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Improving Atmospheric Processes in Earth System Models with Deep Learning Ensembles and Stochastic Parameterizations

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Deep learning has proven to be a valuable tool to represent subgrid processes in climate models, but most application cases have so far used idealized settings and deterministic approaches. Here, we develop ensemble and stochastic parameterizations with calibrated uncertainty quantification to learn subgrid convective and turbulent processes and surface radiative fluxes of a superparameterization embedded in an Earth System Model (ESM). We explore three methods to construct stochastic parameterizations: 1) a single Deep Neural Network (DNN) with Monte Carlo Dropout; 2) a multi-network ensemble; and 3) a Variational Encoder Decoder with latent space perturbation. We show that the multi-network ensembles improve the representation of convective processes in the planetary boundary layer compared to individual DNNs. The respective uncertainty quantification illustrates that the two latter methods are advantageous compared to a dropout-based DNN ensemble regarding the spread of convective processes. We develop a novel partial coupling strategy to sidestep issues in condensate emulation to evaluate the multi-network parameterizations in online runs coupled to the ESM. We can conduct Earth-like stable runs over more than 5 months with the ensemble approach, while such simulations using individual DNNs fail within days. Moreover, we show that our novel ensemble parameterizations improve the representation of extreme precipitation and the underlying diurnal cycle compared to a traditional parameterization, although faithfully representing the mean precipitation pattern remains challenging. Our results pave the way towards a new generation of parameterizations using machine learning with realistic uncertainty quantification that significantly improve the representation of subgrid effects.

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