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Effects of obliquity and carbon cycle on the multistable solutions of climate of water-rich extraterrestrial planets

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Water-rich terrestrial planets like the Earth are expected to be found in the extrasolar planetary systems in the near future. To discuss habitability of such planets, we have to investigate characteristic features of climate system of the water-rich terrestrial planets.

One of the key factors which controls climate is ”obliquity”, that is, the inclination of planet’s axis. The climate of the Earth is stable partly because the Earth’s obliquity is stabilized by the existence of the Moon, although it is not the case, in general, for other planets. Considering a large influence of obliquity on the solar energy distribution on the planetary surface, obliquity variations could induce large climate change on the planets.

In this study, we investigate the climate of the water-rich terrestrial planets systematically under various obliquities and solar flux conditions, and with a negative feedback mechanism of carbonate-silicate geochemical cycle. We use a one-dimensional energy balance climate model (1D-EBM) with a simple model of carbonate-silicate geochemical cycle in order to understand characteristic behaviors of the climate system of water-rich terrestrial planets.The main results obtained in this study are as follows;

1. We classified the behaviors of the climate system without carbonate-silicate geochemical cycle (i.e. a constant pCO_2 condition) into the following 4 stable solutions: 1) ice-covered solution (snowball solution), 2) seasonal ice-cap solution, 3) permanent ice-cap solution, and 4) ice-free solution. Seasonal ice-cap solution exists at lower solar flux conditions compared with ice-free solution at low obliquity, shrinking with an increase in the obliquity and disappearing at 54 degrees. Permanent ice-cap solution also exists at lower solar flux compared with seasonal-ice-cap solution at the obliquity less than 28 degrees. Above the obliquity of 54, either ice-free solution or snowball solution can exist.

2. When carbonate-silicate geochemical cycle is taken into account, the range of solar flux condition for all the solutions expand at any obliquities, indicating that the carbon cycle make the condition for habitable climate broader range of semi-major axis inside the habitable zone.

3. In the planets with carbonate-silicate geochemical cycle, we found that pCO_2 does not depend strongly on obliquity, even if the climate mode is different. This is because, with an increase in obliquity, a decrease of weathering rate at low latitudes may tend to be compensated by an increase of weathering rate at high latitudes.

4. Large CO_2 degassing rate could maintain warm climate even if the solar flux is lower. At low obliquity (for example, 23.4 degrees), warm climate cannot be maintained by much lower CO_2 degassing rate (for example, 0.6 times the degassing rate of the Earth today). However, at high obliquity (for example, 90 degrees), warm climate can be maintained by lower CO_2 degassing rate (for example, at most 0.3 times the degassing rate of the Earth today), compared with at small obliquity condition.

Keywords: extraterrestrial planet, planetary climate, obliquity, carbonate-silicate geochemical cycle, degassing, EBM