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Global Stability Properties of the Climate: Melancholia States, Invariant Measures, and Phase Transitions

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For a wide range of values of the incoming solar radiation, the Earth features at least two attracting states, which correspond to competing climates. The warm climate is analogous to the present one; the snowball climate features global glaciation and conditions that can hardly support life forms. Paleoclimatic evidences suggest that in past our planet flipped between these two states. The main physical mechanism responsible for such instability is the ice-albedo feedback. Following an idea developed by Eckhardt and co. for the investigation of multistable turbulent flows, we study the global instability giving rise to the snowball/warm multistability in the climate system by identifying the climatic Melancholia state, a saddle embedded in the boundary between the two basins of attraction of the stable climates. We then introduce random perturbations as modulations to the intensity of the incoming solar radiation. We observe noise-induced transitions between the competing basins of attractions. In the weak noise limit, large deviation laws define the invariant measure and the statistics of escape times. By empirically constructing the instantons, we show that the Melancholia states are the gateways for the noise-induced transitions in the weak-noise limit. In the region of multistability, in the zero-noise limit, the measure is supported only on one of the competing attractors. For low (high) values of the solar irradiance, the limit measure is the snowball (warm) climate. The changeover between the two regimes corresponds to a first order phase transition in the system. The framework we propose seems of general relevance for the study of complex multistable systems. Finally, we propose a new method for constructing Melancholia states from direct numerical simulations, thus bypassing the need to use the edge-tracking algorithm.

Refs.

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