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Dynamic Multiscaling in Two-Dimensional Fluid Turbulence

Samriddhi Sankar Ray,1,∗ Dhrubaditya Mitra,2,† Prasad Perlekar,3,‡ and Rahul Pandit4,§

1Laboratoire Cassiopee, Observatoire de la Côte d’Azur, UNS, CNRS, BP 4229, 06304 Nice Cedex 4, France
2NORDITA, Roslagstullsbacken 23, SE-10691 Stockholm, Sweden
3Department of Mathematics and Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
4Centre for Condensed Matter Theory, Department of Physics, Indian Institute of Science, Bangalore 560012, India

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We obtain, by extensive direct numerical simulations, time-dependent and equal-time structure functions for the vorticity, in both quasi-Lagrangian and Eulerian frames, for the direct-cascade regime in two-dimensional fluid turbulence with air-drug-induced friction. We show that different ways of extracting time scales from these time-dependent structure functions lead to different dynamic-multiscaling exponents, which are related to equal-time multiscaling exponents by different classes of bridge relations; for a representative value of the friction we verify that, given our error bars, these bridge relations hold.

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The scaling properties of both equal-time and time-dependent correlation functions close to a critical point, say, in a spin system, have been understood well for nearly four decades [1,2]. By contrast, the development of a similar understanding of the multiscaling properties of equal-time and time-dependent structure functions in the inertial range in fluid turbulence still remains a major challenge because it requires interdisciplinary studies that must use ideas from both nonequilibrium statistical mechanics and turbulence [3–12]. We develop, therefore, a complete characterization of the rich multiscaling properties of time-dependent vorticity structure functions for the direct-cascade regime of 2D turbulence in fluid films with friction, which we study via a direct numerical simulation (DNS). Such a characterization has not been possible hitherto because it requires very long temporal averaging to obtain good statistics for quasi-Lagrangian structure functions [13], which are considerably more complicated than their conventional, Eulerian counterparts as we show below. Our DNS study yields a variety of interesting results that we summarize informally before providing technical details and precise definitions: (a) We calculate equal-time and time-dependent vorticity structure functions in Eulerian and quasi-Lagrangian frames [13]; (b) we then show how to extract an infinite number of different time scales from such time-dependent structure functions; (c) next we present generalizations of the dynamic-scaling Ansätze, first used in the context of critical phenomena [2] to relate a diverging relaxation time to a diverging correlation length, where is the dynamic-scaling exponent. These generalizations yield, in turn, an infinity of dynamic-multiscaling exponents [5,6,8–12]. (d) A suitable extension of the multifractal formalism [4], which provides a rationalization of the multiscaling of equal-time structure functions in turbulence, yields linear bridge relations between dynamic-multiscaling exponents and their equal-time counterparts [5,6,8–12]; our study provides numerical evidence in support of such bridge relations.

The statistical properties of fully developed, homogeneous, isotropic turbulence are characterized, among other things, by the equal-time, order- structure function , where is the Eulerian velocity at point and time , and is the Eulerian velocity at point and time . In the inertial range , the structure function , with , is the Eulerian structure function of Kolmogorov (K41) predicts simple scaling with for 3D homogeneous, isotropic fluid turbulence. However, experiments and numerical simulations show marked deviations from K41 scaling, especially for , with a nonlinear, convex function of ; thus, we have multiscaling of equal-time velocity structure functions.

To examine dynamic multiscaling, we must obtain the order-, time-dependent structure functions , which we define precisely below, extract from these the time scales , and then the dynamic-multiscaling exponents via dynamic-multiscaling Ansätze like . This task is considerably more complicated than its analog for the determination of the equal-time multiscaling exponents [5–12] for the following two reasons: (I) In the conventional Eulerian description, the sweeping effect, whereby large eddies drive all smaller ones directly, relates spatial separations and temporal separations linearly via the mean-flow velocity, whence we get trivial dynamic scaling with for all . A quasi-Lagrangian description [5,13] eliminates sweeping effects so we calculate time-dependent, quasi-Lagrangian...
vorticity structure functions from our DNS. (II) Such
time-dependent structure functions, even for a fixed order
p, do not collapse onto a scaling function, with a unique,
order-p, dynamic exponent. Hence, even for a fixed order
p, there is an infinity of dynamic-multiscaling exponents
[5,6,8–12]; roughly speaking, to specify the dynamics of an
eddy of a given length scale, we require this infinity of
exponents.

