A framework to analyze regime behaviors and metastability in the climate system

Stochastic nonlinear data-reduction methods
with detection and prediction of critical rare event

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Abstract

Information theory and statistical mechanics are promising approaches to build a predictive model for the climate system and its components (e.g. atmosphere and ocean). Instead of looking at the detail of the evolution of these systems, which is very complex, often unpredictable, and quite uninformative *per se* as it involves a wide range of interacting spatio-temporal scales, the idea is to identify their most likely state(s) that are consistent with global constraints on their dynamics (e.g. conservation of energy and enstrophy). While appealing due to their relative simplicity, these approaches have the disadvantage that they only predict where the dynamics is likely to drive the system but not how this evolution arises. This is especially an issue when the theory predicts more than one state of maximum likelihood, i.e. when the invariant measure of the system is multi-modal. This is the signature of metastability: the system is likely to stay trapped for a long time near one state until it switches to another.

Examples of such metastable behavior abound in climate system. The atmospheric midlatitude circulation over the North-Atlantic was observed to have two long-existing patterns: A high-index flow characterized by strong zonal flow and weak wave motion and a low-index flow with relatively weak zonal flow and large wave amplitude. This is referred as Grosswetterlagen by Baur. Similar bimodal behavior also appears in the dynamics of oceanic current: Long time observation indicates that Kuroshio in the North Pacific Ocean presents large and small meandering behavior off the southern coast of Japan; Gulf stream in the Atlantic Ocean displays strong and weak deflected paths near the coast of South Carolina.

A central issue is to predict how transitions between these regimes happen and what their frequency is. Here we investigate this question in the context of the barotropic quasi-geostrophic equations on a beta plane with topography. We resort to the application of information theory in geophysical fluid mechanics, and look for dynamical models consistent with the invariant measure predicted by this theory. This leads to energy-constrained stochastic models which can display metastability. As the strength of noise approaches zero in these models, the transition path between regimes often distributes sharply around a certain deterministic path: the maximum likelihood path. Properties of such a path tells crucial information on the mechanism of the transition and we show how to use a generalized String method to compute them.