Effects of CO on carbon-silicate cycle and on surface environmental evolution of terrestrial planets

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The surface environment of rocky planets, in particular the surface temperature, is important in discussing the origin of life and habitability. The surface temperature of a planet is greatly influenced by its atmospheric composition, which is known to evolve over time due to the surface- mantle carbon-silicate cycle.

Previous studies of the Earth's carbon-silicate cycle assumed that the mantle is sufficiently oxidized and the carbon is degassed in the form of CO_2 . Recently, however, geochemical studies suggested that the early Earth's mantle may have been reduced (e.g., Aulbach and Stagno, 2016), and that carbon monoxide (CO) may have been present in the early atmosphere (Endo et al., 2016). Such a scenario is still controversial (e.g., Trail et al., 2011), and it is unclear how the surface environment changes when CO is added to the atmosphere.

In this study, we examine how the presence of CO in the volcanic gas and the atmosphere affects the evolution of the surface environment of Earth and other rocky planets. Our approach consists of two steps. First, we calculated the 1D atmospheric structure with varying CO_2 and CO pressures, using the 1D radiative-convective model "atmos (Kasting et al. 1984)". This allowed us to find the relation between the atmospheric composition and the surface temperature. The second step is to calculate the carbon-silicate cycle with CO over 4.5 billion years. We considered two models for the degassing composition; one model assumed the constant CO to CO_2 ratio that is same as the value of the present Earth, while the other assumed a more CO-rich degassing compositions (i.e., a more reduced mantle) at the early stage. In this study, we assume that the CO oxidation rate is determined by the hydrogen escape rate.

From the radiative-convective calculation of the CO-CO_2 atmospheres with various pressures, we found that the increase of CO pressure results in a lower surface temperature if CO_2 pressure is less than 1 bar, while it results in a higher surface temperature if CO_2 pressure is larger than 1 bar. This is because of the two counteracting effects of CO: (1) to increase the planetary albedo through Rayleigh scattering, and (2) to promote the greenhouse effect of CO_2 by increasing the total pressure (pressure broadening). With a small CO_2 pressure, the former effect wins and the planet becomes cooler.
By calculating the carbon-silicate cycle with such a climatological effect of CO, we found that the planet does not experience significant hydrogen loss throughput the geological evolution, and as a result, a large amount of CO (4-70 bar) remained in the atmosphere, regardless of the initial conditions or the oxidation state of the early mantle. The amount of CO remained in the atmosphere was larger for the models with an initially reduced mantle, and these models underwent a colder climate, with a surface temperature below 273 K for a long time, as the CO_2 pressure were always less than 1 bar. This is inconsistent with the geological evidence of the Earth, which indicates that the Earth has been mostly unfrozen. On the other hand, the model with a constant CO-to-CO_2 degassing ratio resulted in surface temperature above 273 K most of the time. This result favors the scenario that the oxidation stage of the early mantle was similar to that at present. However, the decreased solar constant may also make the latter scenario too cold, which would suggest that there may have been other CO removal processes that were not considered in this study.

Keywords: terrestrial planets, planetary surface environment, carbon-silicate cycle, redox degree

