On small-scale and large-scale intermittency of Lagrangian statistics in canopy flow

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Abstract

The interaction of fluids with surface-mounted obstacles in canopy flows leads to strong turbulence that dominates dispersion and mixing in the neutrally stable atmospheric surface layer. This work focuses on intermittency in the Lagrangian velocity statistics in a canopy flow, which is observed in two distinct forms. The first, small scale intermittency, is expressed by non-Gaussian and not self-similar statistics of the velocity increments. The analysis shows an agreement in comparison with previous results from homogeneous isotropic turbulence (HIT) using the multifractal model, extended self-similarity, and acceleration autocorrelations. These observations suggest that the picture of small-scale Lagrangian intermittency in canopy flows is similar to that in HIT, and therefore, they extend the idea of universal Lagrangian intermittency to certain inhomogeneous and anisotropic flows. Second, it is observed that the RMS of energy increments along Lagrangian trajectories depend on the direction of the trajectories’ time-averaged turbulent velocity. Subsequent analysis suggests that the flow is attenuated by the canopy drag while leaving the structure function’s scaling unchanged. This observation implies the existence of large-scale intermittency in Lagrangian statistics. Thus, this work presents a first empirical evidence of intermittent Lagrangian velocity statistics in a canopy flow that exists in two distinct senses and occurs due to different mechanisms.

1 Introduction

Turbulent flows are often characterized by bursts of activity amongst long quiescent periods, and thus, they are said to be intermittent. Intermittency can occur in turbulence in two different forms. The first is called small-scale intermittency; it was first reported by Batchelor et al. (1949), and it was reviewed by Frisch (1995); Tsinober (2009). Small-scale intermittency is evident in statistics of velocity differences, both in the Eulerian and the Lagrangian frames, since their probability distribution functions (PDFs) develop increasingly heavier tails as the scale of separation is reduced (e.g. Kailasnath et al. (1992); Arnèodo et al. (2008)). Despite numerous models that have been suggested, a comprehensive theory for small-scale intermittency is still missing (e.g. She & Leveque (1994); Elsinga et al. (2020)), and yet, it is believed to be a universal feature of high Reynolds number turbulence. The second kind of intermittency is termed large-scale intermittency, and it may occur due to variability of the flow at low frequency. For example, transitions between the turbulent and non-turbulent states occur in jets or in transitional pipe flows (Corrsin, 1943; Wygnanski & Champagne, 1973), and mesoscale flows change local turbulence parameter in the atmospheric boundary-layer (Muchinski et al., 2004). This work focuses on flows that are typical of the atmospheric surface layer, so-called canopy flows. In these flows, a fluid flow interacts with large surface-mounted obstacles, leading to high turbulence intensities. Furthermore, turbulence in canopies is said to be non-local since a significant fraction of turbulent kinetic energy is produced at the top of the obstacles and is then transported into the canopy layer itself (Finnigan, 2000). The non-local character of the turbulence in canopy flows leads to

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large-scale intermittency inside the canopy, which is expressed by a velocity skewness, sparse extreme events of momentum and scalar fluxes or time-varying Hölder exponents (e.g. Finnigan (1979); Gao et al. (1989); Louka et al. (2000); Keylock et al. (2020)). Therefore, canopy flows provide a fruitful ground for observing the two phenomena in conjunction, which is the aim of this work.

Intermittency in turbulence was studied previously mostly in the Eulerian framework, yet the advent of technological advances of the 2000s enabled empirical investigations in the Lagrangian framework as well (as reviewed by Toschi & Bodenschatz (2009)). Previous Lagrangian studies have revealed the existence of anomalous scaling of velocity differences (Chevillard et al., 2003; Arnèodo et al., 2008; Benzi et al., 2010; Huang et al., 2013), have examined local flow features associated with extreme events (Liberzon et al., 2012; Xu et al., 2014; Watteaux et al., 2019) and proposed modeling strategies (Wilczek et al., 2013; Bentkamp et al., 2019). Nevertheless, these works focused on homogeneous isotropic turbulent flows and, inevitably so, only addressed small-scale intermittency. Indeed, there is a marked absence of Lagrangian studies focusing on intermittency in inhomogeneous flows and on large-scale intermittency. In fact, there are no empirical investigations of intermittency in Lagrangian statistics in canopy flows despite its importance to Lagrangian stochastic models with applications for dispersion and mixing in the environment (Wilson & Sawford, 1996; Reynolds, 1998; Duman et al., 2016; Shnapp et al., 2020; Viggiano et al., 2020; Keylock et al., 2020).

