Fourth International Conference on Earth System Modelling
4ICESM-187, 2017

How does the climate, defined as statistics of weather, evolve with a time-varying atmospheric CO_2-concentration?

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When defining climate as statistics of weather, what we observed at a particular time is just one of many possible realizations, all consistent with the external forcing at that time. A climate prediction should be, strictly speaking, a prediction of the pdf that quantifies the population of all possible realizations subjected to the same future changes in the external forcing. Such a pdf is defined in the phase space of the climate system. For the climate simulated by a climate model, the respective phase space is well defined but high-dimensional, even when the model is run at a moderate resolution of 1 degree, making a quantification of the evolution of the pdf extremely difficult. Sofar, this is normally done using a multi-model ensemble, an ensemble of opportunity more suitable for studying model uncertainties than for studying the pdf evolution of the climate simulated by one and the same climate model.

In this context, understanding how the pdf evolves with a time-varying forcing is crucial for forming the theoretical foundation of climate prediction. Here we make a first attempt to address this problem using a super ensemble of climates, all simulated by the MPI-ESM-1.1 and all forced by the same CO_2-forcing, namely a CO_2-increase at the rate of 1% per year. The ensemble size is 68. Assuming that the
(marginal) pdfs of most components of the state vector in the model phase space are Gaussian, the evolution of the whole pdf is described by the evolutions of the first two moments. We considered dynamical variables, such as velocities, streamfunction and velocity potential, as well as thermodynamical variables, such as temperature. With respect to the mean, we found not only features that are consistent with CO_2-induced changes found in some multi-model ensembles, such as the widening of the Hadley circulation, but also features that are less well described, such as the upward lift of the jets. With respect to the variance, we found a decreasing tendency in centers of large variabilities for some variables. Such a tendency suggests that the respective pdf narrows with the increasing CO_2 concentration. In this case, the cloud of climate states would not only move, but would also shrink, at least in some directions, with increasing CO_2-concentration.