LACK OF SNOWBALL BIFURCATIONS ON EARTH-LIKE TIDALLY-LOCKED EXOPLANETS.

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Introduction: M-stars are the most common type of stars in the galaxy, and in recent years there has been a large amount of work on whether tidally-locked exoplanets in the habitable zone of M-stars could host life (e.g., [1]-[6]). The discovery of a likely terrestrial planet in the habitable zone of the late M-star Proxima Centauri b [7], our nearest stellar neighbor, makes this topic particularly timely. One issue that influences planetary habitability is the occurrence of global glaciations, which are called Snowball Earth events in Earth history [8]-[9]. Snowball Earth events are an acute stressor on life, but may increase the complexity of life through evolutionary pressure and by increasing the atmospheric oxygen concentration. Moreover, planets in the habitable zone with low levels of CO2 outgassing may experience limit cycles between habitable and snowball climate states [10]-[14]. It is therefore important to understand the transitions into and out of snowball events for tidally-locked planets.

In this work, we use a 3D Global Circulation Model (GCM) to show that tidally-locked exoplanets cannot go through a Snowball bifurcation. We then use a 1D Energy Balance Model (EBM) to explain our results.

Methods: We use the 3D GCM PlanetSimulator with modern-Earth continental configuration and with a slab ocean of constant depth. The atmospheric constituents are as on modern-Earth. We fix the orbit of the planet so that it is tidally-locked: it rotates synchronously with the star. For different values of insolation, we run the model to equilibrium starting from both ice-free (cold start) and ice-covered (warm start) solutions. We record the final 5-year averages of the equilibrium surface temperature and sea ice cover to build bifurcation diagrams.

Results & Discussion: We recover a strong hysteresis and Snowball bifurcation for the Earth model (non-tidally locked), in accordance with widely-accepted previous results (Fig. 1). When modifying the model for a tidally-locked planet, we do not find any bifurcations (Fig. 2). We see a slight difference in surface temperatures for certain intermediate values of insolation. However, this is due to the simple sea ice scheme of the GCM, where one grid cell can only be fully ice-covered of fully ice-free. Increasing the model resolution can suppress this gap.

We can understand this result with a simple 1D Energy Balance Model. Although we cannot explain this in detail in this note, the take-away message is that it has to do with the shape of the insolation. A tidally-locked planet has an insolation shape that increases sharply as we approach the substellar point, while the Earth has a flatter insolation shape. This prevents a tidally-locked planet from going through a Snowball bifurcation.

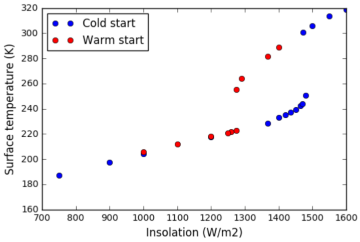

Fig. 1. Bifurcation diagram of the surface temperature for Earth-like planet. "Cold start" indicates the model was first ran at 750 W/m2. "Warm start" indicates the model was first ran at 1600 W/m2.

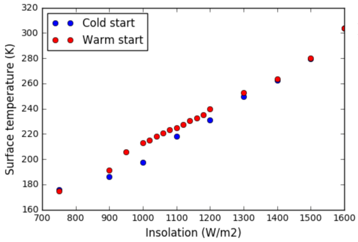

Fig. 2. Similar as Fig.5; Bifurcation diagram of the surface temperature for tidally-locked exoplanet.

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