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

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We explore the potential multistability of the climate for a planet around the habitable zone, taking the Earth system as starting point. 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, a simplified general circulation model, the solar constant $\mathcal{S}^*$ 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 ($\mathcal{S}^*$, $\log[CO_2]$) space. The dynamical and thermodynamical properties – energy fluxes, Lorenz energy cycle, climate efficiency, material entropy production – of the W and SB states are very different: W states are dominated by the hydrological cycle; the SB states are eminently dry climates where heat transport is realized through sensible heat fluxes and entropy mostly generated by dissipation of kinetic energy. We also show that the climate efficiency regularly increases towards each transition between W and SB, with a large negative jump at the point of each transition. 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. The generality of the obtained results is investigated by e.g. changing the day/year ratio. 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 parameterizations are only weakly affected. Instead, multistability is lost below a critical value for the length of the year.