Two mechanisms of VLSM modulation by inertial particles in open channel flow

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Very large-scale motions (VLSM) and large-scale motions (LSM) coexist at moderate Reynolds numbers (e.g. $Re_\tau = 550, 950$) in a very long open channel flow. Direct numerical simulations two-way coupled with inertial particles are analysed using spectral information to investigate the modulation of VLSMs. Particle distributions show two layers corresponding to LSMS and VLSMs in the wall-normal direction. This results in particle inertia’s non-monotonic effects on the VLSMs: low and high inertia both strengthen the VLSM whereas moderate and very high inertia have very little influence. Through conditional tests, low and high inertia particles enhance VLSMs following two distinct paths. Low inertial particles promote VLSMs indirectly through the enhancement of the regeneration cycle (LSMs) in the inner region whereas high inertial particles enhance the VLSM directly through contribution to the Reynolds shear stress (upwelling/downwelling fluid motion) at similar temporal scales in the outer region. This understanding also provides more general insight into inner-outer interaction in high Reynolds number, wall-bounded flows.

Key words: VLSM, modulation, open channel, DNS, inertial particles

1. Introduction

Very large-scale motions (VLSMs) extending to over $20h$ (where $h$ is the boundary layer thickness) are found in very high Reynolds number, wall-bounded turbulent flows and are distinct from the wall-understood large-scale motions (LSMs) which form canonical streaks and hairpin vortices (Hutchins & Marusic 2007). These long, meandering features are observed to be energetic, carrying $40-65\%$ of the kinetic energy and $30-50\%$ Reynolds shear stress in pipe flow (Balakumar & Adrian 2007), which is contradictory to the notion of “inactive” motion proposed by Townsend (1980). In environmental flows, these anisotropic structures also have significant influence on the dispersion of pollutants, sand, and other constituents. At the same time, understanding the modulation of turbulence by inertial particles is itself a formidable challenge (Balachandar & Eaton 2010), and nearly all numerical studies of two-way coupling in particle-laden wall turbulence have been restricted to low Reynolds numbers. It is therefore the aim of this investigation to study the effects of particles on VLSMs, in particular focusing on the question of whether particles act directly or indirectly on these large motions.

The importance of LSMs to the flow dynamics in the near-wall region has been

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Figure 1. Schematic of inertial particle effects on LSMs and VLSMs through the regeneration cycle and direct impact on velocity fluctuations. In the top-right are streamwise velocity contours in the cross-stream plane of $Re_{\tau} = 550$ open channel flow (the flow simulated here). In the bottom-left is the flow field in turbulent plane Couette flow at $Re_{\tau} = 40$, used by Wang & Richter (2018) to study particle effects on turbulence regeneration cycles.

demonstrated in many different contexts. The LSMs are found to follow a self-sustaining process (i.e. a regeneration cycle) characterized by three key structures shown in the lower left of figure 1: large-scale streaks (LSSs), large-scale vortices (LSVs), and meandering streaks. Associated with these structures are three regeneration processes: streak formation, stream breakdown, and vortex regeneration (Hamilton et al. 1995; Waleffe 1997). The typical scales of VLSMs, meanwhile, are far larger than LSMs, with their spanwise wavelength $\lambda_z > h$ and their streamwise wavelength $\lambda_x > 10h$ (Kim & Adrian 1999; Guala et al. 2006; Adrian & Marusic 2012). These structures co-exist with LSMs, and the interaction between them is still an open question. It is generally accepted that the regeneration cycle of LSMs does not require the existence of VLSMs (Jiménez & Pinelli 1999; Hwang & Bengana 2016), and Guala et al. (2006) propose that the formation of LSMs and VLSMs results from different mechanisms. Rawat et al. (2015) argue that VLSMs are self-sustained and do not draw energy from LSMs in buffer layer, however, Kim & Adrian (1999) and Adrian & Marusic (2012) suggest that VLSMs are not a new type of turbulent structure but merely the consequence of the alignment of coherent LSMs. Toh & Itano (2005) show numerically that LSMs and VLSMs interact in a co-supporting cycle. In the current work, we find that the enhancement of VLSMs can be caused by the promotion of LSMs via inertial particles.

