Habitability of Earth-like planets with high obliquity and eccentric orbits: results from a general circulation model

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Introduction and experimental setup

We explore the effects of the two parameters obliquity θ and orbit eccentricity e for the habitability of idealized Earth-like planets. We use the **general circulation model** PlaSim coupled to a **thermodynamic sea ice model**. All planets are covered with a global ocean (aquaplanets), which is represented by a vertically-diffusive slab ocean (no horizontal oceanic heat transport). The atmospheric CO_2 concentration is set to Earth's value.

For each set of parameter values we gradually reduce the irradiation S - which is equivalent to changing the planet-star distance - and analyse the planet's surface temperature and ice coverage. From the ice coverage of the planet we deduce its habitability.

Multistability of climate

Close to the outer boundary of the habitable zone, planets can exhibit **two stable climate states** that differ in the ice-coverage of the surface, one warm and one cold state (Lucarini et al., 2013). This **multistability** is strongly influenced by the obliquity θ, in particular on circular orbits. The **largest extent of the warm state** is found for $\theta = 55^\circ$, where the surface temperature distribution is **most homogeneous** (Figure 1). The smallest extent of the warm state and the largest extent of the cold state is found for planets with low θ.

On eccentric orbits, the range of distances that allow for two stable climate states shrinks relative to circular orbits, possibly leading to **monostability for planets with very large seasonal variability** (Figure 1). Furthermore, our results show that the maximal distance allowing for the existence of a warm state is a good proxy for habitability on planets without seasonal variability, but underestimates the habitability of planets with high seasonal variability (red vertical lines in Figure 3).

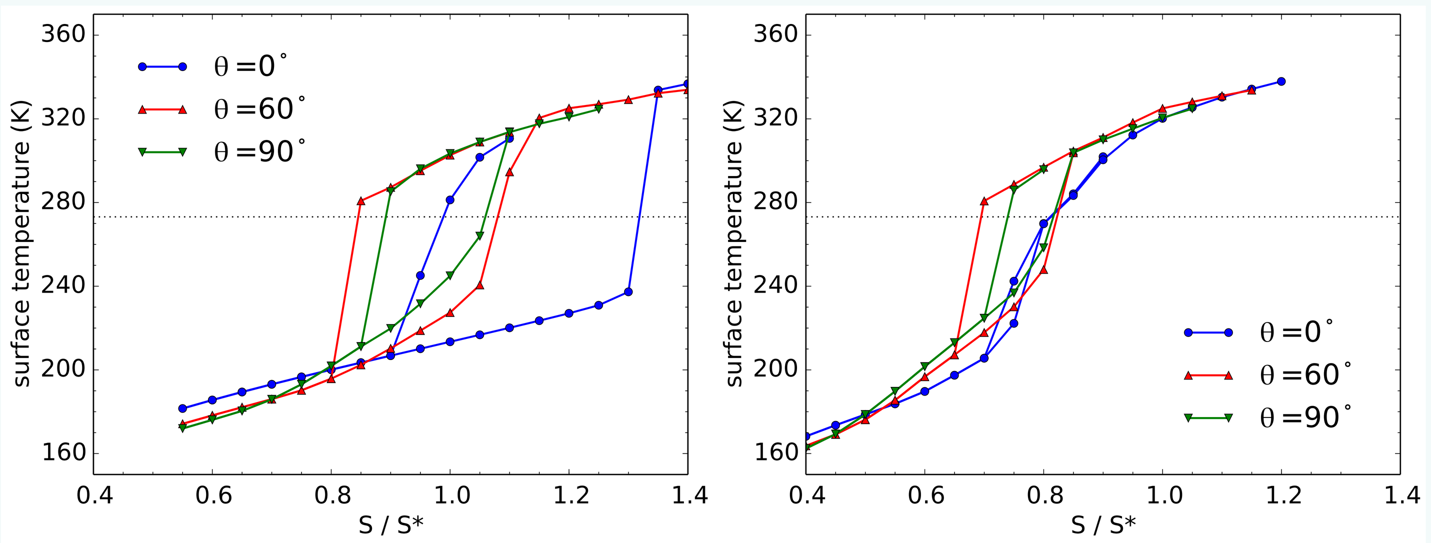

Figure 1: Global and annual mean surface temperature depending on irradiation S; eccentricity $e = 0$ (left) and $e = 0.5$ (right)

Implications for habitability

Planets with **low obliquity** receive most energy **at the equator**, whereas planets with **high obliquity** receive most of their energy **at the poles**. On an eccentric orbit with $e = 0.5$, different values of obliquity can result in very different distribution of surface temperature and sea ice coverage (Figure 2). This has important implications for habitability (Figure 3).

