Extreme orbital forcing and its implications on habitability

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Objectives

Two stable climate states might be a common feature of terrestrial planets. While in a warm state liquid water can exist on the surface of such planet, the initiation of a snowball state sets the **outer boundary of the habitable zone** (HZ). Here, seasonal forcing is expected to be crucial in prohibiting or triggering transitions from one state to the other through the **sea-ice albedo feedback**. Using the general circulation model PlaSim and building on studies that are based on one-dimensional energy balance models ([1, 4]) we address the following questions:

What are the individual and combined effects of two astronomical parameters, **obliquity and eccentricity**, on the habitability of a planet? How robust are the results against changes in further parameters, such as heat capacity, oceanic transport, and rotation speed?

Model description

The PlanetSimulator (**PlaSim,** [2]) is a general circulation model of intermediate complexity that

- solves the **primitive equations** via spectral transformation
- includes parametrizations for long- and shortwave radiation, interactive clouds, moist and dry convection, large scale precipitation, boundary layer fluxes of latent and sensible heat, vertical and horizontal diffusion, and a mixed layer (swamp) ocean with a 0-dimensional **sea-ice model**
- is freely available at **www.mi.uni-hamburg.de/plasim**

Methods and experiments

For each simulation a **bifurcation analysis** is performed in order to detect the range in which warm and cold climate states are stable. Therefore, steady states are simulated for solar luminosities ranging from ~ 0.4 - 1.5 S* (S* = 1366 Wm $^{-2}$).

Each climate state is then classified as either completely habitable (if there is no ice at all), partially habitable (if there are ice-free areas at some time in the year), or unhabitable (if the planet is completely frozen). In order to characterise the bistable region, a complete **hysteretic cyle** is simulated. This method has already been used in a thermodynamic framework for the case of Earth ([3]). Here it is applied to different model setups, each representing an idealized Earth-like planet (with regards to planetary attributes such as mass, radius, rotation speed, atmospheric composition). All planets are completely covered with a vertically diffusive ocean (aquaplanets).

In our first set of simulations, different combinations of the parameters obliquity and eccentricity are chosen such that the results can be compared to previous results that are based on 1d EBM (table 1).

obliquity	eccentricity
0	0
60	0
90	0
0	0.5
60	0.5
90	0.5

Table 1: set of 6 experiments with different combinations of the two parameters obliquity and ecentricity

Results and discussion

Both obliquity and eccentricity affect the temporal and spatial distribution of incoming radiation. While annual and global mean insolation $\overline{<S>}$ increases with eccentricity e according to

$$\overline{<S>} \propto \frac{1}{\sqrt{1-e^2}}$$

obliquity determines the spatial distribution of the extrema of annual mean insolation. While for an obliquity below ~55 degrees the equator receives most radiation, the poles receive most radiation from that value on (figure 1). Our results show a strong influence of the variability implied by these two parameters on climate stability (figure 2,3).

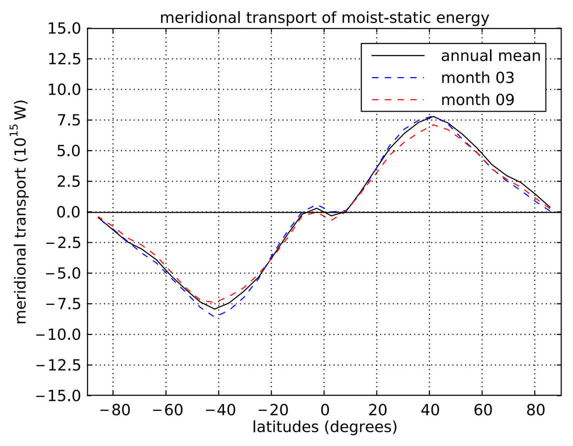
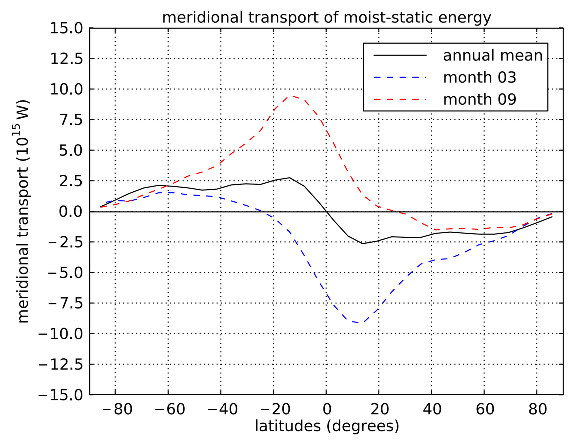


