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Climate of Earth-like planets with high obliquity and eccentric orbits: Implications for habitability conditions

Manuel Linsenmeier [a,*], Salvatore Pascale [a], Valerio Lucarini [a,b,c]

[a] KlimaCampus, Meteorologisches Institut, Universität Hamburg, Hamburg, Germany
[b] Department of Mathematics and Statistics, University of Reading, Reading, UK
[c] Walker Institute for Climate System Research, University of Reading, Reading, UK

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ABSTRACT

We explore the effects of seasonal variability for the climate of Earth-like planets as determined by the two parameters polar obliquity and orbital eccentricity using a general circulation model of intermediate complexity. In the first part of the paper we examine the consequences of different values of obliquity and eccentricity for the spatio-temporal patterns of radiation and surface temperatures as well as for the main characteristics of the atmospheric circulation. In the second part of the paper we analyse the associated implications for the habitability of planets close to the outer edge of the habitable zone (HZ). The second part focuses in particular on the multistability property of climate, i.e. the parallel existence of both an ice-free and an ice-covered climate state. Our results show that seasonal variability affects both the existence of and transitions between the two climate states. Moreover, our experiments reveal that planets with Earth-like atmospheres and high seasonal variability can have ice-free areas at much larger distance from the host star than planets without seasonal variability, which leads to a substantial expansion of the outer edge of the HZ. Sensitivity experiments exploring the role of azimuthal obliquity and surface heat capacity test the robustness of our results. On circular orbits, our findings obtained with a general circulation model agree well with previous studies based on one dimensional energy balance models, whereas significant differences are found on eccentric orbits.

1. Introduction

Over the last two decades, more than 1000 planets outside our Solar System (exoplanets) have been confirmed and several thousands are classified as candidates (Udry and Santos, 2007; Borucki et al., 2011). Beyond the sheer detection, observation techniques based on the radial velocity and transit method also allow one to infer some planetary properties such as mass, radius, and orbit. Today, much research is devoted to the interpretation of the statistical distribution of these properties (Howard, 2013).

One of the current research questions in the field of exoplanets is how different orbital and planetary parameters affect the habitability of a planet, i.e. its ability to host life (Seager, 2013). Commonly, a planet is considered habitable if its surface conditions allow for the existence of liquid water. The estimation of habitability is then usually provided as an estimation of the habitable zone (HZ), i.e. the range of distances from the host star that would allow for habitable conditions. Consequently, two different processes define the inner and outer boundaries of the HZ: at the inner boundary, the run-away greenhouse effect leads to a complete evaporation of water at the surface; at the outer boundary, a completely frozen surface limits the habitability of a planet (Hart, 1979; Kasting et al., 1993).

Climate models can provide insights to the investigation of exoplanets and their habitability. Ranging from toy models to general circulation models, they allow one to study the effect of different processes with variable degree of approximation and computational cost. Radiative-convective models (RCMs) were the first climate models applied to the investigation of exoplanets (e.g. Kasting et al., 1993). In these one dimensional vertical models, the atmosphere of the planet is treated as a single column. As they do not capture effects of temporal or spatial heterogeneity, they were subsequently complemented by latitudinally resolved energy-balance models (EBMs) (e.g. Williams and Kasting, 1997). More recently, also general circulation models (GCMs) have been employed in habitability studies and, more generally, to study the climates and circulations of exoplanets (Merlis and Schneider, 2010; Pierrehumbert, 2011; Heng et al., 2011a,b; Menou, 2012; Showman et al., 2013).

Estimates of the HZ differ among these models, as they include different processes at different degree of approximation. Simulations with RCMs yield an extent of the HZ of an Earth-like planet

* Corresponding author.
E-mail address: manuel.linsenmeier@zmaw.de (M. Linsenmeier).

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orbiting around a Sun-like star from 0.99 AU to 1.70 AU (Kopparapu et al., 2013). Results obtained from EBMs and GCMs, however, indicate that RCMs tend to underestimate the extent of the HZ due to processes that are not or not sufficiently represented in these models. Simulations with EBMs show that the inclusion of seasonal variability due to either a non-zero planetary obliquity, an eccentric orbit or both can extend the outer boundary of the HZ relative to results from RCMs (Williams and Kasting, 1997; Spiegel et al., 2009; Dressing et al., 2010). As recent work shows, the extension of the HZ can be further increased if planetary obliquity and orbital eccentricity vary over time (Armstrong et al., 2014). Moreover, results from a GCM show that a better representation of cloud feedbacks can lead to an extension of the HZ relative to results from RCMs also at its inner boundary (Leconte et al., 2013; Yang et al., 2013).

Large seasonal variability might indeed be a common feature of extra-solar planets as detected planets exhibit a large diversity of orbital eccentricities (Ford et al., 2008; Moorhead et al., 2011; Kane et al., 2012). Around 35% of the detected exoplanets are located on an orbit with an eccentricity $e > 0.2$ and around 9% on an orbit with $e > 0.5$ (Fig. 1). Highly eccentric orbits feature dramatic intra-annual variability: while for $e = 0.2$ a planet at periastron receives about twice the amount of energy at apoastron, this factor increases to around 9 for $e = 0.5$ (Dressing et al., 2010). Also the polar obliquity of a planet θ plays an important role in determining seasonal variability (Spiegel et al., 2009; Dobrovolskis, 2013). In particular the combination of a high value of e and a high value of θ can lead to extreme seasonal variability (Dressing et al., 2010).

