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Unlocking Dynamical Insights across the Model Hierarchy with Interpretable Machine Learning

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Hierarchical modelling is a valuable tool, which has supported our understanding of, for example, controls on jet latitude, and the nature of monsoon circulations. However, it is not always clear if and how the insights developed in simpler models, such as aquaplanets, generalise to more realistic situations (e.g. CMIP or reanalysis). Here, we present a new, interpretable machine learning framework for translating dynamical insights across the model hierarchy, and show how this can develop our understanding of large-scale monsoon circulations.

Our goal is to identify dominant balances between terms in the governing equations, which characterise dynamical regimes. We identify these balances, both regionally and across the climatological year, at each stage in a model hierarchy. Our hierarchy comprises simulations with different levels of complexity in the lower boundary conditions, from aquaplanets up to reanalysis. This approach allows us to explore when, where, how and why different dynamical processes arise at each level in the model hierarchy, and to investigate how their extents and timings are altered by changes to model parameters.

Specifically, we employ NEMI, a pipeline previously applied to the vorticity budget of realistic ocean simulations. This pipeline uses UMAP to reduce the complexity of the selected equation into a low-dimensional latent space. Agglomerative hierarchical clustering, along with a combinatorial hypothesis selection algorithm, then facilitate partitioning and labelling the latent space into distinct dynamical regimes. Evaluating entropy, a measure of how consistently a sample is assigned to a given cluster, allows us to objectively choose appropriate hyperparameters, and also conveniently allows study of the regional and seasonal robustness of the different regimes identified.

We apply NEMI to the 200-hPa momentum budget, which has previously been used to study the Hadley cells in aquaplanets. We demonstrate how parallels to known regimes identified in aquaplanets can then be objectively studied in more complex datasets such as ERA5. Within the global tropics, in addition to angular momentum conserving/eddy-driven Hadley circulations, we identify regimes influenced by geostrophic balance and rotational flows. Implications for our understanding of the tropical circulation are discussed.