Emulating climate variability and extremes with a diffusion-based model trained on CESM2 and finetuned on ERA5

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Abstract

In the context of increasing interest in machine learning-based emulators to overcome the computational cost and limited scenario coverage of Earth System Models (ESMs), some key challenges remain, such as capturing internal variability, handling non-stationarity, and realistically representing compound and extreme events - especially at high spatial and temporal resolution.

We present a probabilistic emulator of climate dynamics based on a diffusion model trained on the CESM2 Large Ensemble (Danabasoglu et al., 2020) under the SSP3-7.0 scenario. Our approach leverages a score-based diffusion framework (Song and Ermon, 2021) to reproduce the spatiotemporal variability of climate on a monthly timescale, globally and in a multivariate setting. The model is conditioned on greenhouse gas concentrations and we evaluate the capability of the model to generate physically consistent climate fields and to capture the full ensemble spread of the original ESM, including tail behavior and potential extreme events. To ensure a better reproduction of referenced climatological variability, the diffusion model is fine-tuned on ERA5 reanalyses (Hersbach et al., 2020). This should enable the emulator to act as a stochastic generator of plausible climate states under GHG forcing trajectories, accounting for the non-stationarity introduced by anthropogenic climate change, and allowing for the assessment of rare or compound extreme events within the generated ensemble. Our results assess the model's ability to reproduce ensemble-scale statistics, cross-variable dependencies, and evolving climate distributions across time.

Keywords: emulator, ESM, extremes, finetuning, diffusion model, generative

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