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ABSTRACT

We employ spectral-space and real-space quantities to characterize large-scale motions (LSMs) and very-large-scale motions (VLSMs) in open-channel flows (OCFs). The obtained data on velocity auto- and co-spectra, spectral correlation coefficient, and structure functions of the second and third orders are consistent with the hypothesis that VLSMs are a special type of coherent structure rather than an alignment of LSMs, even if active interactions between LSMs and VLSMs most likely take place. The Letter is concluded with a conceptual velocity spectrum for OCFs and an explanation of the mechanism of VLSMs' contribution to the Reynolds shear stress.

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Recent long-term high-precision velocity measurements in open-channel flows (OCFs) confidently revealed the presence of fluid motions up to 50 flow depths long in addition to conventionally reported eddies of 4–6 flow depths.¹ These findings complement earlier studies on pipe, conduit, and boundary layer flows, which introduced the terms large-scale motions (LSMs) for eddies of 3–6 flow depths, and very-large-scale motions (VLSMs) for much longer motions.^{2–4} The presence of LSMs and VLSMs and their representative dimensions are typically identified using pre-multiplied velocity spectra and co-spectra, where LSMs and VLSMs are manifested with two spectral “hills.” The origin and topology of LSMs have been extensively studied, suggesting that LSMs in wall-bounded flows can be viewed as packets of hairpin vortices arising from the bed due to velocity shear.⁴ However, the origin and topology of VLSMs remain largely unclear. The initial explanation given by Kim and Adrian² suggests that the VLSM hill in velocity spectra is due to the “coherent alignment” of LSMs; therefore, VLSMs do not represent a separate structure type. An alternative explanation is that VLSMs are somewhat independent structures, formed by a separate self-sustained mechanism.⁵ Some data suggest that topologically VLSMs can be viewed as very long meandering counterrotating streamwise vortices,^{1,4} while there is also evidence sustaining the “LSM alignment” hypothesis.⁶

In this Letter, we would like to report experimental findings, which appear to support the hypothesis of the independent nature of

VLSMs in OCFs. We consider both spectral-space and real-space quantities and conclude this Letter with a conceptual velocity spectrum for OCFs and an explanation of the mechanism of VLSMs' contribution to the Reynolds shear stress at large scales. Such an explanation has not yet been proposed.³

In our analysis, we employ two datasets of acoustic Doppler velocimetry measurements in uniform rough-bed OCFs, with a sampling frequency of 100 Hz. The first dataset was collected in the RS flume (12 m long and 0.40 m wide) of the Fluid Mechanics Laboratory at the University of Aberdeen. Velocity was measured at nine streamwise locations evenly spread along the flume, from $x/H = 12$ to 112 (x is streamwise coordinate with $x = 0$ at the channel entrance, and H is the mean flow depth). The measurements were performed at the channel centerline, at an elevation of $z/H = 0.3$ (z is bed-normal coordinate), with a continuous duration at each location of 8 h. The channel bed was covered by micro hooks of height $\Delta = 1.1$ mm. The second dataset consists of 6 h velocity measurements taken in an open-channel flume (18 m long and 2 m wide) at the Hydraulics and Hydro-morphology Laboratory of INRAE, Lyon-Villeurbanne, France. The flume bed was covered by rigid artificial grass with $\Delta = 5$ mm. Velocity was measured at $z/H = 0.5$ and at a spanwise distance of $0.5 \text{ m} \approx 4.3H$ from the right-hand sidewall, where the effects of sidewall-related secondary currents are minor. Similar to the first dataset, the measurements were carried out at different streamwise

locations, i.e., $x/H = 30, 65, 100$, and 130 . The background parameters of the used datasets are given in Table I, with more details to be found in Zampiron *et al.*^{7,8} and Cerino *et al.*⁹