Statistically steady fluid turbulence is very different in
3D and 2D; the former exhibits a direct cascade of energy
whereas the latter shows an inverse cascade of kinetic
energy from the energy-injection scale to larger length
scales and a direct cascade in which the enstrophy goes
towards small length scales [14]. In many physical realiza-
tions of 2D turbulence, there is an air-drag-induced fric-
tion. In this direct-cascade regime, velocity structure
functions show simple scaling but their vorticity counter-
parts exhibit multiscaling [15–17], with exponents that
depend on the friction. Time-dependent structure functions
have not been studied in 2D fluid turbulence; the elucidation
of the dynamic-multiscaling of these structure func-
tions, which we present here, is an important step in the
systematization of such multiscaling in turbulence.

We numerically solve the forced, incompressible, 2D
Navier-Stokes equation with air-drag-induced friction, in
the vorticity (ω)–stream-function (ψ) representation with
periodic boundary conditions:

$$\partial_t \omega - J(\psi, \omega) = \nu \nabla^2 \omega - \mu \omega + f,$$

where $\nabla^2 \psi = \omega$, $J(\psi, \omega) = (\partial_x \psi)(\partial_y \omega) - (\partial_y \psi)(\partial_x \omega)$,
and the velocity $u = (-\partial_y \psi, \partial_x \psi)$. The coefficient of
friction is $\mu$ and $f$ is the external force. We work with
both Eulerian and quasi-Lagrangian fields. The latter are
defined with respect to a Lagrangian particle, which was at
the point $\xi_0$ at time $t_0$, and is at the position $\xi(t|\xi_0, t_0)$
at time $t$, such that $d\xi(t|\xi_0, t_0)/dt = u[\xi(t|\xi_0, t_0), t]$, where
$u$ is the Eulerian velocity. The quasi-Lagrangian velocity
field $u^{QL}$ is defined [13] as follows:

$$u^{QL}(x, t|\xi_0, t_0) \equiv u[x + \xi(t|\xi_0, t_0), t];$$

likewise, we can define the quasi-Lagrangian vorticity field
$\omega^{QL}$ in terms of the Eulerian $\omega$. To obtain this quasi-
Lagrangian field we use an algorithm developed in
Ref. [18], described briefly in the Supplemental
Material [19].

To integrate the Navier-Stokes equations we use a pseudo-
doplerian method with the 2/3 rule for the removal of
aliasing errors [17] and a second-order Runge-Kutta
scheme for time marching with a time step $\delta t = 10^{-3}$.
We force the fluid deterministically on the second shell in
Fourier space. And we use $\mu = 0.1$, $\nu = 10^{-5}$, and
$N = 2048^2$ collocation points [20]. We obtain a turbulent
but statistically steady state with a Taylor microscale
$\lambda \approx 0.2$, Taylor-microscale Reynolds number $Re_\lambda \approx 1400$,
and a box-size eddy-turnover time $\tau_{eddy} \approx 8$. We remove
the effects of transients by discarding data up to time
$\approx 8\tau_{eddy}$. We then obtain data for averages of time-
dependent structure functions for a duration of time
$\approx 10\tau_{eddy}$. The energy spectrum averaged over the same
time interval is shown in Fig. 1(a).

