Extremely high wall-shear stress events in a turbulent boundary layer

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Abstract. The present work studies the fluctuating characteristics of the streamwise wall-shear stress in a DNS of a turbulent boundary layer at $Re_{\tau}=1500$ from a structural view. The two-dimensional field of the fluctuating friction velocity $u'_\tau(x,z)$ is decomposed into the large- and small-scale components via a recently proposed scale separation algorithm, Quasi-bivariate Variational Mode Decomposition (QB-VMD). Both components are found to be dominated by streak-like structures, which can be regarded as the wall signature of the inner-layer streaks and the outer-layer LSMs, respectively. Extreme positive/negative wall-shear stress fluctuation events are detected in the large-scale component. The former’s occurrence frequency is nearly one order of magnitude higher than the latter; therefore, they contribute a significant portion of the long tail of the wall-shear stress distribution. Both two-point correlations and conditional averages show that these extreme positive wall-shear stress events are embedded in the large-scale positive $u'_\tau$ streaks. They seem to be formed by near-wall ‘splatting’ process, which are related to strong finger-like sweeping (Q4) events originated from the outer-layer positive LSMs.

1. Introduction
Wall-shear stress is of obvious importance in wall-bounded turbulence. It sets the boundary condition for the sustenance and dissipation of near-wall turbulence [1–3], thus determines the viscous scales that well characterizes the scaling of the inner-layer cycle. On the practical side, the skin friction reduction over the surface of transportation vehicles is the persistent pursuit of engineers [4].

To date, various works have built up the empirical or semi-theoretical formulation between the mean wall-shear stress, $\tau_w$, and Reynolds number ($Re$) in smooth-wall-bounded turbulence [5–8]. Nevertheless, less progress on the statistics and dynamics of wall-shear stress fluctuations has been made in the past. The law of the wall [9] assumes a $Re$-independency of the statistics of wall-shear stress. This is consistent with early experiments [10–13], which reported compatible values of high-order moments (variance, skewness and flatness) of the streamwise component of the fluctuating wall-shear stress $\tau'_\tau$ that were less sensitive to $Re$ if taking the measurement uncertainty into consideration. Traditionally, the root-mean-squared value was regarded to be $\tau_{x,rms} \approx 0.47 \tau_w$ [13], but recent experiments and DNS [14–19] have shown a slow variation of $\tau_{x,rms}$ with respect to $Re$. Based on assessing different DNS datasets of a canonical turbulent boundary layer with zero pressure gradient, Schlatter and Örlü [8] proposed an empirical scaling
of $\tau_{x,rms} \sim 0.018 \ln Re_\tau$, and Diaz-Daniel et al. [20] recently extended it to the spanwise component $\tau_{z,rms}$.

The $\ln Re_\tau$ variation of $\tau_{x,rms}$ and $\tau_{z,rms}$ is consistent with the so-called high $Re$ effect on the near-wall turbulence, which is majorly characterized as the increasing influence of the outer-layer large-scale and very-large-scale motions (LSMs and VLSMs) on the near-wall dynamics in high $Re$ scenario [21–29]. Considering the traditional viewpoint that the generation of wall-shear stress is directly linked to the near-wall processes [4, 30, 31], the existing drag reduction techniques aimed at controlling the inner-layer cycles might be challenged by this high $Re$ effect [32, 33]. In fact, the near-wall motions were found to have less importance in skin-friction generation with the increase of $Re$ [34, 35]. This gives new impetus to further investigate the dynamical correlation between shear stress fluctuations on the wall and the turbulent structures with various sizes in the flow.

In this aspect, Marusic and Heuer [36] for the first time measured the fluctuating wall-shear stress in an atmospheric surface layer at $Re_\tau \sim O(10^5)$, and calculated the cross-correlation between the fluctuating wall-shear stress and the streamwise velocity in the logarithmic region. Abe et al. [16] identified the footprint of VLSMs in both the physical and the spectral space of two-dimensional (2D) wall-shear stress field in a DNS channel flow up to $Re_\tau = 640$. Marusic et al. [37] and Mathis et al. [38] developed a predictive model for the wall-shear stress distribution based on the concept of the amplitude modulation of near-wall small-scale streamwise velocity by the large-scale outer layer structures. However, de Giovanetti et al. [39] recently showed that in a channel flow up to $Re_\tau \approx 4000$, the largest amount of skin friction is generated by the self-similar energy-containing motions in the form of Townsends attached eddies, while the contribution of LSMs and VLSMs are of limited importance. This is inconsistent with the idea that the near-wall dynamics are increasingly affected by the large-scale outer-layer structures at higher $Re$, and deserves to be further studied.