We first consider pre-multiplied velocity auto-spectra $kS_{uu}(k)$ and co-spectra $kC_{uw}(k)$ normalized on the shear velocity u_* , where u and w are streamwise and vertical velocity components, and k is the streamwise wavenumber [Figs. 1(a)–1(d)]. The pre-multiplied spectra are chosen as they represent the distribution of turbulent energy across the scales rather than its density. Pre-multiplied auto-spectra of the vertical velocity $kS_{ww}(k)$ are not shown for brevity, as they contain limited energy at the VLSM wavelength range, consistent with other studies [e.g., Ref. 10]. The wavenumber (k) spectra have been obtained from the measured frequency (f) spectra using Taylor's frozen turbulence hypothesis, employing the local mean velocity \bar{u} as eddy convection velocity, i.e., $k = 2\pi/\lambda = 2\pi f/\bar{u}$, $kS_{uu}(k) = fS_{uu}(f)$, and $kC_{uw}(k) = fC_{uw}(f)$, where λ is the spectral streamwise wavelength. The applicability of this hypothesis for OCFs at relative distances from the bed, used in this study, has been demonstrated in Nikora and Goring.¹¹ For both datasets, the shape and magnitude of $kS_{uu}(k)$ and $kC_{uw}(k)$ evolve with increase of x/H up to $x/H \approx 100$, after which the spectral shape can be considered established, with two evident spectral hills [Figs. 1(a)–1(d)]. At this point, it should be noted that Taylor's hypothesis may not be strictly valid for locations at $x < 100H$ where the flow is not fully developed. Nevertheless, we show the data for these locations in Fig. 1 to demonstrate that the data for $x > 100H$ relate to fully developed LSMs and VLSMs, and thus are applicable for our analysis. The spectral hills in Figs. 1(a)–1(d) represent the signatures of LSMs ($\lambda/H \approx 2-4$) and VLSMs ($\lambda/H \approx 20-30$). Some differences in peak magnitudes and their locations between Aberdeen's and Lyon's datasets can be explained by different relative distances of the measurement points from the bed, flow conditions, and roughness type.¹ The shape of $kC_{uw}(k)$ indicates that both LSMs and VLSMs significantly contribute to the Reynolds shear stress $-\overline{u'w'}$ (prime defines deviation from mean values, and overbar denotes time averaging) that follows from $\overline{u'w'} = \int_0^\infty C_{uw} dk$. If the production mechanisms of $-\overline{u'w'}$ at the LSM scale are reasonably understood,^{3,4} the mechanisms of the $-\overline{u'w'}$ generation at the much larger VLSM scale remain unclear. Note that while the "LSM alignment" hypothesis is consistent with the emergence of the VLSM hill in the auto-spectrum of streamwise velocity, it does not explain the appearance of the VLSM hill in $kC_{uw}(k)$. In the "LSM alignment" model, the long regions of low-momentum fluid between hairpin legs are intermittently interrupted by higher momentum regions. This low-high momentum sequence may increase the overall variance of streamwise velocity at the VLSM scale, but cannot explain an emergence of correlations between streamwise and vertical velocity at the same scale.

TABLE I. Experimental conditions.^a

Data set	H (mm)	u_* (cm/s)	H/Δ	B/H	Re	H^+	Fr
Aberdeen	80.0	29.0	72.7	5	30 000	2300	0.43
Lyon	117.0	35.0	23.4	17	61 000	4100	0.48

^a H is the mean flow depth, $u_* = (gS_b H)^{0.5}$ is the shear velocity, g is the gravity acceleration, S_b is the bed slope, H/Δ is the relative submergence, Δ is the roughness height, B/H is the flow aspect ratio, B is the flume width, $Re = UH/\nu$ is the Reynolds number, U is the depth-averaged streamwise velocity, ν is the fluid kinematic viscosity, $H^+ = u_* H/\nu$ is the friction Reynolds number, and $Fr = U/(gH)^{0.5}$ is the Froude number.