Multistability of the climate state further complicates estimates of the outer boundary of the HZ. Since the experience gathered with the first EBMs, it is well known that the climate of a planet can exhibit two stable states with different degree of ice-coverage (Budyko, 1969; Sellers, 1969), usually referred to as warm (ice-free or only partially ice-covered) and cold (completely or mostly ice-covered) climate state. Evidence suggests that Earth might have entered and exited a cold state several times in the past (Hoffman and Schrag, 2002), and the transition to the cold state can be reproduced with state-of-the-art GCMs (Marotzke and Botzet, 2007; Voigt and Marotzke, 2010; Voigt et al., 2011). While the multistability property has been extensively discussed in the context of paleoclimate (see also Romanova et al., 2006; Yang et al., 2012a,b), its implications for the habitability of exoplanets is a relatively new area of research. Lucarini et al. (2010) provide an investigation of bistability in a thermodynamic framework, which has recently been extended to include the parameters rotation rate and atmospheric opacity (Boschi et al., 2013; Lucarini et al., 2013).

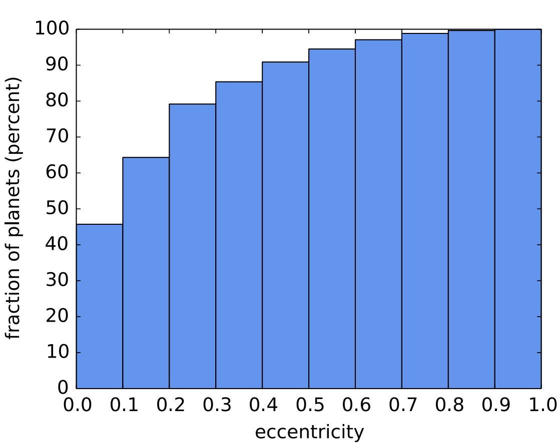

Fig. 1. Cumulative histogram of orbital eccentricities of 855 exoplanets whose eccentricity was estimated; the data were retrieved from the Extrasolar Planets Encyclopedia on October 5th 2014 (Schneider, 2014).

The effect of obliquity and eccentricity has so far primarily been investigated with EBMs (Williams and Kasting, 1997; Spiegel et al., 2009; Dressing et al., 2010). Their results reveal that both parameters have substantial implications for the extent of the HZ, particularly on eccentric orbits (Spiegel et al., 2009; Dressing et al., 2010). As downside of the numerical efficiency of these models, however, they rely on crude simplifications. One of their most critical simplifications is that ice is represented by simply assuming a temperature dependent surface albedo. Moreover, they do not include any dynamical processes apart from a simple diffusion parametrisation of meridional heat transport. However Ferreira et al. (2014) show that the phenomenological transport efficiency relating temperature gradients and heat transport varies by an order of magnitude amongst Earth-like planets at different obliquities. As these parameterisations used in EBMs for meridional heat transport are tuned to reproduce the climate of Earth, their validity is challenged by the very different shapes of atmospheric circulations and climates that can be expected on exoplanets with high polar obliquities, highly eccentric orbits, and variable degree of ice-coverage.

Despite the need for simulations with climate models of higher complexity, only three studies assessed the effect of either obliquity or eccentricity on atmospheric circulations and climate with a GCM so far (Williams and Pollard, 2002, 2003; Ferreira et al., 2014). They did, however, not provide a systematic investigation of the implications for habitability. This is the aim of this work. Using a GCM of intermediate complexity we explore the atmospheric circulations and climates of idealised Earth-like planets for different astronomical parameters and examine the implications for habitability.

It is well known that silicate weathering affects the climate of Earth as a stabilising mechanism acting on timescales of million of years: when surface temperatures are sufficiently low and rocks are not exposed to the atmosphere, the weathering is strongly suppressed, with an ensuing accumulation of CO_2 in the atmosphere (Walker et al., 1981). In our study, we do not consider this process (see instead Williams and Kasting, 1997) but keep the CO_2 concentration at a fixed value, following Spiegel et al. (2009) and Dressing et al. (2010). Therefore, our study should be thought primarily as a parametric exploration of the effect of changing orbital parameters on a planet of given atmospheric composition rather than a realistic study of the HZ.

We anticipate that seasonal variability leads to an increase of the maximal distance between planet and host star that allows for habitable conditions. The combined effect of obliquity and eccentricity on multistability has to our knowledge not been investigated yet. Our results reveal that obliquity is crucial in determining the extent of both the warm and cold state. Moreover, eccentric orbits are generally associated with a narrower range of two stable climate states. Our simulations also show that seasonal variability primarily leads to temporally ice-free regions, which stresses the importance of different definitions of habitability. Sensitivity experiments that include the parameters azimuthal obliquity and ocean heat capacity test the robustness of our results. Since we neglect the effect of silicate weathering, our results of the outer boundary of the habitable zone can only be used as conservative estimates. Large intra-annual variations of temperature and ice-coverage found in many of our experiments however question traditional estimates with energy balance models that do not take these variations into account.

The paper is structured as follows. In Section 2 we introduce and discuss our model PlaSim, explain the experimental setup, and list all simulations. The main features of atmospheric circulations of planets at different obliquities and eccentricities are presented in Section 3. Section 4 shows the implications of obliquity and eccentricity for multistability and the degree of habitability. A