This work presents an analysis of Lagrangian statistics in a canopy flow using empirical results from a recent wind-tunnel experiment (Shnapp et al., 2019). The existence of small-scale intermittency is demonstrated in Sec. 3.1, and the results are compared to previous studies from HIT flows. Both qualitative and quantitative agreement is observed, which supports the idea of the universality of intermittency in isotropic turbulent flows and, inevitably so, only addressed small-scale intermittency. Indeed, there is a marked absence of Lagrangian studies focusing on intermittency in inhomogeneous flows and on large-scale intermittency. In fact, there are no empirical investigations of intermittency in Lagrangian statistics in canopy flows despite its importance to Lagrangian stochastic models with applications for dispersion and mixing in the environment (Wilson & Sawford, 1996; Reynolds, 1998; Duman et al., 2016; Shnapp et al., 2020; Viggiano et al., 2020; Keylock et al., 2020).

This work is focused on a subset of trajectories that were recorded in a small sub-volume of space. The sub-volume had a length of $\frac{3}{4}H$, width of $\frac{1}{2}H$, and it was situated at the top of the canopy layer, 0.9 < $\frac{z}{H}$ < 1.1 (this is sub-volume b3 in Shnapp et al. (2020)). The RMS of velocity fluctuations was $\bar{u} = 0.47 \text{ m s}^{-1}$, the mean dissipation rate was estimated as $\varepsilon = 0.25 \text{ m}^2 \text{s}^{-3}$, the Kolmogorov length scale was $\eta = 0.34 \text{ mm} \approx \frac{1}{100} H$, and the Taylor microscale Reynolds number was $Re_\lambda = 440$.

2 Methods

Lagrangian trajectories in a canopy flow were analyzed using the results of a wind-tunnel, 3D particle tracking velocimetry (3D-PTV) experiment. The full experimental details are given in Shnapp et al. (2019), and Lagrangian statistics were analyzed in Shnapp et al. (2020). For brevity, only the information relevant to this work shall be repeated here.

The experiment was conducted in the environmental wind-tunnel laboratory at the Israel Institute for Biological Research (IIBR), that features a 14 meters long open wind-tunnel with a $2 \times 2 \text{ m}^2$ cross-sectional area. We used a double-height staggered canopy layout, in which flat plates of height $H$ and $\frac{1}{4}H$ were placed in consecutive rows ($H = 100 \text{ mm}$). The plates were thin, their width was $\frac{1}{2}H$, and the spacing between the rows was $\frac{3}{4}H$. The canopy frontal area density, defined as $A_f = A_f / A_T$, (where $A_f$ is the frontal area of the elements and $A_T$ is the lot area of the canopy layer), was $\frac{9}{16}$, which categorizes our canopy as moderately dense. The wind velocity was $U_{\infty} = 2.5 \text{ m s}^{-1}$, corresponding to a Reynolds number of $Re_{\infty} = U_{\infty} H / \nu = 1.6 \times 10^4$ ($\nu$ is the kinematic viscosity). We recorded the trajectories using a real-time image analysis extension of the 3D-PTV method described in Shnapp et al. (2019). The PTV algorithms and the analysis were applied using the OpenPTV (OpenPTV consortium (2014)) open-source software and our open-source Flowtracks package (Meller & Liberzon, 2016). In this work, $x$ is the streamwise direction, $y$ is horizontal span-wise, and $z$ is perpendicular to the bottom wall directed upwards where $z = 0$ corresponds to the bottom wall.

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Furthermore, the Lagrangian streamwise velocity decorrelation timescale was $T = 54\,\text{ms}$, estimated by fitting the autocorrelation function. Notably, the decorrelation timescale varied for each velocity component, and the Lagrangian integral timescale $T_L$ is not trivial to define, so $T$ shall be used as a proxy for $T_L$ for simplicity (see Shnapp et al. (2020) for a detailed discussion).

