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Lyapunov instability study of high-dimensional atmospheric and climate models

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We study the stability properties of two intermediate-order climate models by computing their Lyapunov exponents (LEs). Two different models are considered: PUMA (Portable University Model of the Atmosphere), a primitive-equation simple general circulation model, and MAOOAM (Modular Arbitrary-Order Ocean-Atmosphere Model), a quasi-geostrophic coupled ocean-atmosphere model on a β-plane. Our first goal is to study the effect of the different levels of filtering on the instabilities and dynamics of the atmospheric flows. Secondly, we assess the impact of the oceanic coupling, of the dissipation scheme and of the resolution on the spectra of LEs.

The PUMA Lyapunov spectrum is computed for two different values of the meridional temperature gradient that defines the Newtonian forcing to the temperature field. Increasing the gradient enhances the baroclinicity and generates stronger instabilities. This corresponds to a larger dimension of the unstable manifold and a larger first LE, as well as an increased Kaplan-Yorke dimension of the attractor. The convergence rate of the rate functional for the large deviation law of the finite-time Lyapunov exponents (FTLEs) is fast for all exponents. This can be attributed to the absence of a clear-cut atmospheric time-scale separation in this kind of model.

The LE spectra for MAOOAM reveal that the dominant atmospheric instability is correctly represented even at low resolutions. However, even at intermediate orders, the dynamics of the central manifold is not fully resolved. The central manifold is mostly associated with the ocean dynamics, which involves much longer time scales and smaller spatial scales than that of the atmosphere. Increasing the mechanical atmosphere-ocean coupling coefficient or introducing a turbulent diffusion parametrization reduces the Kaplan-Yorke dimension and Kolmogorov-Sinai entropy. For all considered configurations, it is possible to robustly define large deviations laws describing the statistics of the FTLEs corresponding to the strongly damped modes, while the opposite holds for near-zero LEs and, somewhat unexpectedly, also for the positive LEs.