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Data-driven Fractional Modeling for Anomalous Transport and Turbulent Flows

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Coherent structures/motions in turbulence inherently give rise to intermittent signals with sharp peaks, heavy-skewed distributions of velocity increments, highlighting the non-Gaussian nature of turbulence. This suggests that the spatial nonlocal interactions cannot be ruled out of the turbulence physics. Furthermore, filtering the Navier–Stokes equations in the large eddy simulation of turbulent flows would further enhance the existing nonlocality, emerging in the corresponding subgrid scale fluid motions. This urges the development of new nonlocal closure models, which respect the corresponding non-Gaussian statistics of the subgrid stochastic motions.

The main objective of this study is to develop a robust data-driven framework for fractional modeling of anomalous phenomena, starting from the kinetic level. We extend the framework to turbulent flows by developing a SGS model using fractional operators. In this approach, we treat the source of SGS motions in the filtered Boltzmann equation by employing a Lévy-stable distribution, which leads to the proposed fractional-order modeling of subgrid-scale stresses. Moreover, in the context of modeling scalar dispersion in underground waters, we develop a fast and accurate numerical method for the proposed fractional model and perform a comprehensive theoretical and numerical analysis, as the essential components of the framework.