3 Results

3.1 Lagrangian velocity increments and small-scale intermittency

In the following section, the focus is put on small-scale intermittency. The Lagrangian temporal velocity increment, defined as

$$\Delta_\tau v_i(t_0) \equiv v_i(t_0 + \tau) - v_i(t_0)$$

where $\tau$ is the time lag, is widely used to study velocity statistics at different scales. Here, we use statistics of $\Delta_\tau v_i$ to show the existence of, and to analyze, small-scale intermittency in the canopy flow. Note that assuming stationarity of the flow in the wind tunnel, statistics are reported for different trajectories with different $t_0$, namely, we average over $t_0$.

The PDFs, $P(\Delta_\tau v_i)$, for trajectories from the canopy flow experiment are shown in Fig. 1 (a) as symbols for five values of $\tau$. The PDFs were translated vertically for better visualization. The figure shows that as the time lag is reduced the tails of the PDFs become wider, showing that at smaller scales there is a higher probability for extreme events. In addition, the flatness coefficient of the velocity differences is plotted in Fig 1 (b) against $\tau/\tau_\eta$. The empirical data is shown as symbols, error bars represent the range obtained using bootstrapping with 5 sub-samples of the data, and the Gaussian value of $F = 3$ is shown as a dashed line. At small $\tau$ the flatness is high, reaching roughly 17, and as the time lag grows it reduces monotonously, reaching down to $F \approx 5$. In the Kolmogorov similarity theory, dimensional analysis predicts that moments of the velocity difference scale with the time lag as $\langle (\Delta_\tau v_i)^q \rangle \sim \tau^{q/2}$ (Monin & Yaglom, 1972), and so the flatness coefficient should remain constant in the inertial range, $\tau_\eta \ll \tau \ll T_L$. Thus, the change of $F(\tau)$ for $\tau \gg \tau_\eta$ shows the existence of deviation from the Kolmogorov similarity theory in the canopy flow. As discussed in Sec. 1, this transition of the statistics with $\tau$ is a hallmark of turbulent flows that characterizes small-scale intermittency.

Chevillard et al. (2003) proposed that the transition from the flat to Gaussian PDF in HIT can be described by the multifractal model, and showed that it was in good agreement with results from two experiments and DNS simulations at various $Re_L$. Briefly explained, in the multifractal formalism the
velocity increments are specified as

$$\Delta_{\tau} v_i = B \left( \frac{\tau}{T_L} \right)^{\Delta T_L v_i}$$

(2)

where $\Delta_{T_L} v_i$ is the velocity increments at long-times, and $B (\tau/T_L)$ is a random function. Then, $P(\Delta_{\tau} v_i)$ can be calculated by integrating the PDFs of $B$ and $\Delta_{T_L} v_i$, given a model for $B$. Importantly, this work uses the same model for $B$ that was originally utilized by Chevillard et al. (2003) for studies of HIT flows, and it thus assumes the same singularity spectrum for the canopy flow; a full description of the model is given in the supplementary material. The resulting PDFs that were calculated using the model are shown in Fig. 1 as continuous lines underlying the empirical data. The flatness coefficient that was calculated using the multifractal model is also plotted in Fig. 1(b) as a continuous line, showing a fair agreement between the empirical data and the model. The fair agreement between the empirical results and the model is important because we used here the same function $B$. Indeed, the fact that using the same singularity spectrum we could obtain a close fit for statistics of our data suggests that

$$\text{there exists a similarity between the small-scale dynamics in the canopy flow and HIT, despite the strong inhomogeneity and anisotropy of the canopy flow.}$$

The so-called Lagrangian structure functions are moments of the velocity increments,

$$S_q (\tau) = \langle (\Delta_{\tau} v_i)^q \rangle,$$

(3)