As indicated in figure 1, particles can directly impact velocity fluctuations and turbulent kinetic energy through momentum coupling (Elghobashi & Truesdell 1993). This yields the possibility that particle feedback on structures near the wall (e.g. LSMs, see Wang et al. (2018)) can have upscale, indirect influences on large turbulent structures (e.g. VLSMs, see Toh & Itano (2005)) via nonlinear energy transfer. For inertial particles, Richter & Sullivan (2014) and Richter (2015) use numerical simulations to demonstrate that this upscale influence is a strong function of particle inertia, and as a result, particles can influence turbulence scales far removed from their own response time scale. To better understand this indirect modulation, Wang & Richter (2018) further investigated small particles and their ability to enhance the LSM regeneration cycle (depending
y represents the dimensionless particle time scale based on local Kolmogorov time scale (h where 

Table 1. Parameters of numerical simulations. The friction Reynolds number is Reτ ≡ uτh/ν where h is the depth of the open channel and the particle relaxation time is τp ≡ ρpδd2/(18πντp) where d is the particle diameter. \( \Phi_m \) is the particle mass concentration and \( N_p \) is the total particle number. The superscript “+” is the dimensionless number based on viscous scale, where \( \delta_0 \), \( u_\tau \) and \( ν/ν^2 \) correspond to the viscous length scale, velocity scale, and time scale, respectively. \( St_k \) represents the dimensionless particle time scale based on local Kolmogorov time scale \( (y^+=15\) and \( y^+=157 \) corresponding to LSMs and VLSMs strong region as shown in figure 3(d)).

non-monotonically on particle inertia, see also Saffman (1962)), with the assumption that this was a route through which particles could modify even larger scales in high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow. Therefore as a follow-up, and since to date computational costs have precluded particle-laden direct numerical simulations at sufficiently high Reynolds number flow.

2. Numerical parameters

Direct numerical simulations of the Eulerian flow are performed for an incompressible Newtonian fluid using the same numerical implementation as Richter & Sullivan (2014) and Richter (2015). A pseudospectral method is employed in the periodic directions (streamwise \( x \) and spanwise \( z \)), and second-order finite differences are used for spatial discretization in the wall-normal \( (y) \) direction. We simulate pressure-driven open channel flow because it is characterized by features similar to closed channel flow, while also exhibiting the signatures of VLSMs at a lower, more computationally accessible Reynolds numbers (Nezu & Nakagawa 1993; Adrian & Marusic 2012; Cameron et al. 2017). A no-slip condition is imposed on the bottom wall and a shear-free condition is imposed on the upper surface. The solution is advanced in time by a third-order Runge-Kutta scheme. A single-sided stretched grid (fine grid close to the wall, coarse grid close to the free surface) is used, and a comparison with Yamamoto et al. (2001) at \( Re_\tau = 200 \) produces nearly identical velocity fluctuations and 1D energy spectra.

Particle trajectories and suspension flow dynamics are based on the Lagrangian point-particle approximation where the particle-to-fluid density ratio \( \rho_p/ρ_f \gg 1 \) and the particle size is smaller than the smallest viscous dissipation scales of the turbulence. Only
the Stokes drag force and two-way coupling have been incorporated since we restrict our study to low volume concentration $\Phi_V$ (see Balachandar & Eaton 2010). Gravitational settling is not considered in order to highlight the effect of the particle response time. Particles experience a purely elastic collision with the lower wall and upper rigid free surface. Two-way coupling is implemented via a particle-in-cell scheme, and has been validated against Zhao et al. (2013) and Capecelatro & Desjardins (2013) in turbulent channel flow. Grid convergence of both the flow and of the two-way coupling scheme have been verified as well (Gualtieri et al. 2013).

