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Thermodynamic Analysis of Snowball Earth Hysteresis Experiment: Efficiency, Entropy Production, and Irreversibility

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We present an extensive thermodynamic analysis of a hysteresis experiment performed on a simplified yet Earth-like climate model. We slowly vary the solar constant by 20% around the present value and detect that for a large range of values of the solar constant the realization of snowball or of regular climate conditions depends on the history of the system. Using recent results on the global climate thermodynamics, we show that the two regimes feature radically different properties. The efficiency of the climate machine monotonically increases with decreasing solar constant in present climate conditions, whereas the opposite takes place in snowball conditions. Instead, entropy production is monotonically increasing with the solar constant in both branches of climate conditions, and its value is about four times larger in the warm branch than in the corresponding cold state. Finally, the degree of irreversibility of the system, measured as the fraction of excess entropy production due to irreversible heat transport processes, is much higher in the warm climate conditions, with an explosive growth in the upper range of the considered values of solar constants. Whereas in the cold climate regime a dominating role is played by changes in the meridional albedo contrast, in the warm climate regime changes in the intensity of latent heat fluxes are crucial for determining the observed properties. This substantiates the importance of addressing correctly the variations of the hydrological cycle in a changing climate. An interpretation of the climate transitions at the tipping points based upon macro-scale thermodynamic properties is also proposed. Our results support the adoption of a new generation of diagnostic tools based on the 2nd law of thermodynamics for auditing climate model and outline a set of parameterizations to be used in conceptual and intermediate complexity models or for the reconstruction of the past climate conditions