and their local scaling is denoted $S_q \sim \tau^{\zeta_q (\tau)}$. In the inertial range, the Kolmogorov similarity theory predicts that $\zeta_q (\tau) = q/2$, however, small-scale intermittency leads to deviations from this scaling law. Thus, the deviations can be used to quantify small-scale intermittency. The structure functions for $q = 2, 4, \text{ and } 6$ are shown in the inset of Fig. 2(a). Due to the finite Reynolds number effects that can affect $\zeta_q$, it is common to estimate scaling of the structure functions using the extended self similarity framework (ESS), where $\zeta_q$ is examined relative to $\zeta_2$ (Toschi & Bodenschatz, 2009). Thus, in the main panel of Fig. 2(a), we examine $\zeta_q/\zeta_2$ by plotting $S_q$ against $S_2$ in log-log scales for $q = 4$ and 6. The figure shows a narrow region $\tau_\eta < \tau \leq 6.5 \tau_\eta$ in which a self similar scaling region exists for the canopy flow experiment. Notably, the separation of scales in the canopy experiment was $\tau_\eta \approx 6$, very low as compared to homogeneous flows with similar $Re_\lambda$, due to the so-called rapid decorrelation that was explored by Shnapp et al. (2020), and this limited severely the extent of the scaling range of $S_q/S_2$. The estimates from Fig. 2(a) give $\frac{\Delta_4}{\zeta_4} \approx 1.51$ and $\frac{\Delta_6}{\zeta_6} \approx 1.81$. These values are in remarkable agreement with previous experimental results from HIT flows, for example, Mordant et al. (2004) found $\frac{\Delta_4}{\zeta_4} = 1.54 \pm 0.06$ and $\frac{\Delta_6}{\zeta_6} = 1.8 \pm 0.2$ for the $Re_j = 570$ experiment (cf. Table 4 there).

Let us briefly consider dynamical scenarios for small-scale Lagrangian intermittency. Results from HIT DNS by Biferale et al. (2005); Bec et al. (2006); Bentkamp et al. (2019) suggested that small-scale intermittency is due to encounter of particles with intense vortex filaments for finite times, $\sim 2 \tau_\eta$. Similarly, Liberzon et al. (2012) showed that acceleration-vorticity and acceleration-strain alignment in a quasi-homogeneous flow are associated with intense energy flux. Although the present data does not allow to verify such acceleration-vorticity-strain relations in the canopy experiment, we can still show hints suggesting that similar scenarios occur in the canopy flow using the autocorrelation of velocity differences. In particular, Mordant et al. (2002, 2004) suggested that Lagrangian small-scale intermittency occurs due to long time correlations of Lagrangian particle’s acceleration magnitude, and indeed, Fig. 2 shows that the same is true for the canopy flow data. The figure shows two autocorrelation functions: one for the increments of the streamwise velocity component and one for increments of the magnitude of the velocity vector, taking the time lag $\tau = \tau_\eta$. While the streamwise velocity increments became decorrelated ($\rho = 0$) at about $2 \tau_\eta$, the velocity magnitude difference retained correlation with itself over the whole range of the measurements, with the minimum value of around $\rho \approx 0.4$. This observation suggests that similarly to the HIT case, small-scale Lagrangian intermittency in the canopy flow is related to the encounter of particles with sparse regions of high vorticity intensity in the flow. The inset of Fig. 2 visualizes a convoluted trajectory, which is a possible instance of such a trapping scenario.
Figure 2: (a) The inset shows Lagrangian structure functions, $S_q(\tau)$, for $q = 2, 4$ and 6; the main figure is an ESS plot that shows $S_4$ and $S_6$ against $S_2$ to probe relative scaling. (b) Lagrangian autocorrelation function of temporal velocity increments with $\tau = \tau_\eta$, shown for the streamwise component and for the magnitude of the velocity vector. The inset is a 3D representation of a convoluted trajectory in a box of size $(0.2H)^3$.

### 3.2 Conditional statistics imply large-scale intermittency

In the following section we use conditional statistics in order to detect large-scale intermittency. Consider the velocity of a Lagrangian trajectory $(j)$, between the times $t_0$ and $t_0 + \tau$: $v_{t_0,\tau}^{(j)} \equiv \{v(t) \mid t_0 \leq t < t_0 + \tau\}$. The average of a function in this section shall be denoted with a tilde symbol as

$$\langle f(v^{(j)}) \rangle_{t_{0,\tau}} \equiv \frac{1}{\tau} \int_{t_0}^{t_0+\tau} f(v_{t_0,\tau}) dt .$$