Figure 1: meridional transport of moist static energy of an Earth-like planet on a circular orbit for different values of obliquity, 0 degrees (left) and 90 degrees (right); months are given relative to northern vernal equinox



Eccentric orbits can push the outer limit of the habitable zone far beyond the predictions of zero dimensional models. This expanding effect, however, tends to be over-estimated by 1d EBM (figure 3b). The effect of obliquity is comparatively small on circular orbit, whereas it becomes highly relevant on eccentric orbits. So far, **cold climate states** have not been investigated in habitability context. Our results reveal that they extend farest into the HZ for non-oblique planets, whereas they allow for partially habitable regions on highly oblique planets (figure 2a). On **circular orbits**, planets with a most homogeneous distribution of annual mean insolation are less prone to snowball transitions due to the non-linearity of the ice-albedo feedback, whereas on eccentric orbits a large obliquity can keep a planet in the warm state (figure 3a,b).

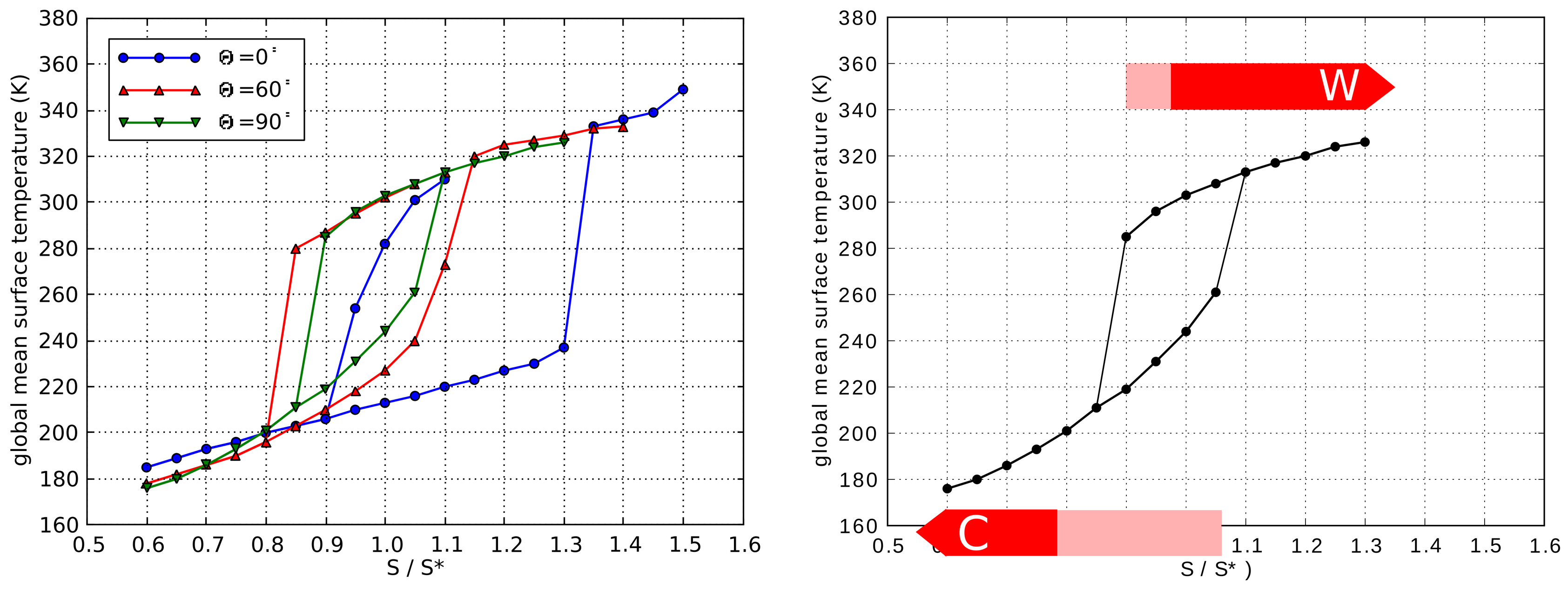


Figure 2: (a) hysteresis plot that shows the global mean surface temperature as a function of stellar luminosity for three simulations with different obliquities; each marker represents one steady climate state; (b) the same plot as on the left but reduced to an obliquity of 90 degrees; the arrows indicate the extent of the respective climate state; the brightness indicates the degree of habitability: dark color denotes completely ice-free and completely ice-covered climates, in warm and cold states respectively, while partially habitable states are shown with brighter colors

