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Stochastic processes in climate modeling: from Lorenz to the El-Niño recharge oscillator and beyond

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In the past few years, much of the climate community's work has gone toward building highly detailed, IPCC-class general circulation models (GCMs) capable of simulating climate change.

In this context, subgrid-scale physics has increasingly been modeled using stochastic processes, but the broader consequences of this approach have not yet
been sufficiently explored.

Stochastic subgrid-scale parametrizations have substantial non-local effects on the low-frequency dynamics itself. Moreover, due to the random forcing present in these parametrizations, traditional dynamical systems concepts — e.g., strange attractors and deterministic bifurcations — are no longer appropriate.

In this talk, we present and apply mathematical concepts and tools developed by L. Arnold and his Bremen school during the last two decades. These tools have not been widely exploited so far in climate research, although they offer powerful theoretical and numerical ways of investigating stochastic models.

More specifically, we use random dynamical systems (RDS) theory to analyze the stochastic dynamics of climate models. To illustrate our approach, we consider at first simple conceptual models. The first example is the well-known 3-variable Lorenz (1963) model, to which we add multiplicative noise. We show how to obtain a full description of the resulting stochastic dynamics by computing this model's random attractor and its associated invariant measure.

The second example is Timmermann and Jin's (GRL, 2002) nonlinear recharge-discharge model of the El Niño/Southern Oscillation (ENSO), a model that captures several essential features of ENSO physics. A multiplicative noise term is added to this TJ model to represent wind bursts. Numerical simulations of the modified
TJ model's random attractor show that Smale horseshoes are excited by the multiplicative noise, even for a parameter regime in which a Hopf bifurcation occurs in the deterministic system; such intricate structures only arise in deterministic systems via homoclinic bifurcations. We thus obtain a fairly detailed description of the statistics in the randomly and seasonally forced ENSO model's phase-parameter space. This description provides novel ways to achieve probabilistic seasonal-to-interannual climate prediction.

We outline ways to connect this description of the random attractor to the behavior of more complex ENSO models, through intermediate coupled models and all the way to coupled, IPCC-class GCMs.