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Bistability of the climate around the habitable zone: A thermodynamic investigation

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ABSTRACT

The goal of this paper is to explore the potential multistability of the climate for a planet around the habitable zone. We apply our methodology to the Earth system, but our investigation has more general relevance. A thorough investigation of the thermodynamics of the climate system is performed for very diverse conditions of energy input and infrared atmosphere opacity. Using PlaSim, an Earth-like general circulation model, the solar constant S^* is modulated between 1160 and 1510 W m^{-2} and the CO_2 concentration, $[CO_2]$, between 90 and 2880 ppm. It is observed that in such a parameter range the climate is bistable, i.e. there are two coexisting attractors, one characterised by warm, moist climates (W) and one by completely frozen sea surface (Snowball Earth, SB). The tipping points of both the transitions (W → SB and SB →W) are located along straight lines in the (S^*,log$[CO_2]$) space. The dynamical and thermodynamical properties – energy fluxes, Lorenz energy cycle, Carnot efficiency, material entropy production – of the W and SB states are very different: W states are dominated by the hydrological cycle and latent heat is prominent in the material entropy production; the SB states are eminently dry climates where heat transport is realised through sensible heat fluxes and entropy mostly generated by dissipation of kinetic energy. We also show that the Carnot efficiency regularly increases towards each transition between W and SB, with a large discontinuous decrease at the point of each transition. Finally, we propose well-defined empirical functions allowing for expressing the global non-equilibrium thermodynamical properties of the system in terms of either the mean surface temperature or the mean planetary emission temperature. While the specific results presented in this paper depend on some characteristics of the Earth system (e.g. rotation rate, position of the continents), this paves the way for the possibility of proposing efficient parameterisations of complex non-equilibrium properties and of practically deducing fundamental properties of a planetary system from a relatively simple observable. As a preliminary result, we obtain that when reducing the rotation rate of the planet by a factor of two, the multistability properties, the quantitative estimators of the thermodynamics of the system, and the approximate parameterisations in terms of the surface of emission temperature are only weakly affected.

1. Introduction

1.1. Planetary atmospheres and extrasolar planets

A very active field of research in astrophysical sciences at the moment, is the observational, model-assisted, and theoretical investigation of extra-solar planetary objects. In less than two decades, the development of new instruments have lead to the detection of the first extra-solar planet in the mid 1990s to more refined observations of the characteristic properties of several hundred planetary bodies. The properties of planets vary greatly, in terms of their compositions – gaseous or rocky – nature of their atmosphere, and of their size-ranging in several orders of magnitude. Astronomical and astrophysical factors of great relevance include the temperature and the intensity of the radiation emitted by the parent star, the orbital parameters, and whether or not the planet is tidally locked. A great deal of effort has been directed at constraining the combinations of physical configurations potentially compatible with life (habitable zone), that is to say with the possibility of observing water, either prominently or at least partially in liquid form at the surface. Obviously, the so-called habitable zone is the setting where we hope to find forms of extraterrestrial life, or at least life analogous to that found on Earth. Recently, ESOs HARPS planet finder estimated that just in the Milky Way billions of habitable Earth-like rocky planets could orbit around faint red dwarfs, with in the order of one hundred being in the immediate vicinity of our Solar System (Bonfils et al., 2013). We refer the reader to the website (http://exoplanet.eu/index.php) – which is dedicated to collecting information on all newly discovered planets and on the related bibliography – and recently published books (Dvorak, 2008; Seager, 2010; Kasting, 2009; Perryman, 2011).

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A great deal of interest is now being paid to the inference, study, and modelling of planetary atmospheres, i.e., in the case of rocky planets "Super-Earths"), the fluid envelope that surrounds the planet and its response to the differential heating due to the absorption of incoming solar radiation. Planetary atmospheres may feature complex chemical compositions and be characterised by the relevant presence of phase transitions of some of these components, which may have large effects on the radiative properties. The geometry describing how the planet and its parent star face each other, determines to a first approximation the horizontal inhomogeneities, whereas the atmospheric optical properties, and in particular its opacity to the incoming radiation, has an effect on the vertical structure (e.g. Earth's optically thin atmosphere is typically heated from the planets surface). The general circulation of the planetary atmosphere is powered, just like a Carnot engine by such inhomogeneities with, on average, heating occurring in regions of higher temperatures before being then removed in cooler areas. The circulation acts to reduce the temperature gradients through transport processes, and on average the generation of kinetic energy is compensated for by irreversible viscous dissipation processes. Irreversible heat transport and dissipation, as well as, processes such as radiative absorption and emission contribute to the generation of entropy. The steady state is realised by balancing energy and entropy fluxes between the planetary atmosphere and the surrounding space. Various aspects of this closed chain of interdependent processes have been described for terrestrial conditions (Lorenz, 1967; Peixoto and Oort, 1992; Johnson, 2000; Lucarini, 2009; Lucarini et al., 2011), but the theoretical framework proposed in these contributions could be applied with more generality to planetary atmospheres.