Various researchers [14, 17, 19, 20, 31] have reported that $\tau'_x$ generally follows a log-normal distribution. The positively skewed long tail of the p.d.f. of $\tau'_x$ indicates the existence of extreme positive $\tau'_x$ events, which seems to increase with $Re$ even if normalized by the r.m.s. value $\tau_{x,rms}$. Diaz-Daniel et. al. [20] argued that this might suggest that the wall-shear stress is a highly intermittent signal. They then proposed a theoretical model to relate the intermittency, which is represented by low-pass-filtered $\tau'_w$, to the velocity fluctuations away from the wall within the framework of attached eddy hypothesis.

To our understanding, the outer-layer large-scale structures are more likely to be responsible for the intermittent behaviour of the wall-shear stress, since the large-scale amplitude modulation coefficient was observed to continuously increase when approaching to the wall [25, 29, 40]. This conjecture inspires the present work to study the extreme high wall-shear stress events from a structural view. For such a purpose, the instantaneous $\tau'_x$ field in a DNS dataset of a spatially developing turbulent boundary layer at $Re_\tau = 1500$ was examined. Unlike previous spectral-based scale separation analysis, a recently proposed method of Quasi-bivariate Variational Mode Decomposition (QB-VMD) is used to decompose the instantaneous wall-shear stress field into the large- and small-scale components. It is shown that those frequently occurred extreme wall events, which contain high positive magnitudes of $\tau'_x$, are mainly carried by the former. Two-point correlation and conditional average analysis further suggest that a ‘splatting’ scenario of strong Q4 events (sweeping motion of high speed fluids towards the wall, defined by $u > 0$ and $v < 0$, see [41] for more details), which are found to be tightly related to the LSMs with positive momentum fluctuation, might be responsible for the generation of these extreme wall events.

2. DNS dataset
The DNS dataset studied here was obtained by Sillero et al. [42, 43] in Universidad Politécnica de Madrid (UPM), who simulated a spatially developing turbulent boundary layer over a
smooth wall with a periodic boundary condition in the spanwise direction and non-periodic inflow/outflow condition in the streamwise direction. Fractional-step method was used to solve the incompressible Navier-Stokes equations expressed in primitive variables, with spectral expansion in the spanwise direction and compact finite difference in the other two directions [44]. This simulation covered a range of \( Re_x = 980 \sim 2000 \). To our knowledge, it is one of DNS of turbulent boundary layer that achieved the highest \( Re_x \).

For the present study, 12 snapshots of volumetric velocity fields of the UPM DNS dataset (http://torroja.dmt.upm.es/ftp/blayers/) were analysed. Instantaneous fields of the streamwise wall-shear stress \( \tau_{w,x}(x,z) \) were estimated by the slope of the linear trend line fitted to the wall-normal profile of the instantaneous streamwise velocity \( u' \) within the viscous sublayer (below \( y^+ < 5 \)) at each \((x,z)\) station. Note that the spanwise component \( \tau_{w,z} \) is not concerned in the present work. The yielded mean value \( \tau_{w,x} \) in the range of \( Re_x = 1000 \sim 1900 \) was in good agreement with the empirical formulation of Nagib et al. [45] with relative difference smaller than 1%, while the variation of the r.m.s. value \( \tau_{x,rms} \) as a function of \( Re_x \) showed the same trend with the formulation of \( \tau_{x,rms} = 0.298 + 0.018 \ln Re_x \) suggested by Schlatter and Örlü [8], but the magnitude was about 4% lower overall.

The whole \( \tau_{w,x}(x,z) \) field was then sliced to a streamwise field of view (FOV) of \( 8\delta \) (\( \delta \) is the local boundary layer thickness, defined by 99% \( U_\infty \) criteria) centering at the streamwise station where \( Re_x = 1500 \). This streamwise FOV is both large enough to accommodate instantaneous large-scale structures and small enough so that the variation of \( Re_x \) is negligible (less than 5%). The spanwise FOV is about \( 10\delta \). \( \tau_{w,x} \) was further converted to the instantaneous friction velocity \( u_\tau \) via \( u_\tau = \sqrt{\tau_{w,x}/\rho} \).

