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Direct Numerical Simulation of Turbulent Channel Flow at $\mathrm{Re}_\tau = 2320$

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Direct numerical simulation of a turbulent channel flow at $Re_\tau = 2320$ was performed in order to examine the flow statistics, and the relationship between the near-wall and outer-layer structures. The number of the total grid points is about 16 billions, and the effective computational speed is about 5.5 TFLOPS by using 2048 CPUs and 4 TB main memory on the Earth Simulator. The mean velocity profile in the region of $100 < y^+ < 600$ follows the $1/7$ power law. The visualized flow field and the turbulent statistics suggest that the streaky structures, of which spanwise spacing is about 100 wall units, exist only near the wall ($y^+ < 30$), while the large-scale structures extend from the center of the channel to the near-wall region ($y^+ \sim 30$). Therefore, the near-wall turbulence depends not only on the near-wall fine-scale structures, but also on the large-scale structures.

1 Introduction

Up to now, various Reynolds number effects in wall turbulence have been reported. Zagarola & Smits [1] suggest that the overlap region between inner and outer scalings in wall-bounded turbulence may yield a log law rather than a power law at very high Reynolds numbers. Moser *et al.*[2] have made direct numerical simulation (DNS) of fully-developed turbulent channel flows at $Re_\tau = 180-590$ (hereafter, Re_τ denotes the friction Reynolds number defined by the wall friction velocity u_τ, the channel half-width δ, and the kinematic viscosity ν). They conclude that the wall-limiting behavior of root-mean-square (rms) velocity fluctuations strongly depends on the Reynolds number, but obvious low-Reynolds-number effects are absent at $Re_\tau > 395$. It is well known that near-wall streamwise vortices play an important role in the transport mechanism in wall turbulence, at least, at low Reynolds number flows [3, 4, 5]. Those streamwise vortices and streaky structures, which are scaled with the viscous wall units [6], are closely associated with the regenerative mechanism [7].

On the other hand, the relationship between the near-wall coherent structures and the large-scale outer-layer structures at higher Reynolds numbers still remains unresolved. Adrian *et al.*[8] show that packets of large-scale hairpin vortices around the low-speed large-scale structures are often observed in high-Reynolds-number wall turbulence. Zhou *et al.*[9] have studied by DNS the evolution of a single hairpin vortex-like structure in a low-Reynolds-number channel flow, and found that a packet of hairpins, similar to that reported in Adrian *et al.*[8], propagates coherently.

In the present study, DNS of turbulent channel flow at a Reynolds number of $Re_\tau = 2320$, which can be reached by the most powerful supercomputer system at this moment, is carried out to examine the flow statistics at high Reynolds numbers and the effect of the large-scale structures on the near-wall turbulence.

2 Numerical method

The numerical method used in the present study is almost the same as that of Kim *et al.*[10]; a pseudo-spectral method with Fourier series is employed in the streamwise (x) and spanwise (z) directions, while a Chebyshev polynomial expansion is used in the wall-normal (y) direction. The fourth-order Runge-Kutta scheme and the second-order Crank-Nicolson scheme are used for time discretization of the nonlinear terms and the viscous terms, respectively. The friction Reynolds number is set to $Re_\tau = 2320$, and the bulk Reynolds number is $Re_m = u_m 2\delta/\nu \approx 103000$, where u_m is the bulk mean velocity. The flow rate is kept constant. The size of the computational domain is $6\pi\delta \times 2\delta \times 2\pi\delta$, and the wave number is $2304 \times 1025 \times 2048$ in x-, y-, and z-directions, respectively. The $3/2$ rule is applied to avoid the aliasing errors involved in computing the nonlinear terms. The number of the total grid points is about 16 billions, and the effective computational speed is about 5.5 TFLOPS by using 2048 CPUs and 4 TB main memory on the Earth Simulator [11]. The two-point correlations in the x- and z-directions at any y-location vanish for large separations, indicating that the computational domain is sufficiently large. The energy density associated with the high wavenumbers is several decades lower than the energy density corresponding to low wavenumbers, pointing that the grid resolution is adequate. Hereafter, u, v, and w denote the velocity components in the x-, y-, and z-directions, respectively. Superscript $(+)$ represents quantities non-dimensionalized with u_τ and ν.

3 Flow statistics

Figure 1 shows the mean streamwise velocity profiles at $Re_\tau = 2320$, 650 [12], and 150 [12]. The profile of $Re_\tau = 2320$ has a viscous sublayer at $0 < y^+ < 5$, a logarithmic layer at $30 < y^+ < 250$, and a wake layer at $y^+ > 250$. The profiles of $Re_\tau = 2320$ and 650 collapse at $y^+ < 200$. On the other hand, the profile of $Re_\tau = 150$ deviates from that at higher Reynolds numbers beyond $y^+ = 10$ due to a low-Reynolds number effect.

