Project title: **Generative AI and Differentiable Modelling for Hybrid Climate Projections**

Principal investigators: Prof. Dr. Veronika Eyring and Dr. Aytaç Paçal

Abstract. Earth system models (ESMs) are the primary tools for projecting future climate change, yet their accuracy on regional scales is constrained by structural uncertainties in subgrid parametrizations, coarse spatial resolutions, and the immense computational cost of adequately sampling internal variability. This project addresses these fundamental limitations by developing a next-generation hybrid modelling framework for the ICON-XPP model, centered on the advancement of differentiable Earth system modelling. The core scientific innovation lies in the development of an end-to-end differentiable, JAX-based architecture where machine learning (ML) parametrizations for unresolved processes, such as clouds, convection, and turbulence, are co-trained directly within the physics-based dynamical core. This allows for exact, gradient-based online calibration against high-resolution reference simulations and observations, fundamentally resolving the offline-to-online inconsistency that destabilizes traditional hybrid ESMs. To complement this structurally robust modelling backbone, the project leverages generative AI to capture multiscale atmospheric dynamics. Physics-Constrained Adaptive Flow Matching (PCAFM) is employed for the physically consistent, kilometre-scale spatio-temporal downscaling of climate outputs, while conditional generative models enable the efficient emulation of massive climate ensembles. Ultimately, integrating end-to-end calibrated differentiable dynamics with generative AI provides a mathematically rigorous pathway to deliver highly resolved, statistically robust climate projections.