Figure 1 gives one snapshot of the fluctuating \( u'_\tau(x,z) \) for illustration, in which a recurring pattern of streak-like structures of positive and negative \( u'_\tau \) is clearly visualized. The inner-scaled dimensions of these \( u'_\tau \) structures are about \( O(10^3) \) in length and \( O(10^2) \) in width, as indicated by the spectral peak in the pre-multiplied spectra \( k_x k_y \Phi_{u_\tau u_\tau} \) shown in figure 3(a). This is consistent with those of the buffer-layer streaks in the flow, again demonstrating the distinct correlation between the inner-layer cycle and the wall-shear stress. Moreover, figure 1 shows a clear tendency of the organization (or concatenation) of multiple successive (or neighbouring) \( u'_\tau \) streaks into a rather large group. Such a tendency indicates the footprint of outer-layer large-scale structures on the wall, which plays a role of synchronizing the inner-layer structures to form a scenario of the co-existence of small- and large-scale wall-shear stress fluctuations.

3. Scale-based decomposition

Another observation from figure 1 is that the small-scale negative \( u'_\tau \) structures seem to be more apt to organize into longer structures with rather strong coherence, while the small-scale positive ones tend to be more like isolated patches with less probability to organize into longer (and wider) structures. The zoom-in plot of figure 2(a) gives a clear illustration. To further credit this observation, the small- and large-scale components need to be separated from the \( u'_\tau(x,z) \) field. A recently proposed QB-VMD algorithm [46] is used for this purpose. This algorithm is a two-dimensional update of one-dimensional (1D) VMD [47]. The essence of VMD is to obtain a set of 1D Intrinsic Mode Functions (IMFs) via an optimization procedure to achieve the most compact bandwidth. Comparing to the traditional Empirical Mode Decomposition (EMD), VMD has a rigorous mathematical foundation, and is free from the so-called ‘mode mixing’ problem. QB-VMD inherits this value by treating the 2D snapshot as a collection of slices along the primary direction with distinct scale separation. Additionally, the continuity of the decomposed length scale along the non-primary direction is kept by an additional carrier frequency re-balancing strategy. These features make it suitable for decomposing non-stationary non-equilibrium 2D dataset with one primary direction. More details about this algorithm can...
Figure 1. Snapshot of the fluctuating friction velocity $u'_\tau(x, z)$. $u'_\tau$ is normalized by $u_{\tau,rms}$. The origin of the $x$ axis is shifted to the station where $Re_\tau=1500$, the same in the following.

be referred to Wang et al. [46].

For the present $u'_\tau(x, z)$ field, QB-VMD took the spanwise direction as the primary decomposition direction. The justification is that either the small- or large-scale streaky structures in the $u'_\tau(x, z)$ fields are quasi-periodically spaced along the spanwise direction. Each snapshot of $u'_\tau(x, z)$ was decomposed into five individual IMFs and one residual mode, among which the first-rank IMF (with the largest scale) itself was regarded as the large-scale component $u'_{\tau,L}$, while the sum of the rest was considered as the small-scale component $u'_{\tau,S}$. It has been checked that the yielded $u'_{\tau,L}$ and $u'_{\tau,S}$ are rather robust to the number of the decomposed IMFs $K$, once only the first IMF is attributed to the large-scale component and $K \geq 4$.

The decomposed $u'_{\tau,L}$ and $u'_{\tau,S}$ fields are illustrated in figure 2(b, c) as a zoom-in plot. Both $u'_{\tau,L}(x, z)$ and $u'_{\tau,S}(x, z)$ are dominated by streaky structures with different spanwise length scales. By comparing to the original $u'_\tau$ field in figure 2(a), the $u'_{\tau,L}$ component is believed to capture the large-scale characteristics, which can be interpreted as the synchronization or amalgamation of finer streaky structures. Moreover, figure 2(b) suggests that the positive large-scale streaks in $u'_{\tau,L}$ are generally shorter than the negative ones, consistent with the observation in the full-order $u'_\tau$ fields in both figure 1 and figure 2(a).

