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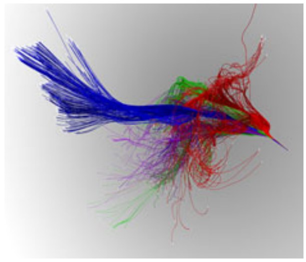
Extreme probing of particle motions in turbulence



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Extreme behaviour of fluid and material motions needs to be understood for engineering processes and the behaviour of clouds or plumes of pollution. Applications in the natural environment require scaling of turbulence behaviour and models beyond current computational or laboratory understanding. New computational studies of Biferale *et al.* (*J. Fluid Mech.*, 2014, vol. 757, pp. 550–572) are probing new regimes of scaling of extreme random events in nature produced by turbulent fluctuations trending towards applications in environmental prediction.

Key words: intermittency, turbulence simulation, turbulent mixing

1. Introduction

Biferale *et al.* (2014) examined fundamental inertial-range properties of turbulent mixing processes of particles expanding on classical work (Richardson 1926*a*; Kolmogorov 1941). These processes are important for industrial (Fox 2012), environmental and even astrophysical distributions of material (Gaensler *et al.* 2011). Cloud dynamics and pollution dispersion are practical examples dependent on particle mixing (Wang *et al.* 2006; Thomson & Wilson 2013).

Advances in understanding mixing have emerged from Lagrangian theory (Taylor 1921), and from simulations of turbulence (Borgas & Yeung 2004). High sensitivity to viscous scaling occurs because the computational scales are bandwidth limited (Sawford 1991; Fung & Vassilicos 1998; Xu *et al.* 2008). The estimate of Taylor (1921) is practically important and free from explicit viscous or molecular diffusion effects on the scales of the atmosphere or ocean. However, to understand more complex mixing such as the relative dispersion of pairs of particles in geophysical flows, on the basis of simulated or laboratory-scale flows, it is necessary to examine systematic corrections of viscous, molecular diffusion and turbulence intermittency effects. Even initial separation 'ballistic' effects can confound scaling estimates (Bourgoin *et al.* 2006).

The work of Biferale *et al.* (2014) focuses on pair separation of heavy particles to diagnose small-scale processes in turbulence within the limited resolution scales of

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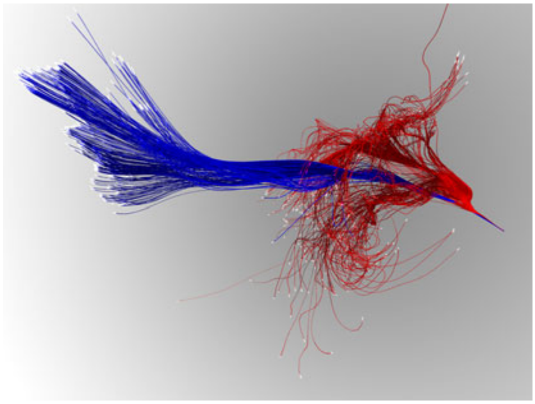

FIGURE 1. An ensemble of tracer particles with $St = 0$ (red) and heavy particles with $St = 5$ (blue), simultaneously emitted from a source of size $\sim\eta$. Trajectories are recorded from the emission time, up to the time $t = 75\tau_\eta$ after the emission.

computational studies. The work considers the dilute particle concentration limit with no feedback of particle dynamics on the underlying turbulent flow field. The results expand upon the classic 'inertial-range' pair separation results of Richardson (1926*a*), and find corrections to such simple diffusion scaling on the basis of multifractal intermittency (Borgas 1993; Xu, Ouellette & Bodenschatz 2006). Such extreme-event behaviours are large deviations from regular behaviour and are important (Sornette 2004). The results of Biferale *et al.* (2014) clearly show variations of the probability of separation events at the tail of the distributions, for pairs of particles that separate much more rapidly than average behaviour. These events are rare and not usually sampled well.

The better statistical sampling of large comprehensive and highly resolved simulations such as that of Biferale *et al.* (2014) compensates for bandwidth limits. The additional trick exploited by Biferale *et al.* (2014) is to use heavy particles with trajectories that are not pure tracers and sample a hybrid Eulerian–Lagrangian world with better scaling characteristics. Regardless of scaling, the separation behaviour of heavy particles is intrinsically interesting and useful for application.

