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Reconstruction of Complex Dynamical Systems Using Stochastic Differential Equations

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A complex system is a system composed of highly interconnected components in which the collective property of an underlying system cannot be described by dynamical behavior of the individual parts. Typically, complex systems are governed by nonlinear interactions and intricate fluctuations, thus to retrieve dynamics of a system, it is required to characterize and asses interactions between deterministic tendencies and random fluctuations.

For systems with large numbers of degrees of freedom, interacting across various time scales, deriving time-evolution equations from data is computationally expensive. A possible way to circumvent this problem is to isolate a small number of relatively slow degrees of freedom that may suffice to characterize the underlying dynamics and solve the governing motion equation for the reduced-dimension system in the framework of stochastic differential equations(SDEs). For some specific example settings, we have studied the performance of three stochastic dimension-reduction methods (Langevin equation(LE), generalized Langevin Equation(GLE) and Empirical Model Reduction(EMR)) to model various synthetic and real-world time series. In this study corresponding numerical simulations of all models have been examined by probability distribution function(PDF) and Autocorrelation function(ACF) of the average simulated time series as statistical benchmarks for assessing the differnt models' performance.

First we reconstruct the Niño-3 monthly sea surface temperature (SST) indices averages across (5°N–5°S, 150°–90°W) from 1891 to 2015 using the three aforementioned stochastic models. We demonstrate that all these considered models can reproduce the same skewed and heavy-tailed distributions of Niño-3 SST, comparing ACFs, GLE exhibits a tendency towards achieving a higher accuracy than LE and EMR. A particular challenge for deriving the underlying dynamics of complex systems from data is given by situations of abrupt transitions between alternative states. We show how the Kramers-Moyal approach to derive drift and diffusion terms for LEs can help in such situations. A prominent example of such 'Tipping Events' is given by the Dansgaard-Oeschger events during previous glacial intervals. We attempt to obtain the statistical properties of high-resolution, 20yr average, $\delta^{18}O$ and Ca^{+2} collected from the same ice core from the NGRIP on the GICC05 time scale. Through extensive analyses of various systems, our results signify that stochastic differential equation models considering memory effects are comparatively better approaches for understanding complex systems.