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Effect of geologically-constrained environmental parameters on the atmosphere and biosphere of early exo-Earths

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Abstract

In this work we address the impact of geologically-constrained environmental parameters such as carbon dioxide (CO_2) content, surface pressure and ocean temperature upon the atmosphere and biosphere of early exo-Earths by applying our updated Coupled Atmosphere Biosphere (CAB) model developed by [1]. We derive atmospheric profiles of ozone and molecular oxygen (O_2) and calculate the corresponding Net Primary Productivity (NPP) of a photosynthesizing biosphere. Furthermore, we investigate the dominant net chemical production and destruction pathways of O_2 by applying the Pathway Analysis Program (PAP) developed by [2].

1. Introduction

The Great Oxidation Event (GOE) about 2.3 Gigayears ago denotes the first major rise of atmospheric molecular oxygen (O_2) - from less than 10^{-5} of the Present Atmospheric Level (PAL) up to at least 0.01 PAL (e.g. [3]) - in Earth's history. As a consequence the planet experienced the emergence of widespread habitability and complex life.

Recently there has been a revolution in improved methods for constraining geological data (for e.g. atmospheric pressure, composition, ocean temperature etc.) of the early Earth. In this study we investigate the effect of this new data upon our understanding of key processes which drove the GOE.

We have updated the Coupled Atmosphere Biosphere (CAB) model to apply it to the constrained environmental conditions of early Earth as a reference for early exo-Earths in order to analyze the effect of CO_2 content, surface pressure and ocean temperature on the atmosphere and productivity of a photosynthesizing biosphere.

2. Summary and Conclusions

In the case of an Archean-like atmosphere increasing CO_2 leads to an increase of O_2 with atmospheric height which is related to its enhanced production via CO_2 photolysis in the upper atmosphere. This is counterbalanced by stronger destruction of O_2 in the lower atmosphere due to higher abundance of CO from CO_2 and NO_x from low OH due to high CO. Therefore, atmospheres having low surface O_2 volume mixing ratios (vmr) such as was the case before the GOE but high amounts of CO_2 could counteract the accumulation of O_2 in the atmosphere from a given photosynthetic whereas moderate CO_2 abundances result in negligible impacts on the Net Primary Productivity (NPP) needed to maintain a specified O_2vmr.

On reducing the surface pressure to 0.5 bar the O_2 concentration profile between 0.5 to 0.005 bar is decreased compared to an early Earth atmosphere with higher surface pressures. This is a result of enhanced O_2 destruction by increased HO_x from enhanced H_2O at a given pressure level below about 0.01 bar and lower O_2 production due to less UV radiation (at a given pressure level due to less backscattering from below) destroying CO_2 in this pressure regime. Lowering the surface pressure to 0.5 bar has a negligible effect on the NPP at 2.7 Gyrs ago. However, shortly before the GOE an approximately 20% lower NPP is sufficient to maintain the same amount of O_2 in the atmosphere as for a 1 bar atmosphere hence the accumulation of O_2 produced by a photosynthetic biosphere is supported.

We identify production and destruction pathways of O_2 for Archean-like Earth by applying the Pathway Analysis Program (PAP) for high CO_2 atmospheres and low/high surface pressure scenarios. In both cases new O_2 production and destructions pathways emerge due to the presence of NO_x containing species.

On increasing ocean temperatures as proposed by proxy data, results suggest that the NPP from oxygenic photosynthesis is strongly reduced due to lower O_2 solubility before the GOE supporting the accumulation of O_2 in the atmosphere more easily.

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