2. Overview

The nature of the heavy-particle trajectories is graphically illustrated in figure 1 of Biferale *et al.* (2014). In this picture, ensembles of trajectories are shown emanating from a small source of length scale $\eta = (\nu^3/\epsilon)^{1/4}$, estimated by Kolmogorov (1941) for the parameters of kinematic viscosity ν and local turbulent energy dissipation rate ϵ. The trajectories shown in blue for heavy particles form a more coherent cluster than the red tracer trajectories as the flow moves right to left from the source.

The Stokes number shown is the ratio of the particle response time τ_s to the Lagrangian viscous time scale $\tau_\eta = (\nu/\epsilon)^{1/2}$: $St = \tau_s/\tau_\eta$. Here $St = 0$ are tracers and $St = 5$ for heavy particles.

For fixed scales of the energy containing eddies of the turbulence, say velocity scale σ and length scale L, define a Reynolds number $Re = \sigma L/\nu$, implying that $\eta = Re^{-3/4}L$, $\tau_\eta = Re^{-1/2}L/\sigma$.

For geophysical flows we anticipate the limit of large Reynolds number $Re \gg 1$, and we see that the length scale η reduces to zero at a faster rate than the corresponding time scale τ_η which is the relevant time scale for Lagrangian processes.

The estimates of turbulent scaling, first promoted by Richardson (1926*b*) and Kolmogorov (1941), is to predict parameters such as velocity differences separated by a length scale r, where viscous or molecular parameters are not important and only 'inertial' scales matter: for example

$$\langle (u_1(x+r) - u_1(x))^2 \rangle \sim C_{kol}(\epsilon r)^{2/3} r \gg \eta, \tag{2.1}$$

where $\langle \bullet \rangle$ means an averaging operation of a velocity difference (say over the x direction) and $C_{kol} \approx 2.13$ is a constant (Sreenivasan 1995). Similarly, the analogous Lagrangian result is

$$\langle (u_1(t+\tau) - u_1(t))^2 \rangle \sim C_0 \epsilon \tau, \quad \tau \gg \tau_\eta \tag{2.2}$$

first examined for viscous scaling corrections by Sawford (1991) estimating that $C_0 \approx 6$.

Viscous scaling means that the resolved dynamic scales of turbulence are smaller in the Lagrangian frame than in the Eulerian frame and for a moderate-*Re* computational simulation it is difficult to unambiguously observe Lagrangian scaling. The intermittency corrections to scaling for higher moments, say $\langle (u_1(x+r) - u_1(x))^q \rangle$ for $q > 2$, are also difficult to untangle from viscous scaling effects at moderate Reynolds number, and difficult to sample sufficiently in geophysical flows for increasingly rare extreme events, which even for highly non-Gaussian multifractal behaviour are highly infrequent (Sornette 2004).

The work of Biferale *et al.* (2014) seeks to untangle this complex world of multiple scaling by using a lens of heavy particle trajectories, which span the Lagrangian tracer view to the Eulerian view for increasingly more massive particles: a very massive particle remains stationary and samples Eulerian velocities in time. In addition, sophisticated diagnostics are used by Biferale *et al.* (2014) including: high-order moments, probability density functions (emphasising the tails) and exit-time statistics which examine the random times taken for particles of a fixed initial separation to move apart by fixed amounts. In the latter case, heavy particles initially close together can have rare extremely long exit times to separate from η to inertial range scales.

3. Future

The goal of the science of heavy particle motions, at least for particle loadings that do not feedback and influence the underlying turbulence, is to help develop models of heavy particle motions and separations. Studies such as those of Fung & Vassilicos (1998), Thomson (1990), Thomson & Devenish (2005) and Borgas & Yeung (2004) show high sensitivity to scaling effects requiring difficult parameterisations. Models for heavy particles are even less well developed and currently cannot incorporate intermittency and complex scaling parameterisations. It is worth noting the famous role of Kolmogorov in the development of stochastic models through the fundamental Chapman–Kolmogorov equation (Gardiner 2009), which has played a pivotal role in the development of stochastic models for tracer advection in turbulence. The scaling of increments and changes, correlations and dependencies, are all important for model fidelity. Only through ongoing discovery about the scaling behaviour of particle trajectories will we be able to advance the modelling of these trajectories for routine geophysical prediction, say for clouds, pollution or clustering behaviour (Falkovich, Gawędzki & Vergassola 2001; Wang *et al.* 2006; Thomson & Wilson 2013). The work of Biferale *et al.* (2014) is an important contribution to this ongoing task.

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