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UNCOVERING A LOG-NORMAL CASCADE PROCESS IN HIGH REYNOLDS NUMBER TURBULENCE FROM WAVELET ANALYSIS

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We present a generalization of the Castaing *et al.* [1] approach of velocity intermittency using the wavelet transform (WT). This description consists in looking for a multiplicative cascade process directly on the velocity field assuming that the probability density function (pdf) of the modulus maxima of the WT (WTMM) at a given scale a , $P_a(T)$, can be expressed as a weighted sum of dilated pdf's at a larger scale $a' > a$:

$$P_a(T) = \int G_{aa'}(u) P_{a'}(e^{-u}T) e^{-u} du, \quad \text{for } a' > a. \quad (1)$$

The reader is referred to Ref. [2] for the computation of the WT of the velocity field and the restriction of the analysis to the modulus maxima of the WT (WTMM method). Our numerical method for estimating the Fourier transform $\widehat{G}_{aa'}$ of the kernel $G_{aa'}$ is described in Refs. [3, 4]. This wavelet-based method is applied to a turbulent velocity signal recorded in the Modane wind tunnel and kindly provided by Y. Gagne and Y. Malecot. The Taylor scale based Reynolds number is $R_\lambda \simeq 2000$ and the sample is $2.5 \cdot 10^8$ points long, with a resolution of roughly 3η (where η is the Kolmogorov scale), corresponding to 25000 integral scales. We then propose a two-point statistical analysis based on space-scale correlations [5].

1. Experimental results of the one-point statistical approach

The computation of $\widehat{G}_{aa'}$ for various pairs of inertial scales $a < a'$ reveals the existence of a function $s(a, a')$ and of a single kernel \widehat{G} such that $\widehat{G}_{aa'} = \widehat{G}^{s(a, a')}$ (*i.e.* formally $G_{aa'} = G^{\otimes s(a, a')}$). According to the definitions given in Ref. [1], this means that the underlying cascade process is self-similar

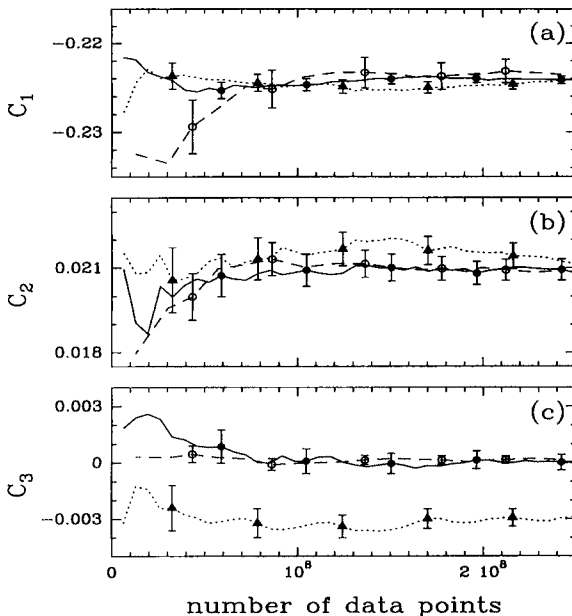


Figure 1. The first three cumulants of $G_{aa'}$ vs the sample length. Turbulent velocity signal for $a = 770\eta$ and $a' = 1540\eta$ (\circ and dashed line), log-normal numerical process with $m = 0.32$ and $\sigma^2 = 0.03$ (\bullet and solid line) and log-Poisson numerical process with $\lambda = 2$, $\delta = 0.89$ and $\gamma = -0.082$ (triangles and dots) for the two corresponding scales $a = 2^8$ and $a' = 2^9$. The analyzing wavelet is a first order compactly-supported wavelet [4].

and that $s(a, a')$ accounts for the number of cascade steps from scale a' to scale a . Such a cascade is said scale-similar (or scale-invariant) if $s(a, a') = \ln(a'/a)$. In the present case, $s(a, a')$ turns out to be very well fitted by the functional form $s(a, a') = (a^{-\beta} - a'^{-\beta})/\beta$, where $\beta \simeq 0.095$ quantifies the departure from scale-similarity (scale-invariance is restored for $\beta \rightarrow 0$) [6]. Thus, the cascade process is self-similar but not scale-invariant.

To analyze precisely the shape of G , we use the Taylor series expansion: $\hat{G}(p) = \exp\left(\sum_{k=1}^{\infty} c_k \frac{(ip)^k}{k!}\right)$, where the (real valued) coefficients c_k are the cumulants of G . Figure 1 shows the first three cumulants $C_k = s(a, a') c_k$ (for a given pair of inertial scales $a < a'$) for the turbulence data and for both a log-normal (mean m and variance σ^2) and a log-Poisson (with the λ , δ and γ parameters consistent with the ones proposed by She and Leveque [7]) synthetic numerical processes. Even though both numerical processes perfectly fit the first two cumulants, the log-Poisson model yields a third order cumulant that is more than one order of magnitude higher than the experimental one, whereas the very small (theoretically zero) third order cumulant of the log-normal numerical process still remains within the

