The evolutionary climatic track of the hypothetical Earth with different conditions of central star and semi-major axis

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The climate of the Earth is affected strongly by the insolation from the Sun and also by the amount of greenhouse gasses, especially CO_2, in the atmosphere. The former depends on the mass and age of the central star, and the semi-major axis of the planet, while the latter depends on the degassing rate of CO_2, which, in turn, depends on the thermal evolution of the planetary interiors. Thus, the climate of the Earth may be controlled both by the evolution of the planetary interior and the evolution of the host star. It is however unknown how the climate of planet could evolve if the central star and semi-major axes are different from those of the Earth today. In this study, we examine the climatic evolution of the Earth with different conditions of host stars and orbital semi-major axes.
We use a one-dimensional energy balance model coupled with a carbon cycle model to estimate the climate, a parameterized convection model coupled with a mantle degassing model to estimate the evolution of the CO_2 degassing rate, and a standard evolution model of the Sun with a relationship between mass and lifetime of main sequence stars to estimate the evolution of luminosity of the central star.
We found that, while the climate of the Earth orbiting at the inner region of the habitable zone (HZ) becomes hot owing to the increase in the luminosity of the central star, the climate of the Earth orbiting at the outer region of the HZ becomes cold because the CO_2 degassing rate of the Earth decreases with time. In particular, the Earth orbiting at the outer region of the HZ becomes the snowball climate mode after 3 Gyr, irrespective of the mass of the central star. This timescale depends mainly on the planetary parameters, such as the land fraction and land distribution. Thus, the lifetime of the habitability of the planets orbiting at the outer region of HZ is controlled largely by the evolution of the planetary interiors rather than the stellar evolution. This is essentially because the greenhouse effect of CO_2 is necessary for the planets orbiting even in the HZ to have a warm and wet climate.

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