The equal-time, order-p, vorticity structure functions we
consider are $S^\phi_p(r) \equiv \langle [\delta \omega^\phi(r, t)]^p \rangle \sim r^{z^\phi_p}$, for $\eta_\phi \ll r \ll L$, where $\delta \omega^\phi(r, t) = [\omega^\phi(x + r, t) - \omega^\phi(x, t)]$, the
angular brackets denote an average over the nonequilib-
rium statistically steady state of the turbulent fluid, and the
superscript $\phi$ is either $E$, in the Eulerian case, or $QL$, in the
quasi-Lagrangian case; for notational convenience we do
not include a subscript $\omega$ on $S^\phi_p$ and the multiscaling
exponent $z^\phi_p$. We assume isotropy here, but show below
how to extract the isotropic parts of $S^\phi_p$ in a DNS. We also
use the time-dependent, order-p vorticity structure func-
tions

$$F^\phi_p(r, \{t_1, \ldots, t_p\}) \equiv \langle [\delta \omega^\phi(r, t_1) \cdots \delta \omega^\phi(r, t_p)] \rangle; \quad (3)$$

here $t_1, \ldots, t_p$ are $p$ different times; clearly, $F^\phi_p(r, \{t_1 =
\cdots = t_p = 0\}) = S^\phi_p(r)$. We concentrate on the case $t_1 =
t_2 = \cdots = t_i \equiv t$ and $t_{i+1} = t_{i+2} = \cdots = t_p = 0$, with $l < p$
and, for simplicity, denote the resulting time-dependent
structure function as $F^\phi_p(r, t)$; shell-model studies [8,9]
have shown that the index $l$ does not affect dynamic-
multiscaling exponents, so we suppress it henceforth.

Given $F^\phi_p(r, t)$, it is possible to extract a characteristic
time scale $\tau_p(r)$ in many different ways. These time scales

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Given $F^\phi_p(r, t)$, it is possible to extract a characteristic
time scale $\tau_p(r)$ in many different ways. These time scales
can, in turn, be used to extract the order-p dynamic-
multiscaling exponents $z^\phi_p$ via the dynamic-multiscaling
Ansatz $\tau_p(r) \sim r^{z^\phi_p}$. If we obtain the order-p, degree-M,
integral time scale

$$T^I_{p,M}(r) \equiv \left[ \frac{1}{S^\phi_p(r)} \int_0^\infty F^\phi_p(r, t)^{l(M-1)} dt \right]^{1/M}, \quad (4)$$

we can use it to extract the integral dynamic-multiscaling
exponent $z^\phi_p$ from the relation $T^I_{p,M} \sim r^{z^\phi_p}$.
Similarly, from the order-p, degree-M, derivative time scale

$$T^D_{p,M}(r) \equiv \left[ \frac{1}{S^\phi_p(r)} \frac{\partial^M}{\partial r^M} F^\phi_p(r, t) \right]_{t=0}^{1/M}, \quad (5)$$

we obtain the derivative dynamic-multiscaling exponent
$z^\phi_p$ via the relation $T^D_{p,M} \sim r^{z^\phi_p}$. Equal-time vorticity structure functions in 2D fluid tur-
bulence with friction exhibit multiscaling in the direct-
cascade range [15–17]. For the case of 3D homogeneous,
isotropic fluid turbulence, a generalization of the multi-
fractal model [4], which includes time-dependent velocity
structure functions [5,9,11,12], yields linear bridge rela-
tions between the dynamic-multiscaling exponents and
their equal-time counterparts. For the direct-cascade re-
gime in our study, we replace velocity structure functions
functions are isotropic, to a good approximation for small $r_c$, the origin $r_c$ we use $r_c = (i, j), 2 \leq i, j \leq 5$. These averaged structure functions are isotropic, to a good approximation for small $R$, as can be seen from the illustrative pseudocolor plot of $S_{op}^{QL}(R)$ in Fig. 1(a). The purely isotropic parts of such structure functions can be obtained \cite{17,21} via an integration over the angle $\theta$ that $R$ makes with the $x$ axis; i.e., we calculate $S_{op}^{R}(R) = \int_0^{2\pi} S_{op}^{\phi}(R) d\theta$ and then the equal-time multiscaling exponent $\xi_p$, the slopes of the scaling ranges of log-log plots of $S_{op}^{R}(R)$ versus $R$. The mean of the local slopes $\xi_p$, obtained as defined in the text, versus the separation, from $p = 1$ (bottom) to $p = 6$ (top). (d) Log-log (base 10) plot of the order-2, degree-1, integral time scale $T_{2,1}^{QL}(R)$ versus the separation $R$ showing our data points (open red circles) and the best-fit line (full black) in the scaling range; the inset shows the local slopes $\chi_p$, obtained as defined in the text, versus the separation, from $p = 1$ (bottom) to $p = 6$ (top).

