Turbulent flows in the Earth's climate system span a vast range of scales, making it challenging to resolve all relevant dynamics in numerical models, even on the most powerful supercomputers. This necessitates modeling small-scale processes and limits our ability to capture "grey swan" extremes.

We address these challenges by leveraging artificial intelligence (AI) in two complementary ways. First, we use an equation-discovery algorithm informed by fluid physics to discover interpretable, data-driven subgrid-scale (SGS) closures. Second, we develop deep learning–based generative AI diffusion models to emulate geophysical turbulence, producing long-duration simulations that enable the study of "grey swan" extremes. We develop and evaluate these approaches in the context of 2D geophysical turbulence.

We demonstrate that equation-discovery methods can yield closed-form SGS closure equations that are derivable analytically, providing accurate, stable, and generalizable performance in large-eddy simulations. We further demonstrate that a deep learning-based turbulence emulator produces extremes that are rarer than those present in the training data, although challenges remain to accurately reproduce the frequency of these rare event extremes. Together, these results demonstrate both the promise and the limitations of AI in advancing geophysical turbulence modeling and emulation.