The skewness of the large- and small-scale $u'_\tau$ components are $S_{u'_{\tau,L}}=0.203$ and $S_{u'_{\tau,S}}=0.189$, respectively. Comparing to the magnitude of the full-order component, i.e. $S_{u'_\tau}=0.487$, the
skewness of the scale-separated components get remarkably decreased. Nevertheless, \( S_u'_{\tau,L} \) is still positive, indicating the positively skewed nature of the large-scale wall-shear stress. This is somehow consistent with the qualitative observation of the existence of the asymmetry of the length scale between the positive and negative \( u'_{\tau,L} \) streaks. Note that such a weak asymmetry was also observed in the large-scale \( u' \) component in the buffer layer by Agostini [33], who used bi-dimensional-EMD (B-EMD) for scale decomposition.

The pre-multiplied spectra of \( u'_{\tau,S} \) and \( u'_{\tau,L} \), as shown in figure 3(b), are separated from each other at about \( \lambda_z^+ = 200 \). The former retains the energetic spectra patch of the original \( u' \) field centering at \( \lambda_x^+ \sim O(10^5) \) and \( \lambda_z^+ \sim O(10^4) \), while the latter is primarily confined in the large \((\lambda_x, \lambda_z)\) domain, with a distinct spectral peak at \( \lambda_z^+ \sim 1600 \) and \( \lambda_z^+/\delta \sim 1.1 \) and \( \lambda_z^+/\delta \sim 0.24 \) in outer scaling. Note that this spectral peak is not present in the original spectra. Moreover, a self-similar scaling of \( \lambda_z \approx 4.5 \lambda_x \) is found to well characterize the ridge of the energetic \( k_x k_z \Phi_{u_{\tau,L}u_{\tau,L}} \) patch in the large-scale component, and the energy-containing length scale extends to \( \lambda_x \sim 2 \delta \) and \( \lambda_z \sim 0.45 \delta \). Such a self-similar scaling seems to indicate the wall-signature of attached eddies whose longitudinal/lateral length scales linearly grow in wall-normal direction.

Figure 2. Comparison of the original \( u' \) field in (a) to the large-scale \( u'_{\tau,L} \) field in (b) and the small-scale \( u'_{\tau,S} \) field in (c).
Figure 3. Pre-multiplied spectra $k_x k_z \Phi_{u_x u_y}$ of (a) the original $u'_r$ fields and (b) the QB-VMD separated large-scale $u'_{r,L}$ fields (indicated by pseudo-color plot) and small-scale $u'_{r,S}$ fields (contour plot). In each plot, $k_x k_z \Phi_{u_x u_y}$ is normalized by the square of the r.m.s of $u'_r$, $u'_{r,L}$ or $u'_{r,S}$, respectively.

In the QB-VMD operation, the length scales along the primary (spanwise) direction is necessarily decomposed by definition. This is the reason that the spectra of $u'_{r,S}$ and $u'_{r,L}$ are well separated into distinct ranges of the spanwise length scales. The slight overlap of the spectra at the separation boundary of $\lambda_{+}^z = 200$ might be attributed to the non-stationary nature of spanwise scales in individual snapshots. This stresses the difficulty in drawing a pre-determined sharp cut-off to differentiate small and large scales.

On the other hand, the scales along the non-decomposed (streamwise) direction need not be decomposed and the spectra of $u'_{r,S}$ still contain non-negligible energy in the large $\lambda_x$ domain. Inspection of the instantaneous $u'_{r,S}$ field (figure 2c) and the non-decomposed $u'_r$ field (figure 2a) suggests that the large $\lambda_x$ contents in $k_x k_z \Phi_{u_x u_y}$ may not indicate the failure of the scale separation, but imply the actual existence of longer streaks with the spanwise length scales $\lambda_z \sim O(10^2)$ (despite the spatial growth of the boundary layer). Moreover, it has been tested that both pseudo-bi-dimensional-EMD (PB-EMD) [48] and B-EMD [49] lead to similar scale-separated spectra (not presented here for simplicity). Such a consistency indicates that the fluctuations with the large-scale $\lambda_x$ in $u'_{r,S}$ fields are not enforced by the QB-VMD algorithm. Previous studies [25, 40] on the amplitude modulation usually applied a cut-off threshold to single-point time-series signal of $u'(t)$ via Taylors frozen hypothesis. It is argued that the length scale along the homogeneous spanwise direction might be a more ideal candidate criteria for the scale separation. However, on considering that the present studied $Re_{\tau}$ does not guarantee a full inner- and outer-scale separation, this conjecture needs to be further studied at higher $Re$.