Particle modulation of turbulence is associated with the relative time scales between particles and local turbulent structures. The multiple turbulent structures spanning a wide spatial and temporal range (e.g. LSMs and VLSMs) result in a wide parameter space of the particle inertia to be investigated. As shown in table 1, we choose $St^+$ based on the viscous scale in the range of 2.42–908, corresponding to $St_k$ based on the Kolmogorov scale in the range of 1.08–403 at $y^+ = 15$ and 0.31–117 at $y^+ = 157$. For $Re_\tau = 550$ the streamwise domain extent $L_x = 6\pi$ was determined by gradually increasing it until after the appearance of a bimodal energy spectra in the spanwise direction. Cases 1–6 are then designed to investigate the effects of particle inertia by systematically increasing the particle Stokes number. In single-phase flow it is well-known that VLSMs are very long in the streamwise direction and fully capturing their extent is computationally expensive (Lozano-Durán & Jiménez 2014). Therefore as a test, case7 doubles the streamwise extent for single-phase flow in order to check any effects of streamwise confinement on VLSMs by comparing to case1 (negligible differences were observed). In order to further examine particle direct modulation of VLSMs, case8 and case9 are performed at a higher $Re_\tau = 950$ for single-phase and particle-laden flow — these ultimately yield identical conclusions.

3. Results

3.1. Particle distribution in two distinct layers

It is well-established that for wall-bounded turbulent flow, low-inertia particles tend to distribute homogeneously in wall-normal planes, while intermediate Stokes numbers exhibit particle clustering in near-wall streaks and high-inertia particles behave with ballistic trajectories (thus eliminating much of the clustering). This qualitative transition with $St^+$ is observed in the inner region of the simulated open channel flow (i.e. near the wall). Figures 2 (b-f) present isosurfaces of particle concentration in two layers (inner...
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Figure 3. (a, d) Premultiplied 1D $u$-spectra as functions of wavelength in wall-normal direction: (a) streamwise, (d) spanwise. The contours are 0.2(0.2)0.8 times the common maximum value. 

“+”: isolines of (0.2,0.4,0.8) from del Álamo & Jiménez (2003), containing (a) streamwise modes only with $\lambda_x < 5h$ and (d) spanwise modes only with $\lambda_z < 0.75h$; Shaded contours: case7; line types representing for case1 to case6 are same as (e). (b, c) and (e, f) show $k_i \phi_{u'u'}$ as functions of the streamwise wavelength $\lambda_x$ and $k_i \phi_{u'u'}$ as functions of the spanwise wavelength $\lambda_z$, respectively. Two wall-normal distances are shown: (b, e) are at $y^+ = 15$ and (c, f) are at $y^+ = 157$.

For increasing Stokes numbers $St^+ = 2.42$ to 908, where we find particles accumulating in the inner-flow streaks at intermediate $St^+ = 24.2 - 60.5$; the same as observed in Wang & Richter (2018). At the same time, new type of organized, particle-clustering structure in the outer flow region is formed in low-vorticity regions ejected from the inner region, especially at high $St^+ = 182$. However, with a very high $St^+ = 908$, particles behave ballistically in the outer flow region, tending to distribute more as tracers similar to low $St^+ = 2.42$. This non-monotonic particles accumulation behaviour has an influence on the non-monotonic modulation of the VLSMs in the outer region.