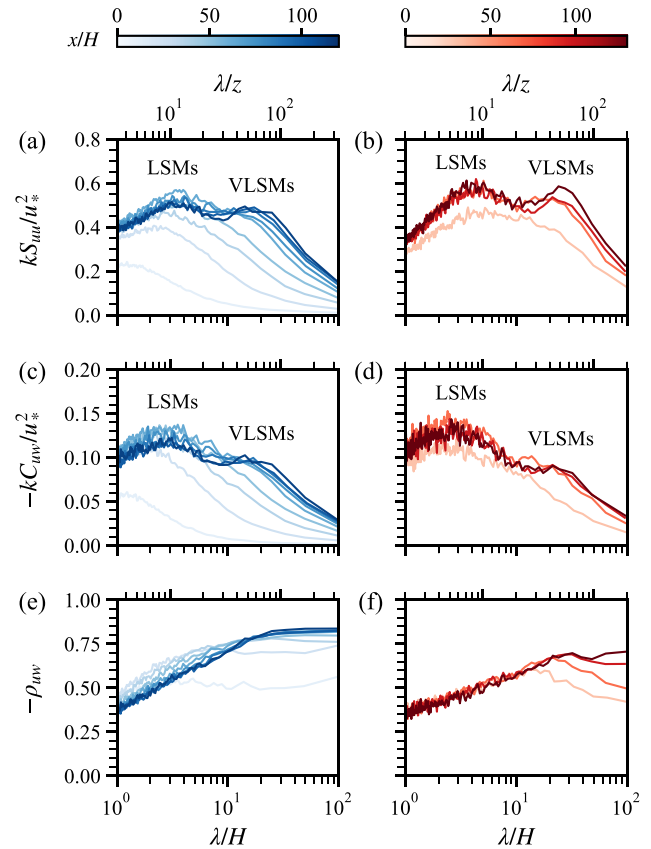


FIG. 1. Spectral-space energy functions [(a) and (b)] $kS_{ii}(k)$ and [(c) and (d)] $kC_{ij}(k)$, and [(e) and (f)] spectral correlation coefficient $\rho_{ij}(k)$. Left: Aberdeen data; right: Lyon data.

In addition, using velocity auto- and co-spectra, one can construct the spectral correlation coefficient $\rho_{uw} = C_{uw}/\sqrt{S_{uu}S_{ww}}$, which was initially introduced to test the isotropy assumption for small-scale turbulence, for which $\rho_{uw} \equiv 0$.¹² Here, we interpret the quantity $\rho_{uw}(k)$ as a measure of efficiency of the turbulent momentum delivery toward the bed. In other words, it characterizes a portion of turbulent fluctuations directly involved in the vertical momentum flux at a particular wavenumber (or frequency). The obtained values of ρ_{uw} demonstrate steady growth with increasing λ/H , reaching a maximum at the VLSM scale, after which ρ_{uw} either reduces or remains constant [Figs. 1(e) and 1(f)]. This pattern indicates that VLSMs are noticeably more efficient in momentum delivery to the wall compared to LSMs. This seems to be inconsistent with the "LSM alignment" hypothesis, at least from a statistical point of view (i.e., streamwise alignment of small-scale correlated signals cannot lead to a correlation at large scale).

The outlined spectral data can be supplemented with the real-space analysis of the second-order structure functions for a steady and streamwise-uniform flow as follows:

$$D_{uu}(r) = \overline{[u'(x+r) - u'(x)]^2}, \quad (1a)$$

$$D_{uw}(r) = \overline{[u'(x+r) - u'(x)][w'(x+r) - w'(x)]}, \quad (1b)$$

where r is the streamwise spatial separation. It has been shown that $D_{ij}(r)$ can be interpreted as a sum of energy in eddies of size $< r$ and $r^2 \times$ enstrophy in eddies of size $> r$.¹³ The energy contribution to $D_{ij}(r)$ at large scales (i.e., $> H$) is expected to be of the leading order, and thus $D_{ij}(r)$ for this scale range can be considered as a cumulative distribution of turbulent energy. Therefore, its derivative $d_{ij} = \partial D_{ij} / \partial r$ represents the energy density at a given spatial separation r . Multiplying d_{ij} by r , one can obtain a function rd_{ij} , representing the energy at a particular scale, similar to the pre-multiplied velocity spectra.^{13,14} Here, we apply this approach, for the first time to our knowledge, to analyze actual turbulence data in relation to large scales. Similar to spectral considerations, we employ the frozen turbulence hypothesis to convert the time domain into spatial domain. Distributions of rd_{uu} [Figs. 2(a) and 2(b)] and $-rd_{uw}$ [Figs. 2(c) and 2(d)], which are analogues of the pre-multiplied auto- and co-spectra, exhibit similar shapes with two LSM and VLSM characteristic hills. Values of r corresponding to LSMs and VLSMs are four to five times smaller than the spectral wavelengths λ for LSMs and VLSMs in Figs. 1(a)–1(d). This difference reflects the complex interrelation connecting pre-multiplied spectra and rd_{ij} , and the need for a calibration procedure for linking explicitly the characteristic scales of LSMs and VLSMs

