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Systematic search of climate attractors in a coupled aquaplanet

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The Earth climate is an extremely complex, forced, dissipative system that evolves under a number of positive and negative feedbacks. In order to reduce the complexity of the problem, we consider the evolution of an aquaplanet, *i. e.* a planet where the ocean covers the entire globe, under the effect of a constant forcing, represented by fixed values of mean annual solar radiation and atmospheric CO_2 content. Despite these simplifications, a coupled aquaplanet, where nonlinear interactions between atmosphere, ocean and sea ice are fully taken into account, provides a relevant framework to understand the role of the main feedbacks at play in climate dynamics.

In general, under the action of a constant external forcing and at fixed values of internal parameters, the solutions of a dynamical system are attracted toward stable regions of phase space, named attractors. They represent the skeleton of the unperturbed dynamics. Therefore, the first step in exploring the properties of dynamical systems like the Earth climate is to identify the different attractors toward which the trajectories asymptotically evolve. While well within the attractor basin linear theory is valid and small changes produce small effects, at their boundaries the opposite is true, small changes leading to large and potentially irreversible effects. Thus the attractors are key regions for understanding the system's response to perturbations.

Here we present the results of a systematic search of attractors in aquaplanets, performed using the MIT general circulation model in its coupled atmosphere-ocean sea ice configuration. We prove, for the first time, the existence of up to five attractors, ranging from snowball Earth (where ice covers the entire planet) to hot state conditions (where ice completely disappears). The exact number of attractors depends on the details of the coupled atmosphere–ocean–sea ice configuration. In particular, the cloud parameterisation plays a crucial role in the occurrence of the hot state.

We characterise each attractor by describing the associated climate feedbacks and by measuring quantities borrowed from the study of dynamical systems, namely instantaneous dimension, persistence, sample entropy, and principal components. We relate the occurrence of each attractor to the competition of the main nonlinear mechanisms that regulate the climate (ice-albedo, Boltzmann and cloud feedbacks), providing physical insight into their individual dynamics.

Our work illustrates the need to start the study of climate systems, including present-day, planetary, and geological past climates, by investigating their stability diagram. It suggests that applying the same approach to more complex climate systems could improve our understanding on climate stability and on the perturbations needed to shift the climate from an attractor to the other.