Abrupt Climate Transition of Icy Worlds from Snowball to Moist or Runaway Greenhouse. Jun Yang[1], Feng Ding[2], Ramses M. Ramirez[3], W. R. Peltier[4], Yongyun Hu[1], and Yonggang Liu[1], [1]Department of Atmospheric and Oceanic Sciences, Peking University (junyang@pku.edu.cn; yyhu@pku.edu.cn), [2]Department of the Geophysical Sciences, University of Chicago, [3]Department of Astronomy, Cornell University, and [4]Department of Physics, University of Toronto.

Abstract: Ongoing and future space missions aim to identify potentially habitable planets in our Solar System and beyond. Planetary habitability is determined not only by a planet's current stellar insolation and atmospheric properties, but also by the evolutionary history of its climate. It has been suggested that icy planets and moons become habitable after their initial ice shield melts as their host stars brighten. Here we show from global climate model simulations that a habitable state is not achieved in the climatic evolution of those icy planets and moons that possess an inactive carbonate-silicate cycle and low concentrations of greenhouse gases. Examples for such planetary bodies are the icy moons Europa and Enceladus, and certain icy exoplanets orbiting G and F stars. We find that the stellar fluxes that are required to overcome a planet's initial snowball state are so large that they lead to significant water loss and preclude a habitable planet. Specifically, they exceed the moist greenhouse limit, at which water vapour accumulates at high altitudes where it can readily escape, or the runaway greenhouse limit, at which the strength of the greenhouse increases until the oceans boil away. We suggest that some icy planetary bodies may transition directly to a moist or runaway greenhouse without passing through a habitable Earth-like state (Fig. 1).

Background and Conclusion: Icy worlds are common in the solar system (such as Europa, Enceladus, Ganymede, and early Earth) and plausibly also in extra-solar systems. A fundamental question is that: Would such icy planets and moons become habitable once their ice cover melts? There are two ways for the icy worlds to escape the globally ice-covered snowball states. One is that continuous atmospheric accumulation of CO_2 from volcanic outgassing during the snowball phase triggers the melting [1]; this is plausible for planets having an active carbon cycle (e.g., Earth), and they become habitable for life after the ice melts. The other is that the stars brighten with time and the ice melts once the stellar flux exceeds a critical value; this is the case for planets and moons lacking an active carbon-silicate cycle and having low concentrations of greenhouse gases (e.g., Europa). Here, we investigate the second case using a series of three-dimensional (3D) climate model experiments.

Using 0D and 1D energy balance climate models and a 3D gray-gas atmospheric general circulation model (GCM), previous studies had examined the climate evolution of a snowball planet having low concentrations of greenhouse gases [2-4]. However, their models were unable to account for the effects of clouds, lapse rate, spatial snow and ice distributions, realistic atmospheric radiative transfer, and/or meridional atmospheric heat transport, which have been identified to be critical for simulating the snowball climate. Moreover, the simple climate models cannot simulate vertical water vapor transports or the onset of a moist greenhouse state. These studies showed that a post-snowball climate should be hot, but whether it is habitable for life or not remains unclear. In contrast to previous studies [5-7] that suggest the existence of a habitable world after the snowball deglaciation, here we show that the increased stellar insolation will force the planet into an uninhabitable moist or even runaway greenhouse state. Note that our conclusion applies to planets that have an inactive carbonate-silicate cycle and low concentrations of greenhouse gases in G-star and F-star systems, but not to Earth-like planets with active carbonate-silicate cycle and massive CO_2 accumulation in a snowball state.

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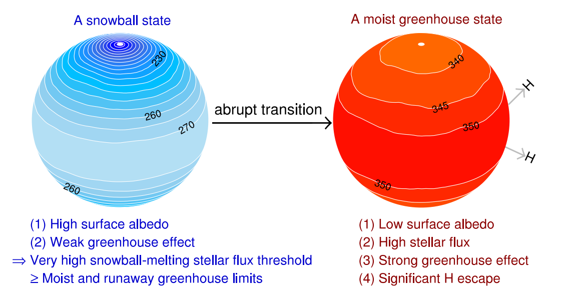

Fig. 1. Schematic illustration of the climate transition under stellar brightening and the underlying physical mechanisms. The contour lines are surface temperatures right before snowball melting (left) and after the melting (right), with a contour interval of 5 K.

For more details, please see our paper: Abrupt Climate Transition of Icy Worlds from Snowball to Moist or Runaway Greenhouse, *Nature Geoscience*, in press.