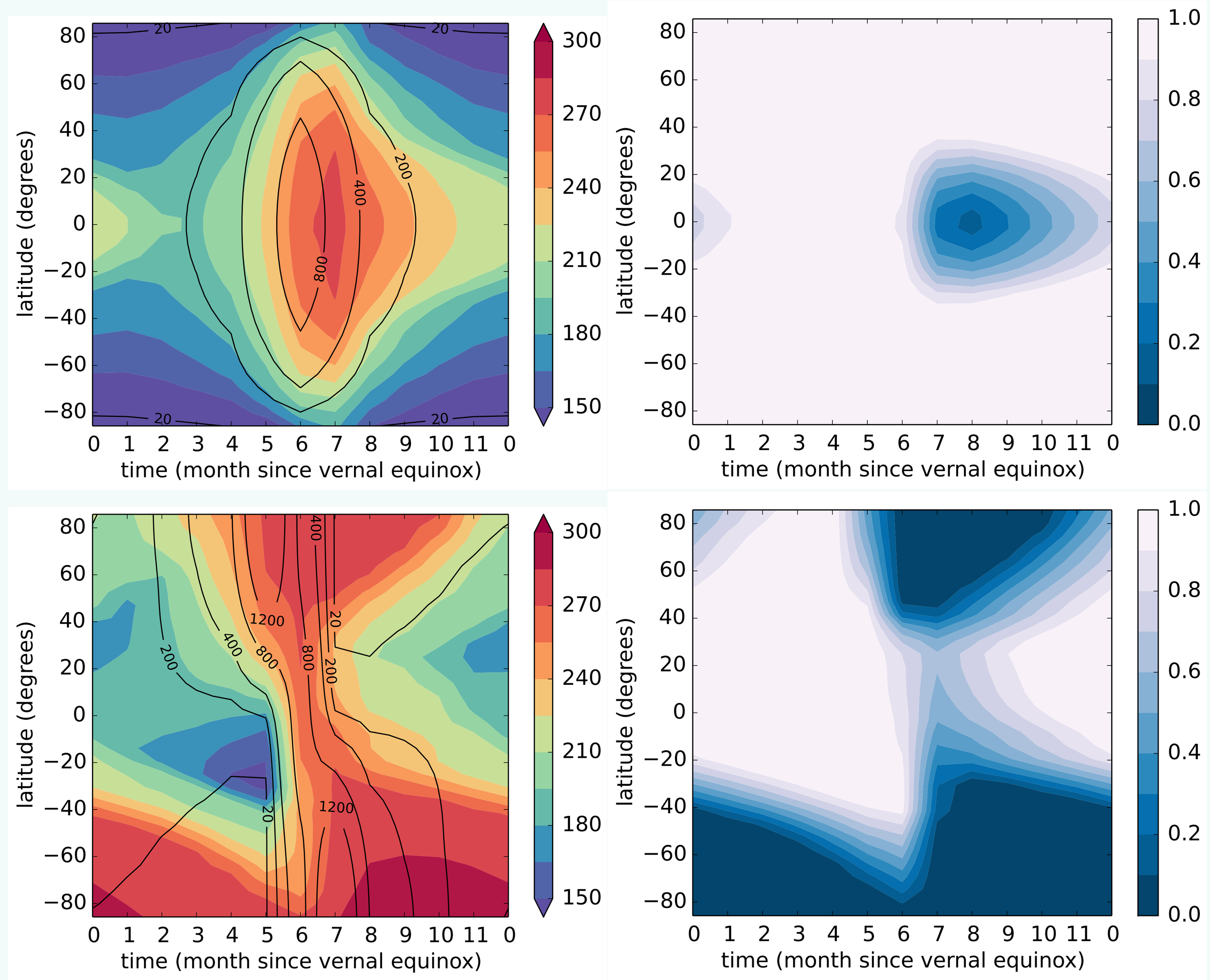

Figure 2: Surface temperature (left) and normalized sea ice thickness (right) at $S = 0.7S^*$; eccentricity $e = 0.5$ and obliquity $\theta = 0^\circ$ (top) and $\theta = 90^\circ$ (bottom)

Overall, our results show that **seasonal variability can extend the maximal distance** between planet and host star that still allows for **habitable conditions** on planets with Earth-like atmospheres (Figure 3). While the effect of obliquity on habitability is comparatively small on circular orbits, it becomes highly relevant on eccentric orbits. This effect of seasonal variability on habitability is primarily **due to regions that are ice-free only at some time of the year**. An appropriate assessment of the HZ therefore asks for a clear distinction between **different degrees of habitability** (Figure 3).