The awareness of recent findings in planetary astronomy and astrophysics are gradually filtering through to the classical geophysical sciences (by definition Earth-centred). The study of, e.g. the general circulation of Jupiter, Venus and Mars has a rather old history, but with the recent and foreseeable future discoveries of exoplanets, the opportunity of facing a vast array of planetary configurations, mean moving from considering special cases of climates, to being able to study a quasi-continuous distribution in some parametric space. Following Read (2011), one should note that it is possible to reduce the variety of climate settings by adopting the fluid-dynamical classical method of similarity, i.e. by defining a set of dimensionless numbers that fully characterise the climate state. When two climate states share the same set of dimensionless numbers, they are dynamically equivalent, so that the statistical properties of one can be mapped into those of the other with simple algebraic operations. At this stage, we are left with two additional elements to cope with:

- How to characterise succinctly a climatic state, conveying minimal but comprehensive physical information for planetary atmospheres which are, in general, turbulent fluids with variability on a very vast range of spatial and temporal scales?
- How to verify, or at least approximately, the validity of our simulations and of our theoretical understanding of planetary circulations that we are able to model?

The two items are closely related to the definition of robust observables. Energy conservation imposes that the incoming radiation onto a planet is instantaneously equal to the sum of the radiation that is absorbed and scattered by the planet. Assuming steady state, when averaging over a sufficiently long time interval, the radiation absorbed by the planet is equal to the radiation the planet emits out to space (assuming that the planet has no internal energy sources). These quantities allow defining the average albedo and the effective thermodynamic temperature, which constitute the most fundamental description of the properties of a planet, in terms of the first law of thermodynamics. As recorded by a telescope, observations made of a planet represented by a single pixel, provides a sufficient level of detail to gather such information. It is then possible for the overall macroscopic properties of the planets atmosphere to be found. Obviously, most observations provide much more than this, such as the emission spectrum of a planet (and that of the star in orbits). Moreover, spectral windows may prove useful for measuring its surface temperature. Nonetheless, in terms of the macroscopic thermodynamic properties of the planet, the spectrally integrated quantities are the most relevant.

Under conditions of steady state, given the inhomogeneity of the incoming radiation and of the boundary conditions, the vanishing net energy budget at the top of the atmosphere (TOA) results from the cancellation between regions of net heating and regions of net cooling (low and mid-high latitudes regions, in the case of the Earth). Steady state arguments imply that the absolute value of the imbalance in either region is equal to the energy transmitted from the regions where the energy balance at the top of the atmosphere is positive from those where such balance is negative, and the transport is performed across the atmospheric fluid envelope through material transport and horizontal deflection of the incoming radiation (in the case of very thick atmospheres). Note that the correct representation of these large scale properties in state-of-the-art models of the Earth's climate is a far from trivial task (Lucarini and Ragone, 2011).

Moreover, the second law of thermodynamics imposes that the regions featuring positive TOA energy budget are warmer (i.e. their total emitted radiation is larger) than those where the balance is negative. One can show that the entropy production due to such irreversible transport of energy from hot to cold regions gives a lower bound to the total material entropy production of the planet. Moreover, it is possible to provide a lower bound to the total dissipation of kinetic energy or, equivalently, to the intensity of the Lorenz energy cycle (Lucarini et al., 2011). This discussion implies that if a telescope allows for an observational resolution involving more than one pixel, and is able to distinguish between warmer and colder regions, it is possible to derive fundamental information on the macroscopic thermodynamic properties of the planet in terms of the 2nd law of thermodynamics. This brief discussion suggests that non-equilibrium thermodynamics provides rather powerful methods and concepts for analysing the fundamental properties of planetary atmospheres, as well as a means of testing model performance, and deriving bounds for the physical properties of the system even when low-resolution data is only available. Following previous work in the field (Pujol, 2003; Fraedrich and Lunkeit, 2008; Lucarini, 2009; Lucarini et al., 2010b, 2011; Pascale et al., 2011a,b; Li and Chylek, 2012), we propose using this framework in order to study planetary atmospheres in a rather general setting of forcings and boundary conditions.

1.2. Habitability conditions and climatic bistability

As mentioned above, a great deal of interest in the investigation of Super-Earth planetary atmospheres is directed at studying conditions within or around the Habitable zone. Nonetheless, being in the Habitable zone is a *necessary but not a sufficient condition* for a planet to have liquid water at the surface, even if the chemical composition of the atmosphere would in principle allow for it. In fact, the paleohistory of our planet provides strong evidence that the astronomical and astrophysical parameters of the Sun–Earth system support two distinct steady states: a warm state (W) characterised by widespread liquid water and a moist atmosphere; with the other characterised by the global glaciation of water and an extremely dry atmosphere, i.e. the so-called Snowball state (SB). Proposed here is a thorough investigation of these two states in a bi-dimensional parameter space, with the goal of detailing the