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On the relative influence of initial H_2O and CO_2 contents on the primitive surface conditions and evolution of rocky (exo-)planets

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Estimates of initial volatile contents inside planets primitive magma oceans (hereafter « MO ») varies by several orders of magnitude. However, the release of greenhouse gasses such as H_2O and CO_2 during cooling and crystallization of the MO will greatly affect the atmosphere formation, the planet cooling time scale, its surface temperature, and its potential for water condensation and habitability. We have therefore conducted a systematic study of the influence of volatile contents on the secular convective cooling and solidification of a MO in interaction with the outgassed atmosphere. We developed a 1D model coupling MO dynamics with a convective-radiative atmosphere using either a grey approximation or k-correlated opacities, with or without clouds. Initial CO_2 and H_2O contents were varied between 10^{-3} and 14×10^{-2} wt%, and from 0.05 to 2.2 times the Earth Ocean current mass (MEO). We considered an Earth-like planet, with its Sun intensity ranging from half to the present-day value and a solar distance from 0.63 to 1.30 AU. The atmosphere albedo was varied between 0.2 and 0.8.

All cases shows the same evolution in two main episodes : after (1) a very rapid cooling stage driven by the MO cooling and crystallization, the planet reaches (2) a quasi-steady state where subsequent evolution will take billions of years. The surface temperature is controlled by the balance between the IR outgoing flux, and the heat flux out of the MO during (1), and the solar flux during (2). At the end of the first regime (hereafter « ERCS »), the planetary surface can (i) still be molten or partially-molten, (ii) solid but dry, (iii) solid and covered by a water ocean, depending on the initial volatile contents, sun characteristics and sun-planet distance. Regimes diagrams were obtained. There is a critical sun-planet distance D_c below which water will never condense, whatever the initial volatile content. For distances larger than D_c, water condensation strongly depends on the relative proportion of CO_2 and H_2O. The larger the H_2O content, the easier it is to reach the equilibrium water vapor pressure and therefore to condense water, for the tested range of CO_2 contents. At a given H_2O content, too much CO_2 precludes the formation of a water ocean by greenhouse effect. We were able to find a simple scaling to predict the limit of water condensation as a function of the atmosphere albedo, the sun-planet distance, the sun characteristics, and the initial MO volatile contents. This allows us to place bounds on the habitability potential of Venus, and/or recently discovered exo-planets such as Proxima-b.