4. Extreme wall-shear stress events
In order to examine the average shape of extreme shear stress fluctuation events, two-point correlation maps of the instantaneous friction velocity fluctuations are utilized. However, the conventional correlation maps of $u'_r$ (figure 4a) are not adequate for such purpose, since their shape is dominated by the more frequently occurring small-scale streaks. Instead, the correlation maps computed from $u'_{r,L}$ fields are used because, as illustrated by the circled regions in figures
Figure 4. Two-point correlation map of (a) the original $u'_{\tau,L}$ fields, (b) the large-scale $u'_{\tau,L}$ fields and (c) the small-scale $u'_{\tau,S}$ fields. In (d), three correlation maps are compared at $\Delta x^+ = 0$, LS is short for large scale and SS for small scale.

2(a,b), the extreme shear stress fluctuation events tend to be large-scale. Note that the extremely positive shear stress fluctuation events seem to appear more frequently than their negative counterparts.

The two-point correlation map of the $u'_{\tau,L}$ field, as shown in figure 4(b), presents a round-shaped region with high magnitude of correlation coefficient ($R_{u'_{\tau,L}u'_{\tau,L}} > 0.85$, see figure 4d for illustration) around the central auto-correlation peak. This round-shaped region is embedded into the streamwise-elongated positive correlation strip, whose spanwise width is about 360 wall units. Considering that two-point correlation reveals the average geometry of coherent fluctuations, such a pattern implies that the spot-like extreme wall-shear stress fluctuation events are a common feature in instantaneous $u'_{\tau,L}$ fields. The absence of a similar high correlation region in the small-scale $R_{u'_{\tau,S}u'_{\tau,S}}$ map (figure 4c) implies that these events might be primarily associated with the large-scale flow structures away from the wall. Again, it has been checked that the switch of the decomposition method to either PB-EMD or B-EMD will not qualitatively change the signature of extreme $u'_{\tau,L}$ events in the correlation map.

Based on the above observation, extreme wall-shear stress events are then detected from the instantaneous $u'_{\tau,L}$ fields. The idea is to detect isolated regions of $u'_{\tau,L}$ whose magnitudes are larger than a threshold. Meanwhile, the isolated regions should have shapes close to circle and are not too small in area. As a first attempt, the magnitude threshold is set as $|u'_{\tau,L}|/u'_{\tau,L,rms} \geq H = 4$ (so that the extreme positive and negative $u'_{\tau,L}$ events are both detected), the round shape threshold is $AR \leq 4$ and the area threshold is $r^+ \geq 40$, with $AR$ and $r^+$ being the aspect ratio (the ratio between the major and minor axis) and the equivalent radius of the isolated candidates of extreme $u'_{\tau,L}$ events, respectively.

In twelve analyzed DNS snapshots, 1625 extreme positive $u'_{\tau,L}$ events and 270 extreme negative $u'_{\tau,L}$ events are detected. Figure 5 compares the conditionally averaged fields of $\tilde{u}'_{\tau,L}$, $\tilde{u}'_{\tau,S}$, and $\tilde{u}'_{\tau,S}$ around the detected extreme positive $u'_{\tau,L}$ event, while figure 6 shows the conditionally averaged fields around the negative one. In the large-scale component, the extreme $\tilde{u}'_{\tau,L}$ event (in figure 5b and figure 6b) resembles the two-point correlation map shown in figure 4(b), i.e. an elliptical region of high magnitude of positive/negative $\tilde{u}'_{\tau,L}$ slightly elongated along the streamwise direction, is embedded into a large-scale $\tilde{u}'_{\tau,L}$ streak with the same fluctuation sign. In contrast, no distinct structures in the conditionally averaged small-scale $\tilde{u}'_{\tau,S}$ fields (in figure
Figure 5. Conditionally averaged fluctuating friction velocity field associated with an extreme positive $u^\prime_{\tau,L}$ event detected at $\Delta x=0$, $\Delta z=0$. (a) the original $\tilde{u}^\prime_{\tau}$, (b) the large-scale $\tilde{u}^\prime_{\tau,L}$, (c) the small-scale $\tilde{u}^\prime_{\tau,S}$.

Figure 6. Conditionally averaged fluctuating friction velocity field associated with an extreme negative $u^\prime_{\tau,L}$ event detected at $\Delta x=0$, $\Delta z=0$. (a) the original $\tilde{u}^\prime_{\tau}$, (b) the large-scale $\tilde{u}^\prime_{\tau,L}$, (c) the small-scale $\tilde{u}^\prime_{\tau,S}$.

