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Modeling oceanic redox conditions during the Phanerozoic: Constraints from a one-dimensional ocean biogeochemical cycle model

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Atmosphere-ocean-system has been oxygen-rich conditions for much of the Phanerozoic Eon. However, widespread black shale depositional intervals termed oceanic anoxic events (OAEs) occurred sporadically under warm climate conditions (e.g., the mid-Cretaceous). Some causal mechanisms of OAEs have been suggested; such as ocean stagnation, enhanced biological productivity in the surface oceans, and an oxygen solubility decrease due to global warming. To elucidate the necessary conditions for generation of large scale anoxia/euxinia quantitatively, we developed a vertical one-dimensional ocean biogeochemical cycle model that involves several chemical reactions in an oxic–anoxic–sulfidic water column (such as denitrification, nitrification, sulfate reduction); and redox-dependent phosphorus (P) regeneration in surface sediments for paleoceanographic applications. This model includes the total dissolved inorganic carbon (DIC), δ^{13}C of DIC, total alkalinity (Alk), oxygen (O_2), phosphate (PO_4), nitrate (NO_3), ammonium (NH_4), sulfate (SO_4), and hydrogen sulfide (H_2S) as dissolved chemical components of seawater, and can reproduce the vertical chemical structures in the modern ocean that are in good agreement with observations. To explore the theoretical constraints for global oceanic redox conditions systematically, we examined the effect of the proposed processes, including riverine phosphorus input rate, ocean thermohaline circulation rate, oxygen solubility for sea water (sea surface temperature), and shelf area on marine biogeochemical cycles. The sensitivity analyses of oceanic redox states in steady-state indicate that (1) enhanced P input rate is an important mechanism for widespread anoxia via expansion of oxygen minimum zone and coastal deoxygenation, resulting in massive P efflux from surface sediments, (2) oceanic anoxia is easily achieved in case of low ocean circulation rate and/or low oxygen solubility, but those are not enough to achieve global anoxia/euxinia by themselves, and (3) high sea-level conditions act as a buffer against oceanic eutrophication (and OAEs) supporting the results of Bjerrum et al (2006). We then reconstruct the oceanic redox states during the Phanerozoic by using geological reconstructions of atmospheric oxygen concentration, riverine P input rate, global averaged temperature, and shelf area in previous studies (e.g., Ronov, 1994; Berner and Kothavala, 2001; Guidry and Mackenzie, 2003; Berner, 2009) as boundary conditions. The reconstructed oceanic redox states are basically oxic during the Phanerozoic. We speculate that a sudden perturbation, such as continental weathering and elevated P river input rate forced by a massive CO_2 release event (e.g., large igneous province) will be required for OAEs. However, the obtained results also indicate that oceanic redox condition strongly depends on the presumed coastal area, implying a possibility that the oxic oceanic condition under greenhouse climate is achieved in case that high sea-level stands act as an effective sink of nutrients. In other words, the paleogeographical setting is crucial to evaluate the necessary conditions for OAEs.