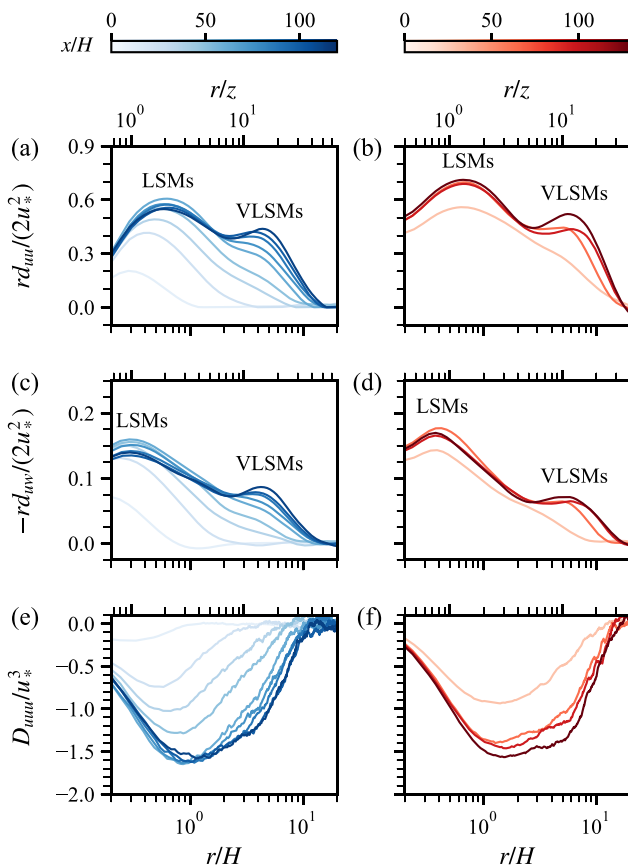


FIG. 2. Real-space energy functions [(a) and (b)] rd_{uu} and [(c) and (d)] rd_{uw} , and [(e) and (f)] third-order structure function D_{uuu} . Left: Aberdeen data; right: Lyon data. Factor 2 in the denominator on the vertical axes title is included in (a)–(d) for normalization.

from both approaches. The energy functions rd_{ij} can be supplemented with the third order longitudinal structure function $D_{uuu}(r) = [u'(x+r) - u'(x)]^3$, which allows to assess the prevailing direction of the energy fluxes across the scales. In a channel flow, negative values of $D_{uuu}(r)$ indicate an energy transfer from larger scales to smaller scales, while positive values reflect the reverse direction,¹⁵ although a more comprehensive assessment of the cross-scale energy budget in the presence of velocity shear would be needed for certainty.¹⁶ Figures 2(e) and 2(f) shows normalized $D_{uuu}(r)$ for both Aberdeen and Lyon datasets. Considered together with the energy functions rd_{ij} [Figs. 1(a) and 1(b)], the distributions of $D_{uuu}(r)$ suggest that the energy transfer occurs from larger to smaller scales within the whole studied range of scales, including LSMs and VLSMs. In addition, the positive sign of $-rd_{uw}$ in Figs. 2(c) and 2(d) indicates the active production of turbulent energy $-\overline{u'w'}(\partial \overline{u} / \partial z)$ within the same range of scales. This is consistent with the co-spectra in Figs. 1(c) and 1(d), where $-kC_{uw}(k) > 0$ for both LSMs and VLSM scales.

Our results in Figs. 1 and 2 can be summarized in a conceptual auto-spectrum of the streamwise velocity in OCFs, which stems from an earlier concept¹⁷ where the presence of LSMs and VLSMs were not accounted explicitly. The conceptual spectrum in Fig. 3 includes four ranges: (1) a VLSM range where large-scale production of turbulent energy co-exists with its transfer from larger to smaller scales (supported by plots of $kS_{uu}(k)$, $kC_{uw}(k)$, $rd_{uw}(r)$, and $D_{uuu}(r)$); (2) an intermediate range where depth-scale energy production coexists with energy cascade to smaller scales, and also where a $S_{uu}(k) \sim k^{-1}$ scaling might co-exist with LSMs, as argued by Nikora;^{17,18} (3) an inertial subrange where energy production and dissipation are negligible and dynamics is driven by direct Kolmogorov’s cascade with $S_{uu}(k) \sim k^{-5/3}$; and (4) a dissipative range of scales. A similar conceptual spectrum for OCF can be proposed for $C_{uw}(k)$. The data reported in this Letter and earlier studies^{1,19} suggest that its shape would be similar to that shown in Figs. 1(c) and 1(d). The above considerations complement findings for other types of wall-bounded flows.²⁰