Moreover, large seasonal variability resulting from extreme orbital forcing has implications for traditional estimates of the outer boundary of the habitable zone based on radiation convection models. In these models, surface temperatures are assumed to be stabilized around 273 K by silicate weathering. As our results show, this assumption of stationary and uniform surface temperatures is challenged on planets with extreme orbital forcing.

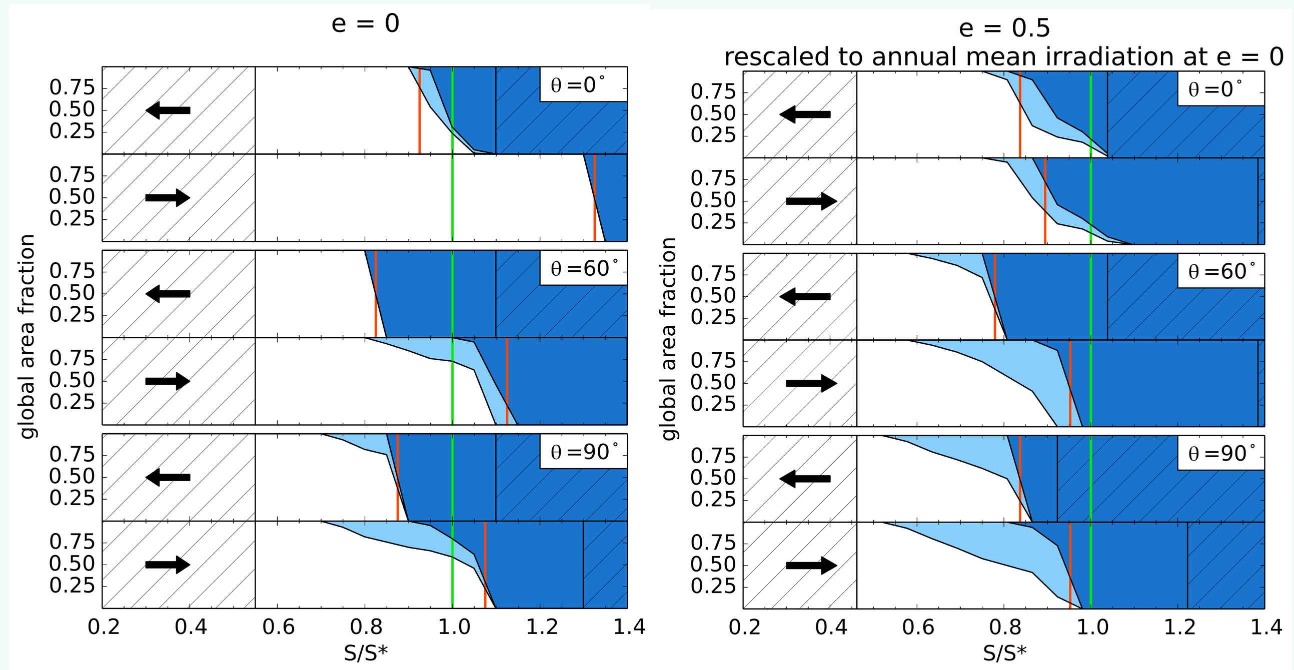

Figure 3: Degree of habitability for simulations with $e = 0$ (left) and $e = 0.5$ (right), and $\theta = 0, 60, 90^\circ$ (from top to bottom); the color denotes the fraction of the planet's surface that is (partially) habitable (dark blue), temporally habitable (light blue) and unhabitable (white); the red vertical line marks the point of transition between the warm and cold state; the solid green vertical line indicates 1 AU as reference; arrows indicate whether an ice-free or ice-covered starting point is assumed; hashes indicate areas outside the simulated range of S

Future perspectives

Our results generally confirm previous studies with energy balance models about the effects of obliquity on circular orbits (Spiegel et al., 2009), but differences are found on eccentric orbits (Dressing et al., 2010). As compared to traditional estimates of habitability based on radiation convection models, our estimates of habitability are **conservative**, because we assume a **fixed CO_2 concentration** and hence neglect the stabilizing climate feedback of **silicate weathering**. Further experiments are required that combine the effects of seasonal variability with a dynamic CO_2 concentration.

References

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