3.2. Premultiplied 1D $u$-spectra

Figures 3(a,d) display as a function of $y^+$ the premultiplied, one-dimensional $u-$spectra $k_i \phi_{u'u'}(k_i)$, $i = x, z$, where $\phi_{u'u'}(k_i) = \langle \hat{u'}(k_i) \hat{u'}^*(k_i) \rangle$, as functions of the normalized streamwise and spanwise wavelengths $\lambda^+_x$ and $\lambda^+_z$ (where $\hat{u'}$ is the Fourier coefficient of $u'$). As a reference, we compare with the results of wall-bounded channel flow from del Álamo & Jiménez (2003) at the same $Re_\tau = 550$, who find that the turbulence in the outer flow is approaching isotropic if VLSMs are artificially removed (i.e. VLSMs introduce anisotropy). Comparing between del Álamo & Jiménez (2003) (who filter out high wavelengths, so only $\lambda_x < 5h$ and $\lambda_z < 0.75h$ are plotted) and the present (unfiltered) simulation in figures 3(a,d), we observe that for unladen flow, VLSMs hardly affect the spectral signature of LSMs (Jiménez & Pinelli 1999), whereas the contribution from VLSMs forms a bimodal spanwise spectra at $\lambda^+_z \sim 1000$ ($\lambda_z \sim 2h$) at heights above the inner layer. The large-scale energetic structures (larger than LSMs) within the inner layer are also attributed to VLSMs, which are referred to as deep $u-$modes (del
Figure 4. Instantaneous contours of streamwise velocity fluctuation \( (u'/u_\tau = -3(0.63)) \) on a wall-parallel plane at \( y^+ = 157 \) at the same time step. An isoline of \( u' = 0 \) is plotted to emphasize the border between upwelling and downwelling fluid motion. (a) case1; (b) case2; (d) case5

Alamo & Jiménez 2003) or “footprints” of VLSMs (Hutchins & Marusic 2007). Figure 3(b,c) and (e,f) show the streamwise and spanwise u-spectra at \( y^+ = 15 \) and \( y^+ = 157 \) normalized by the local streamwise velocity RMS, respectively. As noted previously, any effect of a limited streamwise domain extent \( L_x \) is minimal, since figure 3(c) shows that the energy contained in VLSMs in a short domain (case1) is nearly identical to the long domain (case7). Thus overall our unladen simulations are consistent with the current understanding of VLSMs.

Particle inertia has a non-monotonic effect on LSMs in the inner region (Wang & Richter 2018), which can be seen in figure 3(b): the energy contained in LSMs first decreases then increases with an increased \( St^+ \). At the same time, the energetic LSMs in case3 are elongated compared to single-phase flow (i.e. the peak shifts to larger wavelengths). Focusing on VLSM modulation by inertial particles, figures 3(c,f) show that low inertia (case2) and high inertia (case5) particles significantly enhance the VLSM energy content in the outer region whereas intermediate inertia (case3 and case4) and very high inertia (case6) cases have very little impact on the VLSMs. The enhancement of the VLSM signature at high inertia is also found at \( Re_\tau = 950 \), as shown in figure 3(c,f). The penetration of VLSMs from the outer region to the inner region can be observed in figure 3(e), since the energy contained in turbulent scales at \( \lambda^+_z = 800 \) to 1000 is simultaneously enhanced with the same spanwise wavelength as in figure 3(f) for case2 and case5. Additional evidence can be seen in figure 4, which provides a snapshot of the streamwise velocity fluctuation in the \( x - z \) plane at \( y^+ = 157 \). Comparing between figures 4(b,c) and (a), it is evident that VLSMs are better-organized when \( St^+ = 2.4 \) (case2) or \( St^+ = 182 \) (case5) compared to single-phase flow (case1). We now turn our investigation to understanding why the VLSM modulation appears to have two distinct peaks in Stokes number.