As before, since we assume stationarity we average over $t_0$. In addition, we denote fluctuations of the trajectory averaged velocity with respect to the Eulerian mean velocity as $h_{v_{t_0,\tau}} \equiv v_{t_0,\tau} - \overline{v}_\tau$. Now, using the above averages and in analogy to the Eulerian quadrant analysis (Antonia, 1981; Shaw et al., 1983; Raupach et al., 1986; Zhu et al., 2007), we define the Lagrangian quadrant of a trajectory using the signs of the $h_{v_{t_0,\tau}}$ components on the $x$ and $z$ plane as follows:

$$Q_l \equiv \begin{cases} 1, & \text{if } \overline{v}_x^{(j)} > U_x \text{ and } \overline{v}_z^{(j)} > U_z \\ 2, & \text{if } \overline{v}_x^{(j)} \leq U_x \text{ and } \overline{v}_z^{(j)} > U_z \\ 3, & \text{if } \overline{v}_x^{(j)} \leq U_x \text{ and } \overline{v}_z^{(j)} \leq U_z \\ 4, & \text{if } \overline{v}_x^{(j)} > U_x \text{ and } \overline{v}_z^{(j)} \leq U_z \end{cases} .$$

Fig. 3(a) shows a normalized histogram for the trajectories being associated with the four quadrant states, using the averaging time $\tau = T$. It shows that $Q_2$ trajectories were the most common, followed by $Q_4$ trajectories and then $Q_1$ and $Q_3$ trajectories, which is in qualitative agreement with the duration fractions reported by Yue et al. (2007); Zhu et al. (2007). It is also interesting to see that the time averaged Lagrangian velocity fluctuation components are correlated, similar to the Eulerian turbulent velocity components that make up the Reynolds stress. This is shown in Fig. 3(b) through the elliptical shape of the joint PDF that is elongated in the direction of the negative diagonal, and resulted in the correlation $\langle v^3 \rangle_T -0.26$. Below, conditional statistics based on $Q_l$ are used to probe large-scale intermittency effects on the Lagrangian statistics.

The trajectories in the canopy flow experiment were observed to be associated with more/less strong changes of their kinetic energy ($e \equiv \frac{1}{2} |v|^2$) when trajectories were conditioned based on the value of $Q_l$. To demonstrate this, let us denote the following property:

$$A_{\tau}^{(j)} \equiv \left\langle \left[ e_{\tau}^{(j)} - E_{\tau}^{(j)} \right]^2 \right\rangle_{\tau}^{1/2} .$$
where $E^{(j)} = \langle e^{(j)} \rangle_\tau$ is a shorthand for the average kinetic energy of a trajectory. Thus, $A^{(j)}_\tau$ is the RMS of the kinetic energy increments that were discussed by Xu et al. (2014) along the path of a Lagrangian trajectory during a time $\tau$. For each trajectory, it is a non-negative scalar that quantifies the amplitude of its kinetic energy changes. Loosely speaking, it can be interpreted to show how active a trajectory is. PDFs of $A^{(j)}_\tau$ conditioned on $Q_i$ are shown in Fig. 4 (a) using linear-log scales. It is seen that $A^{(j)}_\tau$ was typically the highest for trajectories with $Q_4$ or $Q_1$, and that it was the lowest for trajectories with $Q_2$. In addition, the average of $A^{(j)}_\tau$ for trajectories with $Q_4$ was more than twice higher than the average over trajectories with $Q_2$, but only 20% higher than the average over $Q_1$ trajectories. It is also noted in passing that the PDFs of $A^{(j)}_\tau$ were roughly log-normal.

Figure 4(a) reveals the existence of anisotropy in the kinetic energy increments of Lagrangian trajectories, since statistics of $A^{(j)}_\tau$ depended on the direction of trajectory’s velocity fluctuations. While it is expected that statistics of $A^{(j)}_\tau$ will depend on the magnitude of velocity even in HIT, a dependence on velocity direction reveals a symmetry breaking that can only persist in anisotropic flows, and is thus a manifestation of large-scale intermittency. In addition, $A^{(j)}_\tau$ was typically higher for both $Q_4$ and $Q_1$ which are associated with higher streamwise velocity, whereas the converse occurred for $Q_2$ and $Q_3$ that are associated with lower streamwise velocity. This suggests that the changes in statistics of $A^{(j)}_\tau$ are due to increased/decreased levels of the canopy drag that fluctuates due to large-scale flow structures in the shear-layer and the boundary-layer above the canopy. This is in quantitative agreement with Keylock et al. (2020) who recently associated streamwise velocity and intermittency in canopy flow.

