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Mathematical Physics of Complex Coevolutionary Systems: Theoretical Advances and Applications to Multiscale Hydroclimate Dynamics

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The fundamental stochastic-dynamic coevolution laws governing complex coevolutionary systems are introduced in a mathematical physics framework formally unifying nonlinear stochastic physics with fundamental deterministic interaction laws among spatiotemporally distributed processes.

The methodological developments are then used to shed light onto fundamental interactions underlying complex spatiotemporal behaviour and emergence in multiscale hydroclimate dynamics.
For this purpose, a mathematical physics framework is presented predicting evolving distributions of hydrologic quantities under nonlinearly coevolving geophysical processes.

The functional formulation is grounded on first principles regulating the dynamics of each system constituent and their interactions, therefore its applicability is general and data-independent, not requiring local calibrations. Moreover, it enables the dynamical estimation of hydroclimatic variations in space and time from knowledge at different spatiotemporal conditions, along with the associated uncertainties. This paves the way for a robust physically based prediction of hydroclimatic changes in unsupervised areas (e.g. ungauged basins).

Validation is achieved by producing, with the mathematical physics framework, a comprehensive spatiotemporal legacy consistent with the observed distributions along with their statistic-dynamic relations. The similarity between simulated and observed distributions is further assessed with novel robust nonlinear information-theoretic diagnostics.

The present study brings to light emerging signatures of structural change in hydroclimate dynamics arising from nonlinear synergies across multiple spatiotemporal scales, and contributes to a better dynamical understanding and prediction of spatiotemporal regimes, transitions, structural changes and extremes in complex coevolutionary systems.

This study further sheds light onto a diversity of emerging properties from harmonic to hyper-chaotic in general stochastic-dynamic systems, and bridges stochastic physics and nonlinear dynamics into a unified mathematical physics framework with broad applications beyond the geophysical sciences.