3.3. Conditional tests of the particle coupling effect

In spectral space, the modulation of LSMs and VLSMs by a dispersed phase is at least partially related to the direct influence on particle fluctuations, which in turn can modify the production of turbulent kinetic energy (TKE) and/or Reynolds shear stress. This is demonstrated more quantitatively in figures 5(a,d), where we present the \( u'u' \)
spectral production term $\tilde{P}_{11} = -\langle u'(k_z, y) u^* (k_z, y) \rangle \frac{dU}{dy}$ as a function of $\lambda_z$ and the wall-normal direction for case2 and case5 in comparison with case1. Comparing figures 5(a,d) with figure 3(d), we find that they have a similar overall shape, and the bimodal spectrum appears both in the premultiplied $u-$spectra as well as the production term $\tilde{P}_{11}$, which is enhanced in case2 and case5 in comparison with the single-phase flow. In addition to the modifications to streamwise TKE production, particles can also act as a direct source/sink in the spectral TKE and Reynolds stress budgets. See for example the schematic in figure 1: particle feedback contributes to $u'u'$, $v'v'$ and $u'v'$ budgets in the inner/outer region, corresponding to indirect/direct modulation of VLSMs, respectively.

In the spectral energy budget particle sources are denoted as $\tilde{\Psi}_{11} = \mathcal{R} \langle \hat{F}_x(k_z, y) u^{*} (k_z, y) \rangle$ to the $u'u'$ budget (figures 5(b,e)) and $\tilde{\Psi}_{12} = \mathcal{R} \langle \hat{F}_x(k_z, y) v^{*} (k_z, y) + \hat{F}_y(k_z, y) u^{*} (k_z, y) \rangle$ to $u'v'$ budget (figures 5(c,f)), where $\mathcal{R}$ stands for the real part and $\hat{F}$ is the Fourier transform of the particle coupling force. We find that $\tilde{\Psi}_{11}$, which is positive in case2 whereas negative in case5 and confined largely to the inner region, and $\tilde{\Psi}_{12}$, which is negative in case2 whereas positive in case5 and extended throughout the entire wall-normal extent, play opposite roles in the turbulent energy and Reynolds stress budgets depending on whether one considers the inner or outer regions. This nearly opposite behavior indicates that there might be two underpinning mechanisms of VLSM enhancement induced by low and high Stokes numbers particles.

Richter (2015) finds that this Stokes-number-dependent source/sink varies with wavelength, and is possibly associated with the particle clusters themselves even though it always responsible for the underlying changes to TKE (Capecelatro et al. 2018). In the inner flow, Wang & Richter (2018) find low inertial particles (case2) enhance LSMs whereas high inertial particles (case5) attenuate LSMs, corresponding to a positive particle feedback $\tilde{\Psi}_{11}$ in case2 (figure 5(b)) but negative in case5 (figure 5(e)). In addition, as shown in figure 5(c), particle feedback $\tilde{\Psi}_{12}$ in case2 always attenuates the generation of $u'v'$. Therefore in case2, the positive feedback $\tilde{\Psi}_{11}$ in the inner flow is the most likely
Figure 6. Premultiplied two-dimension spectra $k_x k_z \Phi_{u'u'}/u'^2$ as function of $\lambda_x$ and $\lambda_z$ in wall-normal direction $y$. Isosurface of 0.1 times the common maximum value is illustrated. (a,c) Only with particle coupling in the outer flow of case 2 and case 5; (b,d) Only with particle coupling in the regeneration cycle region of case 2 and case 5.

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responsible for the enhancement of VLSMs in the outer flow. This process of particles inducing upscale energy transfer (or a reverse cascade), tending to build up the energy level at high wavelengths due to the modulation of small-scale turbulent motions, is also observed in homogeneous turbulence (see Elghobashi & Truesdell (1993) and Carter & Coletti (2018)) and in turbulent Couette flow (see Richter (2015)).

In contrast to case 2, it is more straightforward to understand the VLSM modulation in case 5. As shown in figure 5(f), throughout the whole domain, we observe that $\Psi_{12}$ in case 5 always has a positive contribution to the $u'v'$ budget and is at the same spatial locations as the production $P_{12}$ of the $u'v'$ budget (seen also at $Re_\tau = 950$ in case 9, figure is not shown), whereas $\Psi_{12}$ in case 2 (figure 5(c)) tends to suppress the generation of $u'v'$. However, as shown in figure 5(e), the negative particle feedback $\Psi_{11}$ in the inner region tends to attenuate $P_{11}$ in case 5. This ultimately results in $\Psi_{12}$ exerted in the outer region as the most likely explanation for the enhancement of VLSMs. As the source of Reynolds shear stress $-u'v'$, the ejection/sweep cycles in very large scales (Adrian & Marusic 2012) are directly enhanced by the presence of high inertial particles in the outer flow, and these very large upwelling/downwelling structures further extract energy from the mean flow by working with local mean shear, see Nezu (2005).

