Lagrangian multi-particle analysis of turbulent Rayleigh-Bénard convection

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Abstract

While turbulent convection flows have been studied in-depth from a Eulerian perspective, there has been comparatively little research to investigate the Lagrangian view of turbulent convection. This is, however, crucial to understand atmospheric flow phenomena and particle transport to better predict how flows impact, for example, the propagation of pollen or tracer particles in the air. Performing direct numerical simulations (DNS) with the Rayleigh-Bénard convection (RBC) model allows us to study several aspects of Lagrangian turbulence. To this end, DNS with Lagrangian tracers at different Rayleigh numbers, ranging from the Ra=10ˆ4 to Ra=10ˆ11 were conducted over at least 100 free-fall times each starting from a statistically-stationary state for a Prandtl number of 0.7 for an aspect ratio of 4 or 16 with periodic boundary conditions in the lateral and no-slip boundary conditions in the vertical direction. Pair dispersion of 2ˆ20 particle pairs was analyzed in both the forward and backward direction, highlighting the ballistic, Richardson and diffusive regimes with backward dispersion showing faster separation, illustrating the irreversibility of the turbulent energy cascade. With higher Rayleigh numbers, the Richardson regime becomes increasingly pronounced, underlining the expanding inertial range. Acceleration statistics for all cases were computed and compared for different characteristic layers of the RBC domain (the thermal boundary layers and the bulk), showing increased intermittency in the boundary layers and for larger Rayleigh numbers. Furthermore, clouds of 1,000 particles with a radius equal to the Kolmogorov length each were placed in 3 distinct layers in the vertical direction and advanced over 500 free-fall times. Analyzing their spatio-temporal evolution by virtue of a Principal Component Analysis reveals distinct characteristics of flow regimes at different Rayleigh numbers and gives new insight into how particle clusters disperse. A stochastic model using a simple Langevin equation is proposed and compared to the Lagrangian data with the goal of developing a cheaper surrogate model that captures macroscopic particle transport. Finally, for Rayleigh numbers of up to Ra=10ˆ11, an analysis of the QR-plane to identify distinct turbulence events was conducted from both a Eulerian and a Lagrangian point of view. For the highest Ra, swirling events near the boundary layer (”tornados”) were identified. Their impact on local heat and mass transport is analyzed.

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sciencesconf.org:rbc2026:695666