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A physics-constrained neural network for super-resolution of turbulent Rayleigh-Bénard Convection

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A neural network machine learning model called "Mesh Free Flow Net" based on a study presented in Jiang et al. [2020] is extended and applied to Rayleigh-Bénard convection (RBC) in order to predict the high resolution counterpart of a numerical simulation coarsened to low resolution. RBC is a paradigmatic flow in which a slab of fluid confined between two parallel plates is heated from below and cooled from above, with a constant thermal diffusivity. A large enough temperature difference between the top and bottom plates results in convective motion of the confined fluid. The degree of turbulence is characterised by the Rayleigh number (Ra), which measures the vigor of the convection. We expand the suite of training data to conduct separate experiments that train our model on numerical simulations exhibiting oscillatory laminar flow with $Ra = 10^6$, and turbulent flows with $Ra = 10^8,\ 10^9$ and 10^{10}. The coarsened low resolution input is passed through a U-Net shaped Convolutional Neural Network (CNN), the resultant array being termed the "latent context grid". This intermediate array is upscaled again to attain the high resolution prediction, which is directly compared to the ground truth via a mean squared error loss, and a boundary loss which measures the degree to which the boundary conditions are satisfied. Furthermore, to implement physics-informed constraints, the partial differential equations (PDEs) of the system are evaluated at randomly sampled points from the latent context grid, and the degree to which they are satisfied result in a PDE loss. In addition to the loss, we employ the power spectrum as an additional gauge of the network's performance and capacity to recreate all spatial frequencies present in the ground truth simulation. The proposed extended MeshFree FlowNet architecture performs well on laminar and turbulent flows, with initial results indicating somewhat better performance in the turbulent regime.

References

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