responds only weakly to pCO2 and surface temperature change because an increase in overturning circulation under high pCO2 compensates for the coeval decrease in oxygen solubility.
A box model was set up to study the effects of changing nutrient inventories on deoxygenation. The Cretaceous ocean was represented by 36 boxes and the water fluxes between these boxes were defined using output of the UVic model. The turnover of dissolved oxygen, sulfide, nitrate, ammonium, phosphate, ferrous and ferric iron was simulated considering redox-dependent fluxes across the sediment/water interface and a range of abiotic and biotic redox reactions in the water column. Two classes of phytoplankton (nitrogen-fixing and non-fixing) and three potentially limiting nutrients (reactive nitrogen, phosphate, iron) were considered. Surprisingly, many of the simulations did not converge into a steady state but showed persistent oscillations in deoxygenation and ocean productivity with cycle lengths ranging from 20 kyr to 100 kyr. These cycles were generated in the North Atlantic where dissolved iron accumulated in intermediate and deep waters due to intense deoxygenation and denitrification. This anoxic ocean basin served as dissolved iron source for adjacent basins. Global ocean productivity increased until the benthic iron release in the North Atlantic was diminished by sulfate reduction and pyrite formation. The resulting productivity decrease in adjacent iron-limited basins induced a rise in lateral dissolved oxygen supply to the North Atlantic that reduced the rates of pyrite formation and induced a recovery of the dissolved iron level. The cycle started again when the export production in the North Atlantic promoted sufficient pyrite precipitation to limit benthic iron release. The simulations show that periodic changes on orbital time-scales observed in the geological record are not necessarily related to orbital forcing but may be induced by the internal non-linear dynamics of the marine biogeochemical system.

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