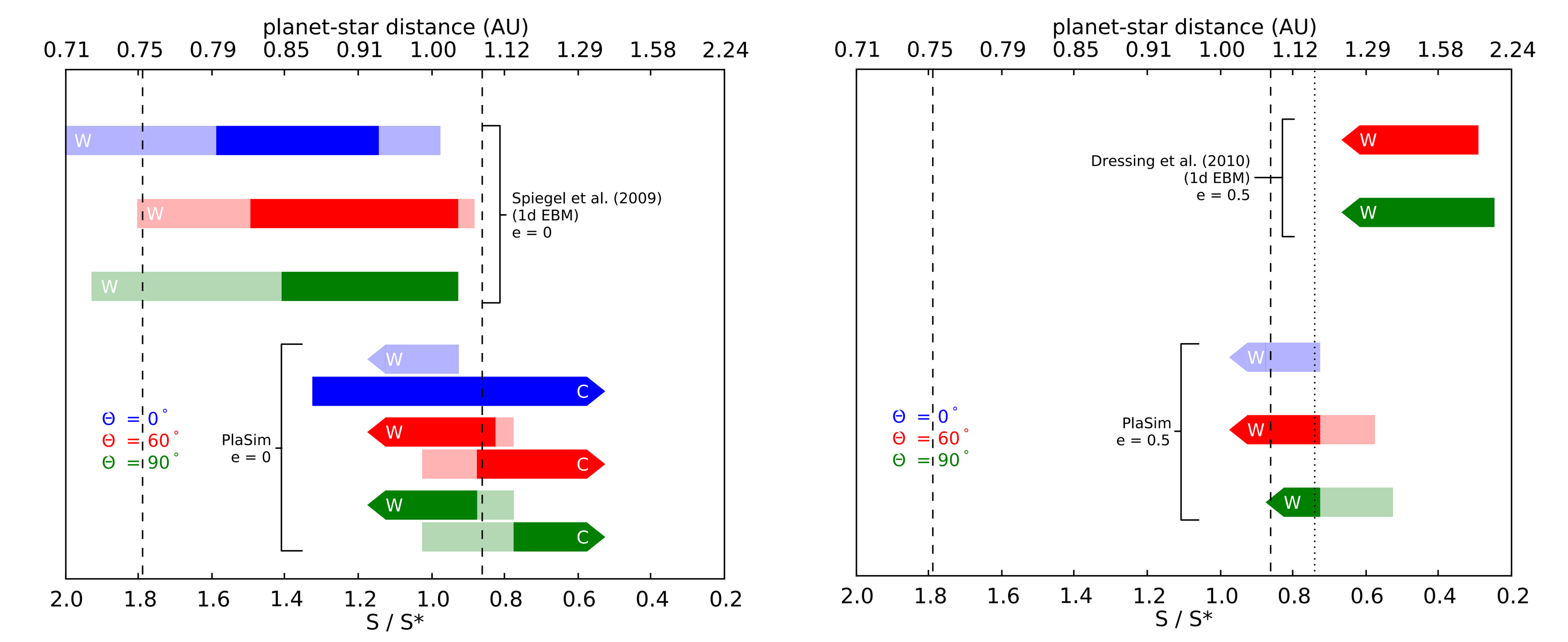


Figure 3: (a) the effect of obliquity on circular orbits on the extent of both climate states; comparison of PlaSim simulations with previous results from 1d EBM; the dashed vertical lines show the boundaries of the HZ according to estimations based on 0d EBM; (b) the effect of obliquity on eccentric orbits: comparison of PlaSim simulations with previous results from 1d EBM ([1, 4]); the dashed vertical lines show the boundaries of the HZ according to estimations based on 0d EBM; the dotted vertical line shows the outer boundary scaled according to the mean flux on an orbit with eccentricity 0.5

Outlook

On eccentric orbits, our results show a strong sensitivity against changes in further parameters, e.g. heat capacity. Therefore, sensitivity experiments will be performed that include heat capacity, (diffusive) oceanic transport, and rotation speed. Also the effect of asymmetric mean insolation will be addressed. Besides seasonal variability, the effect of diurnal variability will be assessed on slowly rotating planets. While simple zero or one dimensional energy balance models provide an efficient way to explore a wide parameter space, we aim at addressing the limitations of these models in order to provide reliable estimations of climate and its constraints on habitability.

References

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