Edge states in the climate system: exploring global instabilities and critical transitions

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Multistability is a ubiquitous feature in systems of geophysical relevance and provides key challenges for our ability to predict a system's response to perturbations. Near critical transitions small causes can lead to large effects and—for all practical purposes—irreversible changes in the properties of the system. As is well known, the Earth climate is multistable: present astronomical and astrophysical conditions support two stable regimes, the warm climate we live in, and a snowball climate characterized by global glaciation. We first provide an overview of methods and ideas relevant for studying the climate response to forcings and focus on the properties of critical transitions in the context of both stochastic and deterministic dynamics, and assess strengths and weaknesses of simplified approaches to the problem. Following an idea developed by Eckhardt and collaborators for the investigation of multistable turbulent fluid dynamical systems, we study the global instability giving rise to the snowball/warm multistability in the climate system by identifying the climatic edge state, a saddle embedded in the boundary between the two basins of attraction of the stable climates. The edge state attracts initial conditions belonging to such a boundary and, while being defined by the deterministic dynamics, is the gate facilitating noise-induced transitions between competing attractors. We use a simplified yet Earth-like intermediate complexity climate model constructed by coupling a primitive equations model of the atmosphere with a simple diffusive ocean. We refer to the climatic edge states as Melancholia states and provide an extensive analysis of their features. We study their dynamics, their symmetry properties, and we follow a complex set of bifurcations. We find situations where the Melancholia state has chaotic dynamics. In these cases, we have that the basin boundary between the two basins of attraction is a strange geometric set with a nearly zero codimension, and relate this feature to the time scale separation between instabilities occurring on weather and climatic time scales. We also discover a new stable climatic state that is similar to a Melancholia state and is characterized by non-trivial symmetry properties.
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