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Surface environment of water-rich extraterrestrial planets with carbon cycle under various obliquities and geographies

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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 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. 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. The climate of the Earth has been stabilized on long timescales by a negative feedback mechanism involving removal of CO2 from the atmosphere by weathering of silicate minerals on land followed by carbonate precipitation in oceans, and continuous supply of CO2 from the planetary interiors to the atmosphere via volcanism. This mechanism should be required for water-rich extraterrestrial planets to maintain warm climate stably. Without this mechanism, the climate of planets cannot be stabilized against changes in the various climate forcings. Considering that the amount of weathering is strongly influenced by surface temperature and the area of continent available for weathering, and that temperature of continent responds to the insolation more rapidly than that of oceans, long-term climate mode would be different under different obliquity or geography.

While the climate of extraterrestrial planets with high obliquities was investigated by Williams and Kasting (1997), there are few studies which systematically investigate the effects of obliquity change on the climate of the planets with carbonate-silicate geochemical cycle. In this study, we therefore investigate systematically the climate of the water-rich terrestrial planets with a negative feedback mechanism of carbonate-silicate geochemical cycle under various obliquities, semi-major axes and different geographies.

We tested with 3 different geographies; "Slice" (continent is distributed at the same fraction for each latitude.), "Equatorial" (supercontinent is centered around the equator.) and "Bipolar" (supercontinent is centered around both poles.). We found that, while the "permanent ice-cap mode" (partially ice-covered throughout the year) and the "seasonal ice-cap mode" (partially ice-covered seasonally) exist stably at low obliquities, the ranges of semi-major axis for these climate modes shrink and finally disappear with an increase of obliquity. This is because latitudinal gradient of annual mean insolation becomes smaller with an increase of obliquity, resulting in meridional heat transport to be insufficient. When carbonate-silicate geochemical cycle is taken into account, the ranges of semi-major axis for all the climate modes expand at any obliquities, compared with the cases without carbon cycle, indicating that the carbon cycle strongly stabilizes the climate for the planets with any obliquities inside the habitable zone. These features are found at any geographies. Dependence of obliquity on climate modes is quite different among different geographies. The climate is cold for lower obliquities at Equatorial geographies, whereas the climate is cold for higher obliquities at Bipolar geographies. This characteristic of climate modes at Slice geography is intermediate, but is closer to those of Equatorial characteristic. The results derive from a negative feedback of carbonate-silicate geochemical cycle. If continent is centered on the equator, at the same semi-major axis, pCO2 decrease with the decrease of obliquity, because weathering occurs effectively throughout 1 year at lower latitude where annual mean insolation and land fraction are large. In contrast, if continent is centered on poles, pCO2 decreases with the increase of obliquity at the same semi-major axis, because weathering occurs effectively throughout 1 year at higher latitude where seasonal insolation largely changes and land is the largest.

Keywords: obliquity, carbonate-silicate geochemical cycle, continental distribution, exoplanet, habitability, planetary climate