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Inner edge of the habitable zone for dry terrestrial planets

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Abstract

Most of the studies for habitable planets have focused on Earth-like planets with globally abundant water on the planetary surface. Liquid water vaporizes entirely when planets receive insolation above a certain critical value, which is called the runaway greenhouse threshold. This threshold forms the inner most limit of the habitable zone. We investigated the effect of the distribution of surface water on the runaway greenhouse threshold for Earth-sized planets using a three-dimensional dynamic atmosphere model. We found that the runaway threshold increases from about 130% (an aqua planet) to 180% of the present insolation at Earth's orbit. Our results indicate that the inner edge of the habitable zone is not a single sharp boundary, but a border whose location varies depending on the surface water distribution.

1. Introduction

Liquid water is thought to be necessary for the emergence and evolution of life on the planetary surface. The habitable zone id defined as the region at such a distance from the host star that liquid water on the planetary surface remains stable [1, 2]. Liquid water vaporizes entirely when planets receive insolation above a certain critical value, which is called the runaway greenhouse threshold. The values for the runaway threshold estimated by three-dimensional general circulation models (GCMs) tend to be higher than that estimated by one-dimensional climate models [3]. This is because an unsaturated region of water vapor appears in 3-D models, which is formed by the descending flow of the Hadley circulation. Estimations of the runaway threshold in previous studies conventionally assumed a water planet with a large amount of water on its surface. In this study, we call such a planet "an aqua planet". The amount of water that a planet has strongly affects the planetary climate. Abe et al. (2011) focused on the amount of water which a planet has and investigated these thresholds using a three-dimensional general circulation model. As results, they found that planets with less amount of water than Earth-like planets have the wider habitable zone. However, it is not enough to understand the relationship between the distribution of water and the climate because their range of the amount of water is narrow, leading the almost same distribution of liquid water on the planetary surface [4]. Thus, we clarify the relationship between the runaway threshold and the surface water distribution by performing GCM calculations.

2. Methods

We assumed various of the distribution of surface water and investigated the effect of the distribution of surface water on both the runaway greenhouse threshold and the complete freezing threshold for Earth-sized planets using a three-dimensional general circulation model. We consider three types of the surface water distribution on a planet: a zonally uniform water distribution, a meridonally uniform water distribution, and water distribution with different water amounts assuming the planetary topography (Earth, Mars and Venus). We use three-dimensional GCM, CCSR/NIES AGCM5.4g, which was developed for modeling of the present Earth's climate. We set the same setting as that of [4] and [5] except for the initial surface water distribution. We perform GCM calculation with increased insolation until the climate reaches a thermal equilibrium where the radiation budget is balanced within about 1 W/m^2. We repeat these steps until the climate cannot reach the equilibrium state and the calculation gets unstable, and determine the runaway threshold as the highest insolation for keeping the thermal equilibrium state.

3. Results and Discussions

We recognized two climate regimes: the aqua planet regime and the land planet regime. In the aqua planet regime, the runaway threshold is almost constant but, in a case for a zonally uniform water distribution, it varies continuously with surface water distribution from aqua planet's value (~130% S_0) to ~180% S_0 (the extreme case of a land planet), where S_0 is the present Earth's insolation. Although the runaway threshold for a meridionally uniform water distribution also increases from the typical value for the aqua planet regime to one for the land planet regime with increasing the dry area, the runaway threshold in the land planet regime is quite low compared to that for a zonally uniform water distribution. It is because that a part of the tropical atmosphere is always wet for a meridionally uniform water distribution, leading the limit of the outgoing longwave radiation. For the surface water distributions determined by the Earth's, Mars' and Venus' topographies, we also recognize two climate regime and the boundary is around a land fraction of ~0.4. The land fraction is the ratio of dry surface area divided by the total area. In a case of a land fraction less than 0.4, the runaway threshold is close to that of an aqua planet. On the other hand, when a land fraction is larger than 0.4, the runaway threshold is located between that for a zonally and meridionally uniform water distributions. Depending on the photography, the amount of water at the boundary between an aqua planet and a land planet is typically around 10% of the amount of the Earth's ocean volume.

4. Summary

Previous studies [4, 5] showed the climate of a planet with a small amount of water on its surface, which is called a land planet, is significantly different from that of an aqua planet. A land planet has a larger runaway threshold which means the inner edge of the habitable zone for a land planet is located closer to the its host star than that of an aqua planet. Since previous studies only investigated a few limited cases for the surface water distribution, the relationship between the runaway threshold and the surface water distribution is still not clear. In this study, we considered three different types of surface water distributions and systematically investigated the runaway threshold for these cases using a GCM. For zonally and meridionally uniform water distribution cases, we recognized two climate regimes: the aqua planet regime and the land planet regime. The runaway threshold increases from ~130% to ~180% S_0. Even if they have the same land fraction, the runaway threshold for a meridionally uniform water distribution is quite lower than that for a zonally uniform water distribution. Also, we found that the runaway threshold for surface water distribution determined by terrestrial planet's topographies is close to that for a meridionally uniform water distribution. The land fraction at the boundary between an aqua planet and a land planet is typically around 0.4 which corresponding with ~10% of the present Earth's ocean volume. Our results indicate that the inner edge of the habitable zone is not a single sharp boundary, but a border whose location varies depending on the surface water distribution.

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