5c and figure 6c) are observed. This implies that the extreme events are mainly associated with the large-scale component, and it is themselves that contribute to the round-shaped pattern in the full-order $\tilde{u}^\prime_{\tau}$ field (shown in figure 5a and figure 6a).

One more finding revealed by figures 5(b) and 6(b) is that on the downstream of the large-scale extreme positive wall-shear stress fluctuation events, the positive $\tilde{u}^\prime_{\tau,L}$ streak gets thinner in width and weaker in strength. As for the extreme negative event, a reverse trend is observed: the negative $\tilde{u}^\prime_{\tau,L}$ streak gets a mild growth downstream of the extreme negative event.

Interestingly, Lee and Sung [50] reported asymmetrically biased behavior of VLSMs with positive and negative streamwise fluctuating velocity along the streamwise direction by calculating the conditional two-point correlation of the positive and negative $u$ fluctuations at $y/\delta = 0.18$ in a DNS of a turbulent boundary layer: the positive VLSMs are biased towards
the upstream, while the negative ones are biased towards the downstream (see figure 28 in [50] for example). Such a biased pattern is similar to that of the conditionally averaged $\tilde{u}_{r,L}'$ shown in figure 5(b) and figure 6(b). Lee and Sung [50] attributed it to the preferential spatial alignment of the vortex packet structures and the Q4/Q2 events, where Q2 events are ejections of low speed fluids away from the wall ($u < 0$ and $v > 0$). In their view, the strong Q4 events belong to positive VLSMs (with positive $u$) in the upstream of the inclined interface of the vortex packets, and the Q2 events are linked to negative VLSMs (with negative $u$) in the downstream of the packets’ interface. Such a spatial alignment is illustrated in figure 7. Since the large-scale wall-shear stress is an integrated signature of all the flow structures above the wall, the positive/negative spot-like extreme wall events might be directly related with these strong Q4/Q2 events. This will be discussed later. Here, it is stressed that if the vortex packet model offers a reasonable explanation for the asymmetric geometry of the conditionally averaged positive/negative $\tilde{u}_{r,L}'$ streaks, one of the inferences is that one decaying positive $\tilde{u}_{r,L}'$ streak associated with a spot-like extreme positive event should appear in the upstream of one negative $\tilde{u}_{r,L}'$ streak. Such a pattern is clearly observed in figure 2(b).

5. Flow structures associated with extreme wall-shear stress event

The conditionally averaged 3D velocity field around extreme negative/positive $u'_{r,L}$ events is calculated and shown in figures 8 and 9, respectively. Figure 8 indicates that the extreme negative $u'_{r,L}$ event is linked to a large-scale low-speed streak, which is originally attached to the wall but gets lifted up downstream of the extreme wall event.

In contrast, the conditionally averaged flow field (shown in figure 9) associated with the extreme positive $u'_{r,L}$ events is characterized by a finger-shaped large-scale negative $\tilde{v}$ region extending from the outer layer to the wall. Quadrant analysis (not shown here) evidences that this $\tilde{v}$ structure corresponds to a large-scale strong Q4 event that transfers outer-layer high-momentum fluids downward (as can be seen in figure 10), which forms a round-shaped thin layer of positive $\tilde{u}$ close to the wall. Note that this strong Q4 event is consistent with the so-called ‘splatting’ process suggested by Agostini et al. [29, 33], it also seems to describe the same structure as the near-wall ‘pocket’ named by Falco [51] or the ‘dark spot’ by Taimon et al. [52] and Lian [53].

If the large-scale $u'_{r,L}$ streaks are indeed the wall signature of outer-layer LSMs or VLSMs, the strong Q4 event will introduce a strong top-down interaction between the outer- and inner-region. The connection of the strong Q4 event with positive outer-layer LSMs can be somehow inferred from the volumetric $\tilde{u}$ plot in figure 10, in which one large-scale streak with high momentum is revealed in the wall-parallel plane of $y^+ = 180$. It moves downstream at a rather high speed, and
Figure 8. Conditionally averaged full-order fluctuating velocity field around an extreme negative $u'_{\tau,L}$ event detected at $\Delta x=0, \Delta z=0$. Blue iso-surface represents $65\% \tilde{u}_{\max}^-$ and red iso-surface represents $65\% \tilde{v}_{\max}^+$, with $\tilde{u}_{\max}^-$ being the maximum negative value of $\tilde{u}$ in the presented volume and $\tilde{v}_{\max}^+$ being the maximum positive $\tilde{v}$. Contour on the wall is the conditionally averaged $\tilde{u}'_{\tau}$ as shown in figure 6(a). Pseudo-color maps on two sliced planes show the planar distribution of $\tilde{u}$ at either $\Delta z^+=0$ or $\Delta x^+=350$.

