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On the habitability of a stagnant-lid Earth

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Whether plate tectonics is a recurrent feature of terrestrial bodies orbiting other stars or is unique to the Earth is unknown. The stagnant-lid may rather be the most common tectonic mode through which terrestrial bodies operate. Here we model the thermal history of the mantle, the outgassing evolution of H_2O and CO_2, and the resulting climate of a hypothetical planet with the same mass, radius, and composition as the Earth, but lacking plate tectonics. We employ a 1-D model of parameterized stagnant-lid convection to simulate the evolution of melt generation, crust production, and volatile extraction over a timespan of 4.5 Gyr, focusing on the effects of three key mantle parameters: the initial temperature, which controls the overall volume of partial melt produced; the initial water content, which affects the mantle rheology and solidus temperature; and the oxygen fugacity, which is employed in a model of redox melting to determine the amount of carbon stored in partial melts. We assume that the planet lost its primordial atmosphere and use the H_2O and CO_2 outgassed from the interior to build up a secondary atmosphere over time. Furthermore, we assume that the planet may possess an Earth-like ocean. We calculate the atmospheric pressure based on the solubility of H_2O and CO_2 in basaltic magmas at the evolving surface pressure conditions. We then employ a 1-D radiative-convective, cloud-free stationary atmospheric model to calculate the resulting atmospheric temperature, pressure and water content, and the corresponding boundaries of the habitable zone (HZ) accounting for the evolution of the Sun's luminosity with time but neglecting escape processes. The interior evolution is characterized by a large initial production of partial melt accompanied by the formation of crust that rapidly grows until its thickness matches that of the stagnant lid so that the convecting sublithospheric mantle prevents further crustal growth. Even for initial water concentrations in excess of thousands of ppm, the high solubility of water in surface magmas limits the maximal partial pressure of atmospheric H_2O to a few tens of bars, which places de facto an upper bound on the amount of water that can be delivered to the surface and atmosphere from the interior. The relatively low solubility of CO_2 causes instead most of the carbon contained in surface melts to be outgassed. As a consequence, the partial pressure of atmospheric CO_2 is largely controlled by the redox state of the mantle, with values that range from a few up to tens of bars for oxygen fugacities between the iron-wüstite buffer and one log-unit above it. At 1 AU and for most cases, liquid water on the surface is possible, hence the planets considered would be regarded as habitable although the atmospheric temperature may be well above the temperature limits for terrestrial life. The inner edge of the HZ depends on the amount of outgassed H_2O and is located further away from the star if no initial water ocean is assumed. The outer edge of the HZ is controlled by the amount of outgassed CO_2, hence by the assumed redox state of the mantle and its initial temperature.