

# **OBSERVABLES FOR EARLY-WARNING SIGNALS OF TIPPING POINTS**

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State-of-the-art Earth system models still show too little agreement to give quantitative estimates on the critical levels of global warming that trigger TPs. An alternative line of evidence are data-driven methods that harness general features of dynamical systems undergoing critical transitions. Such early-warning signals (EWS) based on critical slowing down (CSD) have been identified in various climate sub-systems, but they are not without caveats. While it is said that they require no detailed knowledge of the underlying dynamical system, we argue that in practice they do. This is because in a high-dimensional system only some degrees of freedom (DOF) are directly involved in the bifurcation leading to the TP. These DOF would provide a genuine CSD signal. In contrast, trying to detect EWS in an arbitrary observable can lead to both false negatives and positives. Similarly, an incomplete data set not covering all DOF may be inherently insufficient to detect CSD.

To design robust and optimized EWS requires additional knowledge of the relevant DOF. We propose as a possible avenue the computation in a (sufficiently realistic) numerical model of the edge state that lives between the pre- and post-tipping stable state, or, if possible, a most likely noise-induced transition path (instanton) between the alternative stable states. When modeling an edge state is infeasible, we explore a data-driven method that can reconstruct the leading eigenfunctions of the Fokker-Planck operator. These define useful observables for EWS, since they serve as reaction coordinates of transitions between the alternative states.