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Where are the coexisting parallel climates? Large ensemble climate projections from the point of view of chaos theory

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We review recent results of large ensemble climate projections considering them to be simulations of chaotic systems. The quick spread of an initially localized ensemble in the first weeks after initialization is an appearance of the butterfly effect, illustrating the unpredictability of the dynamics. We show that the growth rate of uncertainty (an analogue of the Lyapunov exponent) can be determined right after the initialization. The next phase corresponds to a convergence of the no longer localized ensemble to the time-dependent climate attractor, and requires a much longer time. After convergence takes place, the ensemble faithfully represents the climate dynamics. Concerning a credible simulation, the observed signal should wander within the spread of the converged ensemble all the time, i.e. to behave just as any of the ensemble members. As a manifestation of the chaos-like climate dynamics, one can imagine that beyond the single, observed time-dependent climate, a plethora of parallel climate realizations exist. Converged climate ensembles also define the probability distribution by which the different climate realizations occur. Large ensemble simulations were shown earlier to be credible in the sense formulated. Here in addition, an extended credibility condition is given which requires the ensemble to be a converged ensemble, valid also for low-dimensional models. Interestingly, to the best of our knowledge, no low-order physical or engineering systems subjected to time-dependent forcings are known for which a comparison between simulation and experiment would be available. As illustrative examples, the CESM1-LE (Community Earth System Model Large Ensemble) climate model and a chaotic pendulum are taken.