A MID-LIFE CRISIS FOR EARTH’S GREENHOUSE. Stephanie L. Olson, Christopher T. Reinhard, and Timothy W. Lyons, University of California—Riverside, Riverside, CA 92521, Georgia Institute of Technology, Atlanta, GA 30332

The temporal proximity between oxygenation events and Snowball Earth events in the Proterozoic supports speculation that a reduced gas, most likely biogenic CH₄, regulated Proterozoic climate—compensating for the Faint Young Sun and explaining the apparent dearth of Mesoproterozoic glacial deposits. Although low O₂ and SO₂ conditions in the Proterozoic likely favored large CH₄ fluxes from the marine biosphere, the geologic record does not provide quantitative constraints on either biogenic CH₄ fluxes or the CH₄ content of the Proterozoic atmosphere. Characterization of the Proterozoic greenhouse is further complicated by: (1) strong nonlinearity in biospheric CH₄ fluxes as a function of marine SO₂²⁻; which arises because both CH₄ production and CH₄ consumption are affected by SO₂²⁻; and (2) strong nonlinearity in the atmospheric lifetime of CH₄ as a function of atmospheric pO₂, which reflects the competing effects of O₂ content and UV shielding by ozone in oxidizing atmospheres.

We use an Earth system model to quantify CH₄ fluxes on the Proterozoic Earth and to critically evaluate the role of CH₄ in regulating Proterozoic climate. Our model consists of a 3D marine biogeochemical model, a 2D climate model, and a 1D atmospheric photochemical model. We find that although oxidant-deficient conditions in the Proterozoic would have allowed substantial CH₄ production in and escape from the ocean, CH₄ survival in the atmosphere would have been severely limited by rapid photochemical destruction under the atmospheric pO₂ conditions suggested by the Proterozoic Cr isotope record (<10⁻³ times present atmospheric level). Thus, in light of recent pO₂ constraints, our numerical results suggest the absence of a substantial CH₄ greenhouse and introduce a potential Mesoproterozoic climate paradox. Our results, however, do not preclude a critical role for CH₄ in triggering Neoproterozoic climate collapse. Instead, our model highlights a dynamic relationship between atmospheric O₂, the marine biosphere, and climate, and provides a novel mechanism for triggering Snowball Earth events via perturbation to the CH₄ cycle.

We suggest that a minor oxygenation event in the Neoproterozoic enhanced UV shielding of CH₄ via ozone and allowed the buildup of a CH₄ greenhouse—which resulted in the drawdown of atmospheric CO₂ to precariously low levels through silicate weathering feedbacks. In this scenario, the resulting CH₄ greenhouse is inherently unstable because rapid destabilization of the atmospheric CH₄ reservoir would be triggered by either: (1) a return to low O₂, as suggested by some proxy records, or (2) the accumulation of SO₂²⁻ in the ocean as a consequence of progressive Earth system oxygenation, which would severely throttle CH₄ supply via inhibition of methanogenesis and enhanced anaerobic oxidation of CH₄. Regardless, during the ensuing glaciation, inhibition of chemical weathering, combined with continued anaerobic respiration, would allow dramatic reduction of the marine SO₂²⁻ reservoir—priming the marine biosphere to generate huge CH₄ fluxes upon deglaciation and leaving the Earth system vulnerable to repeated climate perturbation until a critical oxygenation threshold was achieved in the latest Neoproterozoic or later.