by vorticity structure functions and thus obtain the following bridge relations for time-dependent vorticity structure functions in 2D fluid turbulence with friction:

$$z_{p,M} = 1 + [(\xi_{p,M} - \xi_p)/M].$$

The vorticity field $\omega^\phi = \langle \omega^\phi \rangle + \omega^{\phi_{f}}$ can be decomposed into the time-averaged mean flow $\langle \omega^\phi \rangle$ and the fluctuations $\omega^{\phi_{f}}$ about it. To obtain good statistics for vorticity structure functions it is important to eliminate any anisotropy in the flow by subtracting out the mean flow from the field. Therefore, we redefine the order-$p$, equal-time structure function to be $S_{op}^{\phi}(r_c, R) = \langle \omega^{\phi_{f}}(r_c + R) - \omega^{\phi_{f}}(r_c) \rangle^p$, where $R$ has magnitude $R$ and $r_c$ is an origin. We next use $S_{op}^{\phi}(R) = \langle S_{op}^{\phi}(r_c, R) \rangle_{r_c}$, where the subscript $r_c$ denotes an average over the origin [we use $r_c = (i, j), 2 \leq i, j \leq 5$]. These averaged structure functions are isotropic, to a good approximation for small $R$, as can be seen from the illustrative pseudocolor plot of $S_{2,1}^{QL}(R)$ in Fig. 1(a). The purely isotropic parts of such
successive, nonoverlapping sets of 3 points each. The mean values of these slopes yield our dynamic-multiscaling exponents (column 5 in Table I), and their standard deviations yield the error bars. We calculate the degree-$M$, order-$p$ derivative-time exponents by using a sixth-order, finite-difference scheme to obtain $T^{P,\phi}_{p,M}$ and then the dynamic-multiscaling exponents $z^{Q\phi}_{p,M}$. Our results for the quasi-Lagrangian case with $M = 2$ are given in column 7 of Table I. We find, furthermore, that both the integral and derivative bridge relations (6) and (7) hold within our error bars, as shown for the representative values of $p$ and $M$ considered in Table I (compare columns 4 and 5 for the integral relation and columns 6 and 7 for the derivative relation). Note also that the values of the integral and the derivative dynamic-multiscaling exponents are markedly different from each other (compare columns 5 and 7 of Table I).

The Eulerian structure functions $F_p^E(R,t)$ also lead to nontrivial dynamic-multiscaling exponents, which are equal to their quasi-Lagrangian counterparts (see Supplemental Material [19]). The reason for this initially surprising result is that, in 2D turbulence, the friction controls the size of the largest vortices, provides an infrared cutoff at large length scales, and thus suppresses the sweeping effect. We have demonstrated this in the Supplemental Material [19]. Had the sweeping effect not been suppressed, we would have obtained trivial dynamic scaling for the Eulerian case.

The calculation of dynamic-multiscaling exponents has been limited so far to shell models for 3D, homogeneous, isotropic fluid and passive-scalar turbulence [10]. We have presented the first study of such dynamic multiscaling in the direct-cascade regime of 2D fluid turbulence with friction by calculating both quasi-Lagrangian and Eulerian structure functions. Our work brings out clearly the need for an infinity of time scales and associated exponents to characterize such multiscaling, and it verifies, within the accuracy of our numerical calculations, the linear bridge relations (6) and (7) for a representative value of $\mu$. We find that friction also suppresses sweeping effects so, with such friction, even Eulerian vorticity structure functions exhibit dynamic multiscaling with exponents that are consistent with their quasi-Lagrangian counterparts.

Experimental studies of Lagrangian quantities in turbulence have been increasing steadily over the past decade [22]. We hope, therefore, that our work will encourage studies of dynamic multiscaling in turbulence. Furthermore, it will be interesting to check whether the time scales considered here can be related to the persistence time scales for 2D turbulence [23].

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Note added.—Just as we were preparing this study for publication we became aware of a recent paper [24] on a related study for 3D fluid turbulence.