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Environmental tipping points in random dynamical systems: a quasigeostrophic case study

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Environmental tipping points (TPs) leading to abrupt state changes are usually considered in an autonomous dynamical systems framework, in which case early warnings may be identified in signals with increased autocorrelation and variance. An essential step toward a more realistic description of abrupt transitions in the environment and climate is to analyze TPs in random dynamical systems. In this context, a case study based on an operational definition of stochastic TPs and on a nonlinear low-order quasigeostrophic model is presented (Pierini, Phys. Rev. E, 2012).

Let us suppose that in an autonomous dynamical system (DS), self-sustained relaxation oscillations emerge if (and only if) a control parameter Q is such that Q > Qo: Qo is therefore a (deterministic) TP. The same system perturbed by noise is said to be "excitable" if a range Q < Qo (depending on the noise) exists in which basically the same relaxation oscillations can be noise-induced (such mechanism is usually referred to as "coherence resonance"). In an excitable random DS (a case likely to be quite common in environmental and climate dynamics) a stochastic TP is defined here as the random variable Ro whose realizations satisfy the same conditions required for Qo in the deterministic case.

The low-order model (with four degrees of freedom) used in this study describes an excitable DS driven by a stationary forcing with amplitude Q (the deterministic control parameter) plus a colored noise characterized by its amplitude A and autocorrelation time scale Ta. A 10-member ensemble is constructed by performing forward time integrations of length T, and by letting A and Ta vary within a broad parametric range. The ensemble averages <Ro> and <N> (where the random variable N is the number of relaxation oscillations emerging in T) are then computed.

The results suggest that in an excitable random DS coherence resonance may be the predominant transition mechanism, in which case stochastic TPs should be considered instead of their classical deterministic counterpart. Possible early warning signals (different from those of the deterministic case) are investigated: a preliminary analysis shows a variety of possible cases, among which a behavior typical of ramped systems (i.e. excitation arises when the control parameter undergoes a sufficiently fast rate of ramping).