leaves a footprint in behind that reaches into the inner-layer. Meanwhile, the strong Q4 event is seen to be directly ‘shot’ from this positive LSM. Note that in the conditionally averaged field, the strong Q4 event (in figure 9) appears to lift up from the wall and extend downstream, but the real dynamic sequence is that the positive LSM first ‘shoots’ the strong Q4 event, and then leaves the site at a faster convection speed; while the ‘bullet’ of the Q4 event decelerates when descending towards the wall, and finally forms a splatting in the near-wall region and causes the extreme positive shear stress fluctuation events on the wall.

To our understanding, the origin of this strong Q4 event is still not clear. One possible explanation is the instability that is associated with the decelerating front of the positive streak-like LSMs, which creates a negative local velocity gradient in the streamwise direction. In this aspect, the existing knowledges on the streak instability in transitional flow [54–56] can provide useful guidance, but this is beyond the topic of the present work.

6. Summary
To sum up, the fluctuating characteristics of the streamwise wall-shear stress in a DNS turbulent boundary layer is studied at $Re_\tau=1500$. With the help of QB-VMD, the 2D fields of the fluctuating friction velocity $u'_\tau(x,z)$ are decomposed into the large- and small-scale components, $u'_{\tau,L}$ and $u'_{\tau,L}$, based on the length scale in the spanwise direction, both of which are found to be dominated by streak-like structures elongated along the streamwise direction. Spectral analysis indicates that these two components are actually the wall signature of the inner-layer streaks and the outer-layer LSMs, respectively. A self-similar behaviour of the energetic longitudinal/lateral length scales in the large-scale component is observed, implying the footprints of self-similar attached eddies.

Extreme positive wall-shear stress fluctuation events are detected in the large-scale $u'_{\tau,L}$ component. Most of them present circular (or elliptical) shape if the contamination of small-scale fluctuation is removed. Both non-conditional two-point correlations and conditional averages show that these extreme positive events are embedded in the positive large-scale $u'_{\tau,L}$ streaks.
Figure 9. Conditionally averaged full-order fluctuating velocity field around an extreme positive $u'_r,L$ event detected at $\Delta x=0$, $\Delta z=0$. Blue iso-surface represents $65\% \tilde{v}_{max}$ and red iso-surface represents $65\% \tilde{u}_{max}$, with $\tilde{v}_{max}$ being the maximum negative value of $\tilde{v}$ in the presented volume and $\tilde{u}_{max}$ being the maximum positive $\tilde{u}$. Contour on the wall is the conditionally averaged $\tilde{u}'_r$ as shown in figure 5(a). Pseudo-color maps on two sliced planes show the planar distribution of $\tilde{v}$ at either $\Delta z^+=0$ or $\Delta x^+=350$.

Figure 10. Conditionally averaged full-order fluctuating velocity field around an extreme negative $u'_r,L$ event detected at $\Delta x=0$, $\Delta z=0$. Contour on the wall is the conditionally averaged $u_r$ as shown in figure 5(a). Pseudo-color maps on two sliced planes show the planar distribution of $\tilde{u}$ at either $\Delta z^+=0$ or $\Delta y^+=180$.

The conditionally averaged flow field above the extreme positive wall-shear stress fluctuation events is characterized as a strong finger-like Q4 event, which seems to be ‘shot’ from outer-layer positive LSM, forming a ‘splatting’ of high-speed fluids in the near-wall region. Since these extreme positive wall events contribute a significant portion of the long tail of the wall-shear stress distribution, they need to be well treated in drag reduction control strategy. The origin of the strong Q4 events, their $Re$-dependency and the related spanwise wall-shear stress fluctuation features deserve to be further studied.

On the other hand, extreme negative wall-shear stress fluctuation events embedded in negative
$u_{r,L}$ streaks are also observed. Despite of their spot-like shapes, they are unlikely to be related with the 'splatting' process. Since their occurrence frequency is nearly one-order smaller than that of the extreme positive events, these extreme negative wall events seem to be less important in terms of skin friction control.

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