To inspect the effects of the $Q_i$ conditional statistics as a function of the scale we use conditional structure functions; namely, the same $S_q$ that was defined in Eq. (3) is now calculated with averages
over trajectories with the same $Q_i$. Thus, Fig. 4(b) shows the conditional second-order Lagrangian structures function, $S_2$, plotted on the log-log scale. The $S_2$ for different $Q_i$ have a nearly identical shape, but they are translated vertically with respect to one another. The $S_2$ curves are ordered vertically in the figure according to the levels of $A_2^{(j)}$ observed in Fig. 4(a): $S_2$ is highest for $Q_4$, then $Q_1$, $Q_3$ and the lowest is $Q_2$. This shows that the structure functions are ordered by the trajectory’s "activity" level. Furthermore, since the figure is in log-log scales, the identical shape means that the time scaling for structure-function for different quadrants is the same, namely $\zeta_2(\tau)$ is independent of $Q_i$. In particular, $\zeta_2 \approx 2$ for $\tau \leq \tau_H$ and it reduces below 1 by the end of our measurement range. Therefore, the key observation from Fig. 4(b) is that when conditioning on $Q_i$ the changes in statistics occur homogeneously across the scales. This is in contrast, for example, to inertial particles, where the scaling of the structure-function change due to filtering at times smaller than their inertial timescale (Bec et al., 2006). This observation is important for two reasons. First, it implies that changes in statistics when conditioning on $Q_i$ occur due to variations in turbulence parameters, namely this is indeed large-scale intermittency. Second, it is important for Lagrangian dispersion models since it suggests that temporal fluctuations in canopy drag may be treated by varying the simulation’s parameters with a large timescale, e.g. as discussed in more details by Pope & Chen (1990); Pope (1991); Aylor (1990); Duman et al. (2014, 2016).

4 Discussion and conclusions

To conclude, this work presents observations of both small-scale intermittency and large-scale intermittency of Lagrangian statistics in a canopy flow, by using the results of a recent wind-tunnel experiment. This is the first experimental observation of Lagrangian intermittency in a canopy flow, and thus it presented a unique opportunity to probe these two different types of intermittency in parallel. It thus demonstrates the importance of direct Lagrangian investigation of inhomogeneous and anisotropic turbulent flows.

The Lagrangian small-scale intermittency was manifested by a significant deviation of the velocity increment’s statistics from self-similarity, as their flatness increased strongly when $\tau$ was decreased. Furthermore, a marked similarity was observed between our results for the canopy flow and previous observations from HIT. In particular, using Lagrangian the multifractal model and the extended self-similarity framework we found remarkable quantitative agreement with Chevillard et al. (2003) and Mordant et al. (2004). Lastly, the long correlation of acceleration magnitude along with the short correlation of acceleration components suggests that the source for small-scale intermittency is, similar to HIT (Biferale et al., 2005; Bec et al., 2006; Bentkamp et al., 2019), rooted in encounters of particles with vortex filaments. These results strongly support the picture suggested by Arnèodo et al. (2008) of universal Lagrangian intermittency in turbulence, and it also suggests its extension to certain highly turbulent inhomogeneous and anisotropic flows. It is possible that this similarity to HIT was a result of the dominance of the isotropic dissipation terms over contributions from the flow’s inhomogeneity to the particle’s dynamics, as we reported in Shnapp et al. (2020). In this case, the main conclusion is that even in presence of marked inhomogeneity and anisotropy, the HIT picture may still be relevant at small-scales if the turbulence energy flux is sufficiently high.

It was also observed that when conditioned on the direction of the time averaged velocity fluctuation, Lagrangian trajectories had significantly different statistics for the RMS of kinetic energy increments. It was typically much higher (lower) for trajectories with the streamwise velocity component higher (lower) than the mean. Correspondingly, the second-order Lagrangian structure functions were higher (lower) for these groups of trajectories. This suggests that fluctuations of the canopy drag force affect the activity of Lagrangian trajectories and, therefore, this observation is a manifestation of large-scale intermittency. Furthermore, it was observed that the large-scale intermittency did not affect the scaling of the Lagrangian structure functions, namely that the effect of conditional statistics was felt homogeneously across the different scales. This observation is important for the treatment of
large-scale intermittency in Lagrangian dispersion models.

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