The future life span of Earth's oxygenated biosphere and its controlling factors

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Detecting atmospheric biosignatures on Earth-like exoplanets is one of the primary objectives of ongoing and future exoplanetary observational surveys. Significant gaps, however, remain in our understanding of the atmospheric evolution of exoplanets, and in particular the cause-and-effect relationships with an evolving biosphere. Many of these gaps arise from a lack of quantitative frameworks for interpreting atmospheric biosignatures. Construction of such a framework is a subject of broad inter-disciplinary interest. Numerous potential atmospheric biosignatures have been proposed, but molecular oxygen (O_2) (and commensurately abundant ozone, O_3) is still on top of the list of remotely detectable exoplanet biosignatures. However, a fundamental question of how much longer the remotely observable O_2/O_3 in Earth's atmosphere would be sustained on Earth remains uncertain. Solving this question has great ramifications not only for the future of our planet but also for the search for life beyond our planet. Here, we examine this problem using an Earth system model of biogeochemistry and climate that tracks the coupled carbon, oxygen, phosphorus, and sulfur cycles, and captures the global redox (O_2) budget between the exogenic system (atmosphere, ocean, and crust) and the mantle. Our model, which builds upon previous similar Earth system models, incorporates a variety of biogeochemical processes, such as biological productivity in the surface oceans and on land, a series of respiration pathways under oxic and anoxic conditions, an explicit calculation of carbonate system in the seawater, and terrestrial weathering processes, allowing an examination of biogeochemical response to changes in the O_2 levels over geologic timescales. We also include a global biogeochemical CH_4 cycle (methanogenesis, methanotrophy, a parameterized O_2-O_3-CH_4 photochemistry, and the radiative impact of CH_4 on global energy balance) in this study. The model is designed to capture the major components of the biogeochemistry and climate of Earth (and Earth-like planets more broadly) with oxic/anoxic biosphere, but is abstracted enough to allow for a stochastic approach involving large model ensembles that are run for billions of years.
Implementation of a stochastic approach reveals that the mean lifespan of Earth's oxygenated biosphere (atmospheric pO_2 >1% of the present atmospheric level, PAL) is $0.81^{+0.08}_{-0.10}$ Gyr (1*sigma*), with a most probable value of 0.78 Gyr. The model predicts that a 'great deoxygenation' of atmosphere, with atmospheric pO_2 dropping sharply to levels reminiscent of the Archaean Earth (<<0.01% PAL), could conceivably be triggered within the next 1 Gyr. We also find that the future lifespan of oxygenated atmosphere depends mainly on an exchange flux of reducing power between the mantle and the exogenic (i.e., ocean-atmosphere-crust) system. We estimate that total duration of Earth's oxygenated biosphere would be ~1.5 Gyr, or roughly 25% of Earth's whole history as an inhabited planet, emphasizing the need for robust atmospheric biosignatures for anoxic exoplanet atmospheres.

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