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The duration of habitable condition for large and small Earth-like planets

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The orbital condition for the Earth-like planets which may have liquid water on its surface is known as the habitable zone (e.g., Kasting et al., 1993; Kopparapu et al., 2013). However, the condition for the Earth-like planets which can maintain the warm and wet climate through the evolution may be different from that for the habitable zone. The climate of the Earth-like planets would actually depend on the CO_2 degassing rate via volcanism because the amount of the atmospheric CO_2 is controlled by the carbonate-silicate geochemical cycle (Kadoya & Tajika, 2014, ApJ, 790:107). The CO_2 degassing rate decreases with time owing to decrease in mantle temperature and attenuation of volcanic activity (Tajika & Matsui, 1992, EPSL, 113). The thermal evolution of the planets should, however, depend on the planetary mass.

In this study, we apply a parameterized convection model to the thermal evolution of the Earth-like planet with different masses and with plate-tectonics in order to estimate the evolution of average mantle temperature, seafloor spreading rate, melt generation depth, melt production rate, and the CO_2 degassing rate for the planets. The results are compared with the climate mode diagram for the Earth-like planets proposed by Kadoya & Tajika (2014), and also, the evolutions of the climate of the Earth-like planet are discussed.

The average mantle temperature monotonically decreases with time when an initial average mantle temperature is higher than 3000 K. As expected, the average mantle temperatures of large planets cool more slowly than that of small planets do. However, the difference between the mantle temperatures of the planets is smaller than 100 K, which is consistent with the recent work (e.g., Schaefer & Sasselov, 2015). The seafloor spreading rate is larger on large planets than on small planets because the heat flow is higher on large planets than on small planets. On the other hand, the melt generation depth of large planets is smaller than that of small planets owing to the difference in the surface gravity. The net result of the melt generation rate is larger on large planets than on small planets although the difference is smaller than those of the seafloor spreading rate and the melt generation depth. In addition, because large planets have a larger surface area than small planets, the CO_2 uptake rate via silicate weathering on large planet is larger than that on small planets when the temperature distribution is the same. As a result, the climate evolutions of large and small planets are almost the same as long as the areal ratio of continents and oceans is the same.

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