In order to verify the above hypothesis that the VLSM enhancement in case 2 is due to particles’ modulation of LSMs in the inner flow (we refer to this as indirect modulation of VLSMs) whereas in case 5 it is due to the particles’ direct modulation on the VLSMs in the outer flow, we perform a conditional numerical test to identify the particles’ effective region of influence regarding VLSM enhancement by artificially applying the particle feedback force only in one of three locations: (1) the viscous sublayer ($y^+ < 15$), (2) the regeneration cycle region ($15 < y^+ < 100$), or (3) the outer flow ($y^+ > 100$), separately. The premultiplied two-dimensional energy spectrum of streamwise velocity $k_x k_z \Phi_{u'u'}$, where $\Phi_{u'u'} = \langle \hat{u}'(k_x, k_z, y) \hat{u}^*(k_x, k_z, y) \rangle$, is shown in figure 6 as a function of wall-
normal direction. The figure exhibits a “boot-shaped” isosurface of $\Phi_{u'u'}$. The “forefoot” illustrates the LSMs in the near-wall region whereas the “bootleg” is formed by the VLSMs. It can be seen that the VLSMs only experience enhancement in case2 when particle coupling is included in the regeneration cycle region. For case 5, on the other hand, the opposite is true: VLSM enhancement is found only when particle coupling effects are included in the outer region. Both of these effects are observed throughout the entire range of $y^+$. The tests of two-way coupling applied for $y^+ < 15$ are not shown, but we find the spectrum in the range $\lambda_x^+ > 8000$ and $500 < \lambda_z^+ < 700$ is stronger than in the single-phase flow, but not in the range of VLSMs.

4. Summary and discussion

In this paper, we investigate the effect of inertial particles on VLSMs in moderate Reynolds number open channel flow. The particles are characterized by well-known clustering structures in the inner layer, and additional structures are formed in the outer flow as well but at different Stokes numbers. With very high particle inertia, at timescales slower than even the VLSMs, the particles approach a nearly uniform distribution. In terms of two-way coupling, we find that inertial particles have a non-monotonic effect on the VLSMs, where low and high inertia particles strengthen the VLSMs and the intermediate inertia particles hardly affect their structure and energy.

The most direct route of particle modulation of turbulent motions comes from the particles feedback source in the turbulent energy budget. We find low inertial (high inertial) particles have a positive (negative) $\hat{\Psi}_{11}$ in the inner flow and a negative (positive) $\hat{\Psi}_{12}$ in the outer flow. By utilizing a conditional numerical test, we demonstrate that low inertia particles strengthen the VLSMs due to the enhancement of the LSMs in the inner flow. While the relationship between near-wall LSMs and the outer-scale VLSMs remains a subject of investigation, this suggests that there can exist an upscale transport of energy possible from LSMs to VLSMs. This is consistent with Toh & Itano (2005) who show numerically that LSMs and VLSMs interact in a co-supporting cycle and Marusic et al. (2010) who observe experimentally the high degree of velocity fluctuation correlation between the outer flow with the low-frequency content of the inner flow. In contrast, high inertia particles modulate the VLSM directly. They cluster in the low-vortical region of the outer flow and directly modulate the VLSMs, indicated by the particle feedback effect on the Reynolds shear stress budget with the same scale of VLSMs at the same spatial locations. The high inertia particle clustering signatures and the mechanism of the VLSM enhancement in the outer flow region still require investigation.

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