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Stochastic Dynamics of a Bistable Climate Model

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The climate of planet Earth is in a regime of bistability. The current astronomical and astrophysical conditions, together with the chemistry of the planet, are such that two competing attracting states are present. Such a regime is not unique to the present conditions, but is instead realised for a vast range of values of the incoming solar radiation. One state is the one we live in and that is supportive of life; the other state is characterised by global glaciation and by conditions that can hardly support any life form. This is a robust finding confirmed across a hierarchy of climate models. Paleoclimatic evidences suggest that, indeed, our planet has flipped between the two states. The main physical mechanism responsible for the existence of such a regime is the ice-albedo feedback. In a previous work, using a climate model of intermediate complexity, comprising of a fast component given by a three-dimensional atmosphere coupled to a slow component corresponding to a diffusive ocean, we have been able to define the global stability properties of the climate, by constructing the Melancholia states that sit between the two competing attractors. Such states are embedded in the boundaries between the two basins of attraction and are characterised by having extensive glaciation down to relatively low latitudes. Here, we perturb the system by adding a random modulation to the incoming solar radiation, which introduces a multiplicative noise affecting the system. As a result, we observe noise-induced transitions between the competing basins of attractions. Large deviations laws written in terms of a pseudo-potential define the natural measure and the statistics of escape times. By empirically constructing the instantons connecting the attractors with the edge states, we also show that the edge state is the gateway for the noise induced transitions between the two asymptotic states. Finally, we show that, in the weak-noise limit, in the region of multiple stability, only one of the possible steady state is, in fact, realised, because of the lack of symmetry of the pseudo-potential. For low values of the solar irradiance, the noise selects as natural measure the snowball state, while for large values of of the solar irradiance, the asymptotic state is the warm attractor. The changeover between the two regimes corresponds to a first order phase transition in the system, where the control parameter is the solar irradiance. Different choices of the noise law will lead to different values for the critical value of the control parameter. Taking advantage of the freedom to choose the law of the noise perturbation, we propose a new method for constructing edge states that bypasses the difficulties of the edge tracking algorithm one needs to use in the deterministic setting. While in this paper we analyse a specific yet important problem in paleoclimatology, our results seem to suggest a more general framework for the study of complex multistable systems.