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How do changes in the Diurnal Cycle affect Bi-stability and Climate Sensitivity in the Habitable Zone?

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Abstract

In this study we deal with the effect of varying the length of the diurnal cycle on its bi-stability properties. By using a general circulation model, PlaSim, we consider several values for the diurnal cycle, from tidally locked, to that of 1 Earth day. For each value of the diurnal cycle, we slowly modulate the solar constant between 1510 and 1000 Wm^{-2} and perform a hysteresis experiment.

It is found that the width of the bi-stable region, i.e. the range of climate states - determined here by changes in S* - which support two climatic attractors, reduces when the diurnal cycle is increased in length and disappears - signifying the merging of both attractors - for climates with a diurnal cycle greater than 180 days. Crucial to the loss of bi-stability is the longitudinally asymmetric distribution of solar radiation, incident on the planet's surface, leading to the development of equatorial sea-ice. For diurnal cycles where bi-stability is found, the longitudinally asymmetric heating is sufficiently compensated for by the strength of the zonal winds and the rate of solar distribution, which redistribute heat and maintain the meridional temperature gradient across all longitudes. Conversely, for mono-stable regimes, the energy transport associated with zonal winds becomes insufficient to compensate for the increase in the length of the diurnal cycle, resulting in large zonal temperature gradients along the equatorial band.

Furthermore, the results found here confirm and re-enforce the robustness of those found in Boschi et al (2013), showing that, for climates which support bi-stability, it may be possible to parameterise variables such as the material entropy production and the meridional heat transport in terms of the surface and emission temperatures, within reasonably well defined upper and lower bounds, even when considering a wide range of planetary rotation speeds and changes to the infrared opacity. This paves the way for the possibility of practically deducing fundamental properties of planets in the habitable zone from relatively simple observables.

1. Introduction

Exo-planets currently being discovered orbiting M stars [1], tend to be tidily locked and have relatively short orbital time periods due to the close proximity to their parent star. In time, a vast array of planets with differing orbit properties will be discovered, each of which having diurnal cycles of various lengths in time. Such planets with an atmosphere containing a condensing phase may experience bi-stability, i.e. a warm, moist and a deep frozen, dry atmospheric state (Snowball), despite having the same value for the solar constant. Consequently, a planet in the habitable zone, may be totally frozen and so unfit for sustaining life.

[2] showed that for an Earth-like planet, it may be possible to parameterize various global thermodynamic properties (entropy, Lorenz energy cycle, efficiency and meridional heat transport) as functions of the surface and emission temperatures within well-defined bounds. Furthermore, reducing the planetary rotation rate, Ω by a factor 2 had only a small effect on this functional dependency (see Fig. 1), meaning the bi-stability properties and sensitivity of the climate system did not change much despite a significant change to the atmospheric dynamics.

With this in mind we investigate the role of the diurnal cycle on climate bi-stability, by performing hysteresis experiments using a climate model of intermediate complexity, PlaSim. The solar constant is slowly modulated between 1510 and 1000 Wm^{-2}

for planets with year lengths ranging from 1 Earth day to 1 Earth Year, while maintaining Ω and all other orbital parameters constant.

2. Figures

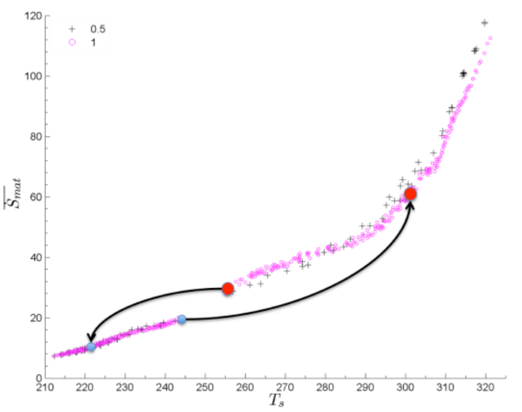

Figure 1: Material entropy production S_{mat} (10^{-3} $Wm^{-2}K^{-1}$) vs. surface temperature, T_s (k) for Ω/Ω_E = 1 (magenta) and Ω/Ω_E = 0.5 (black).

3. Summary and Conclusions

For an Earth-like planet with a diurnal cycle equivalent to 180 Earth days, is roughly the point at which bi-stability disappears and both attractors merge to form a new global climate state. The functional dependences of T_s and T_E remain [2] but the form in which it takes changes, meaning the sensitivity of the global climate has changed. From a phenomenological perspective, bi-stability disappears due to the buildup of equatorial sea-ice on the night side of the planet, even at relatively high solar constant values of about 1400 Wm^2, so that for warm global climates sea-ice exists in both polar and equatorial regions while only the mid-latitudes remain ice free. This break down of the meridional albedo/temperature difference through the inability of the climate system to redistribute heat sufficiently well in the zonal direction, appears to be the main factor in dampening the positive ice-albedo feedback. We then can conclude that the main factors determining whether the climate system supports bi-stability or not are those which play a role in maintaining a flat zonal temperature gradient. This indicates that the diurnal cycle plays a greater role than Ω in determining bi-stability in the climate system, however the exact value this occurs at may be dependent on Ω, which plays a major role in the dynamics and the redistribution of heat.

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