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Carbon Cycle Instability on Arid Terrestrial Planets

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Arid terrestrial planets with low surface water inventories may be a common outcome of planetary evolution. On Earth, the surface water inventory is sufficient to permit high continental weathering fluxes, thereby maintaining habitable conditions via a silicate weathering thermostat [1]. However, shallow oceans on arid planets might limit continental silicate weathering, jeopardizing the balance with volcanic outgassing of CO_2.

Here, we apply a geologic carbon cycle model to terrestrial planets with low surface water inventories (<<1 Earth ocean) to explore if they can remain habitable despite secular changes in instellation and outgassing. Our model couples outgassing/weathering, stellar evolution, planetary hypsometry, and the deep-water cycle. Crucially for the exploration of arid planets, precipitation is limited by wind-driven evaporation or direct heating from sunlight [2], which is justified by comparisons to GCM outputs [3].

We find that the carbon cycle stability is sensitive to surface water inventory. As expected, on a planet with Earth-like water inventories, the carbon cycle is balanced, and surface temperatures are relatively stable on geologic timescales as the silicate weathering feedback buffers against secular stellar evolution (Figure 1). In contrast, an arid planet with a low surface water inventory enters a regime where silicate weathering cannot keep up with degassing, destabilizing the carbon cycle and resulting in runaway warming. Our Monte Carlo results show that planets with Earth-like mass and instellations require water reservoirs greater than 10% of Earth's Ocean mass to maintain a stable carbon cycle and climate (Figure 2). Most model runs show uninhabitable temperatures below this threshold of surface water.

Our preliminary results have implications for the Habitable Zone inner edge and define a minimum threshold of surface water required to maintain a stable carbon cycle and, thus, a habitable planet. These findings could elucidate evolutionary processes on terrestrial exoplanets, and demonstrate that planets in the habitable zone can transition to an uninhabitable state, which may be relevant to Venus's evolution.

[1] Walker J. C. et al. (1981) JGR: Oceans, 86(C10), 9776-9782

[2] Pierrehumbert R. T. (2010) Cambridge University Press

[3] Way M. J. and Del Genio A. D. (2020) JGR: Planets, 125(5), e2019JE006276

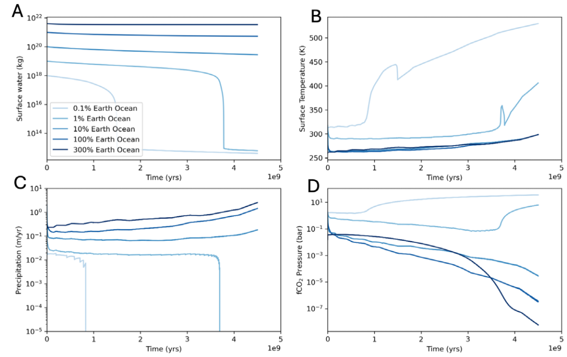

Figure 1: Preliminary outputs show four model runs with varying initial water inventories. (A) Mass of all surface water reservoirs over the planet's 4.5 Ga evolution. Runs with shallow initial water inventories have an unbalanced carbon cycle, increasing the flux of surface water into the mantle while suppressing H_2O outgassing. (B) With sufficient water inventories, surface temperatures are temperate through geologic time. Model runs with low initial water show runaway warming. (C) Precipitation flux was calculated from the MAC weathering model, including wind-driven evaporation. (D) Pressure of CO_2 in the atmosphere and ocean.

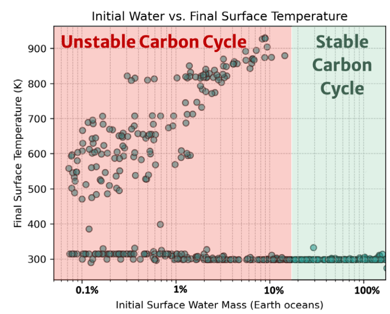

Figure 2: Monte Carlo sensitivity tests that randomly sample the initial surface and mantle water mass, total carbon inventory, initial carbon partitioning between the atmosphere and mantle, soil age, temperature dependence of weathering, and several outgassing parameters. For planets of Earth-like mass, hypsometry, and instellations, greater than 10% Earth Ocean mass is required for a balanced carbon cycle.