The most puzzling feature of $C_{uw}(k)$ is a sizeable region of non-zero values at the VLSM scales that forms a VLSM hill in $-kC_{uw}(k)$ and reflects significant contribution of VLSMs to the Reynolds shear

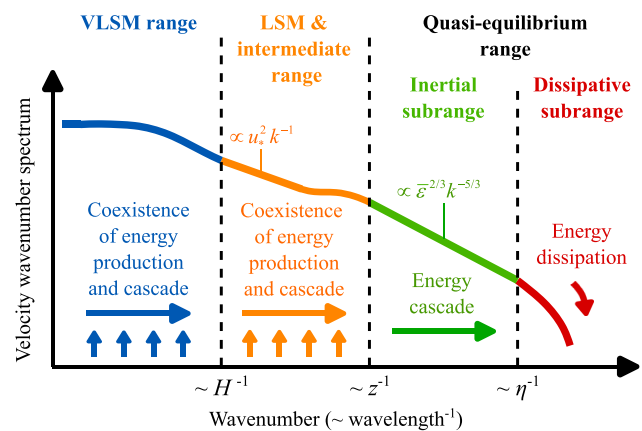


FIG. 3. Schematized wavenumber spectrum of the streamwise velocity in OCF. In the sketch, u_* is shear velocity, z is distance from the bed, k is streamwise wavenumber, ε is the turbulent energy dissipation, H is the flow depth, and η is Kolmogorov’s dissipative scale.

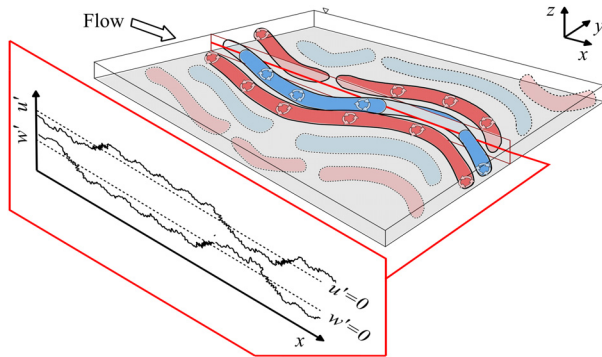


FIG. 4. A sketch showing VLSMs in open-channel flow and explaining the nature of VLSMs' contribution to the turbulent shear stress and uw co-spectra.

stress.^{19,21,22} We propose that the C_{uw} -generating mechanism at the VLSM-scale is represented by long counter-rotating streamwise vortices randomly meandering with a length scale $\lambda/H \approx 20-30$ (as sketched in Fig. 4). At any particular location, the downward motions between VLSM vortices alternates, due to meandering and/or their occasional emergence and disappearance, with upward motions with a spatial periodicity of $\lambda/H \approx 20-30$. As a result, long-term averages of the product $-u'w'$ at the VLSM scale are non-zero and comparable in magnitude with the contribution to the Reynolds shear stress at the LSM scale, which is due to the presence of alternate upward ejections and downward sweeps. This explanation is compatible with the spectral correlation coefficient shown in Figs. 1(e) and 1(f). Thus, the mechanisms of shear stress generation at the LSM and VLSM scales are distinctly different, which is inconsistent, in our opinion, with the “LSM alignment” hypothesis. To conclude, the reported behavior of spectral-space and real-space quantities seem to support the hypothesis that VLSMs are a special type of coherent structures, and not just an alignment of LSMs, even if active interactions between LSMs and VLSMs most likely take place.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

A. Zampiron: Conceptualization (equal); Data curation (lead); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (lead); Writing – original draft (lead); Writing – review & editing (equal). **B. Cerino:** Conceptualization (equal); Formal analysis (equal);

Investigation (equal); Methodology (equal); Writing – review & editing (equal). **C. Berni:** Conceptualization (equal); Methodology (equal); Writing – review & editing (equal). **S. Proust:** Conceptualization (equal); Funding acquisition (equal); Methodology (lead); Resources (lead); Writing – review & editing (equal). **V. Nikora:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Resources (lead); Supervision (lead); Writing – original draft (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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