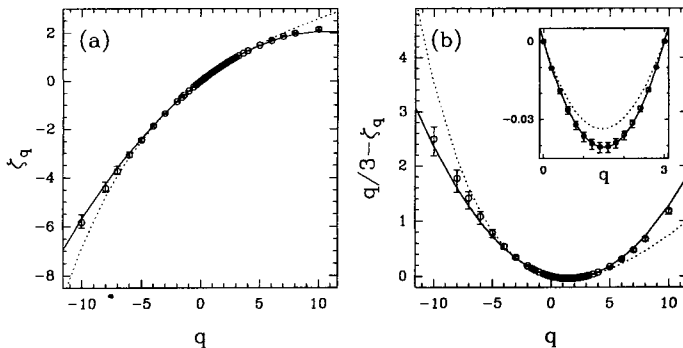


Figure 2. WTMM estimation of the ζ_q spectrum for the turbulent velocity signal [4]. (a) ζ_q vs q . (b) Deviation of the experimental spectrum from $q/3$. The experimental measurements (o) are compared to the theoretical quadratic ESS spectrum of a log-normal process with $m = 0.32$ and $\sigma^2 = 0.03$ (solid line) and to the She and Leveque [7] log-Poisson prediction (dots).

error bars of the experimental one. We thus exclude log-Poisson statistics as proposed in Ref. [7] and conclude that the statistics underlying the velocity fluctuations are log-normal, as soon as $R_\lambda > 1000$.

Testing the convolution formula (1) on the WTMM pdf's using a Gaussian kernel yields results in very good agreement with the log-normal cascade picture [4]. A second test of log-normality lies in the scaling exponents ζ_q of the velocity structure functions. As shown in Fig. 2(a), the experimental spectrum, obtained using extended self-similarity (ESS) [8] and extended to negative values of q thanks to the WTMM method, remarkably coincides with the quadratic log-normal prediction. The log-Poisson prediction [7] provides a good approximation of ζ_q for $q \in [-6, 6]$. However, plotting the deviation of the ζ_q 's from the Kolmogorov (1941) linear $q/3$ spectrum (Fig. 2(b)), reveals a systematic departure of the log-Poisson prediction from the experimental spectrum, whereas the log-normal model still perfectly fits the experimental data.

2. Space-scale correlations of the WT: a two-point statistical analysis

To get a deeper insight into the nature of the statistics, we study the space-scale correlations of the “magnitude” $\omega(x, a)$ of the velocity field at point x and scale a [5]. $\omega(x, a)$ is defined as the logarithm of a local average over a size a of the wavelet coefficients at scale a around the point x . Here, we use the velocity increments to compute $\omega(x, a)$. Figure 3 shows various correlation functions $C(\Delta x, a, a') = \overline{\tilde{\omega}(x, a)\tilde{\omega}(x + \Delta x, a')}$, where the overline stands for ensemble average and $\tilde{\omega}$ for the centered process

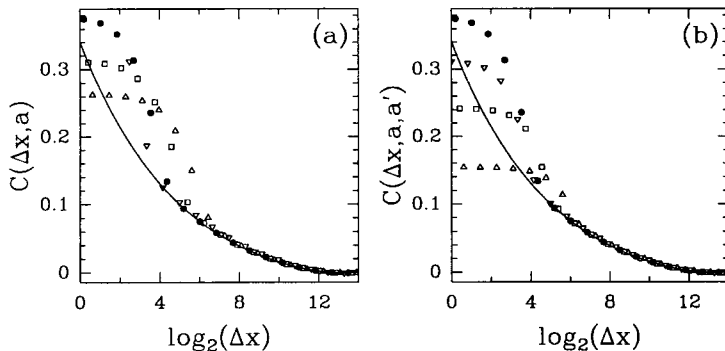


Figure 3. Increment magnitude correlation functions of the turbulent velocity signal. (a) “One-scale” correlation functions $C(\Delta x, a) = C(\Delta x, a, a)$ at scale $a = 8$ (down triangles), 16 (\bullet), 32 (squares) and 64 (up triangles). (b) “Two-scale” correlations functions at scale $a = 8, a' = 16$ (down triangles), $a = 16, a' = 16$ (\bullet), $a = 16, a' = 32$ (squares) and $a = 16, a' = 64$ (up triangles). The solid line corresponds to a non scale-invariant, log-normal cascade model with $\beta = 0.3, \sigma^2 = 0.27$. $a, a',$ and Δx are expressed in mesh size ($\simeq 3\eta$) units.

$\omega - \bar{\omega}$. Once again, the experimental results are in very good agreement with a log-normal, non scale-invariant cascade. However, the cross-over from the value $C(\Delta x = 0, a, a)$ down to the fitted curve and the fact that the scale-invariance breaking exponent β takes a different value when computed from the space-scale correlations of the increment magnitude ($\beta = 0.3$) and from the WTMM estimation of the kernel G ($\beta = 0.095$) suggest that simple (even non scale-invariant) self-similar cascades are not sufficient to account for the space-scale structure of the velocity field.

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