

Planetary climate on terrestrial exoplanets with excess water within the habitable zone

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Conventional theories regarding planetary habitability assumed an Earth-like planet where the amount of ocean water was small enough that land and ocean coexist on the planetary surface. However many recent theories of planet formation predict terrestrial exoplanets in the habitable zone could have much more water than the Earth. Such terrestrial planets are covered entirely with oceans, which are called ocean planets. Ocean planets with much water in the habitable zone are predicted to have extremely hot climate due to strong greenhouse effect of CO₂, because H₂O high-pressure (HP) ice prevents the chemical weathering on the seafloor. However, recent numerical experiments of thermal convection of the HP ice suggested that heat flux from oceanic crust result in melting the HP ice. Although previous studies assumed the horizontally uniform and small heat flux from oceanic crust, plate tectonics produces a large variation of the heat flux, which would lead to melt more larger portion of the HP ice than that in previous studies. Furthermore, melting the HP ice raises the temperature on the interface of rock/water regardless of the surface temperature in contrast to that obtained by the adiabatic condition. Such high temperature enhances seafloor weathering because of temperature dependence of chemical weathering. Consequently, ocean planets would have cold climate due to large removal flux of atmospheric CO₂, if the HP ice was massively melting.

In this study, we consider an Earth-sized ocean planets with plate tectonics and explore the possibility that the high heat flux at the mid-ocean ridge leads to melting the HP ice and thus making seafloor weathering efficiently works. To that end, we develop integrated climate model for ocean planets that includes melting of HP ice, seafloor weathering, and the carbon cycle. As a result, we have found that the high-pressure ice is entirely molten when the high-pressure ice is thin (e.g., < 130 Earth's ocean masses for the current mean heat flow in the Earth's mantle) and then the weathering occurs in the seafloor. We have also found that the planetary climate for large ocean masses (e.g., > 60 Earth's ocean masses for Earth-like degassing flux) lapses into two extreme climates; quite hot ones with a CO₂ rich atmosphere, in which the surface temperature is larger than 350 K, or cold ones with a CO₂ poor atmosphere, even a snowball state. The abrupt transitions from warm to extreme climates are triggered by two runaway processes; CO₂ accumulation induced by the upper limit to the seafloor weathering flux and CO₂ clearing induced by melting of the high-pressure ice. This result suggests a low probability of exoplanets with clement climates, like the present Earth, and necessity that we consider water amounts and their thermo-chemical structure to discuss planetary climate, even if the planet in the habitable zone.

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