Figure 2(a) shows the diagnostic quantity, $\kappa_{local} = 1/(y^+ d\overline{u}^+/dy^+)$, which should be constant and equal to the von Kármán constant (κ) in the logarithmic layer. It is found that the profiles of $Re_\tau = 2320$ and 650 agree at $y^+ < 70$, and this suggests that there is no low-Reynolds number effect on the mean profile in this region. For $Re_\tau = 2320$, this quantity gradually decreases from $y^+ \approx 70$ to $y^+ \approx 600$, indicating that the mean velocity does not obey the logarithmic law in this region. The slope of the curve reduces in this region with increasing the Reynolds number, so that there would be a wide logarithmic layer at higher Reynolds numbers.

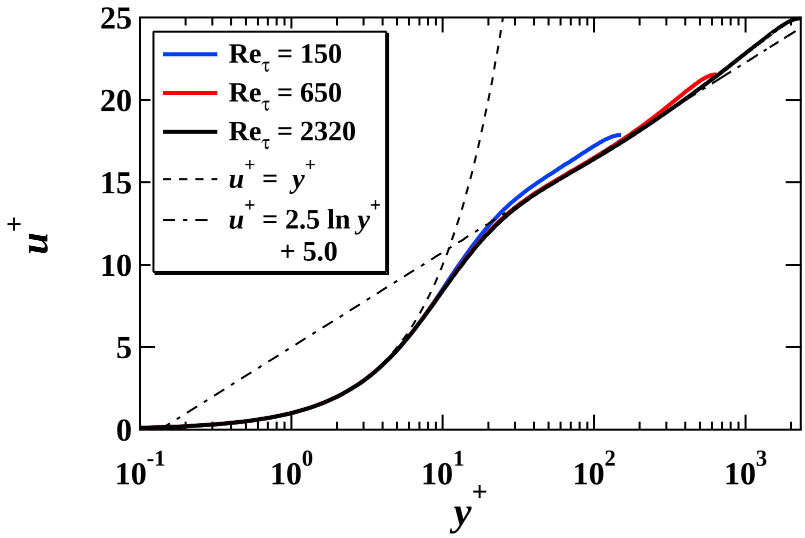

Fig. 1 Mean streamwise velocity profiles at Re_τ = 2320, 650 [12], and 150 [12].

This is in good agreement with the findings of Zagarola and Smits [1], who suggest that the true logarithmic law is only apparent at $600 < y^+ < 0.07\delta^+$ and $Re_\tau > 9000$.

Figure 2(b) shows the diagnostic quantity of $n_{local} = 1/(y^+/u^+)(du^+/dy^+)$. If u^+ behaves like $u^+ = A(y^+)^n$ in some region, then n_{local} has a constant value identical to n in that region. For $Re_\tau < 650$, this quantity is not constant in any region, pointing that the mean velocity profile does not obey the power law. It is found that this quantity of $Re_\tau = 2320$ is constant of $1/7$ at $100 < y^+ < 600$, indicating that this region becomes to obey the power law. This limit is similar to that by Zagarola and Smits [1], i.e., $60 < y^+ < 0.15\delta^+ (\approx 350$ for $Re_\tau = 2320)$.

4 Flow visualization

In this section, the fundamental characteristics of the near-wall coherent structures and large-scale structures are evaluated through the flow visualization. Figure 3 shows the $(x-z)$ plane views of instantaneous near-wall flow fields at $y^+ \approx 11$, in which contours of the streamwise velocity fluctuation u' are visualized. The area of the upper figure is the whole computational domain. It is found that there are some large-scale streaky structures near the wall, of which spanwise scale is estimated at about 1.2δ based on the pre-multiplied energy spectra (not shown here). The lower figure is an enlarged view of the upper one. There are the fine-scale streaky structures with spanwise scale of about 100 wall units, which is similar to that at low Reynolds number flows. It is clearly recognized that the fine-scale streaky structures mix with the large-scale ones, indicating that the large-scale structures affect the near-wall coherent structures.

Figure 4 shows the $(y-z)$ cross-stream planes of an instantaneous flow field, in which contours of the streamwise velocity fluctuation u' are visualized. The area of the upper figure is the whole computational domain. It is found that the large-scale structures exist from the center of the channel to the near-wall region. The spanwise scale at any y-location is roughly estimated at $\sim \delta$ based on the pre-multiplied energy spectra (not shown here). The lower figure is an enlarged view of the upper one. The streaky structures, of which spanwise spacing is about $100\nu/u_\tau$, exist only near the wall ($y^+ < 30$), while the large-scale structures exist from the center of the channel to the very near-wall region ($y^+ \sim 30$).

5 Conclusions

Direct numerical simulation of turbulent channel flows at $Re_\tau = 2320$ was made in order to examine the fundamental flow statistics at high Reynolds numbers and the relationship between the near-wall and outer-layer structures. The following conclusions are derived:

1. The profile of the mean streamwise velocity at $100 < y^+ < 600$ obeys the $1/7$ power law, while the profile at any region does not obey the logarithmic law even at this Reynolds number of $Re_\tau = 2320$.

2. The streaky structures, of which spanwise spacing is about 100 wall units, exist only near the wall ($y^+ < 30$), while the large-scale structures, of which spanwise spacing is about $\sim \delta$, are identified in a wider region from the center of the channel to the near-wall region ($y^+ \sim 30$).

Acknowledgements
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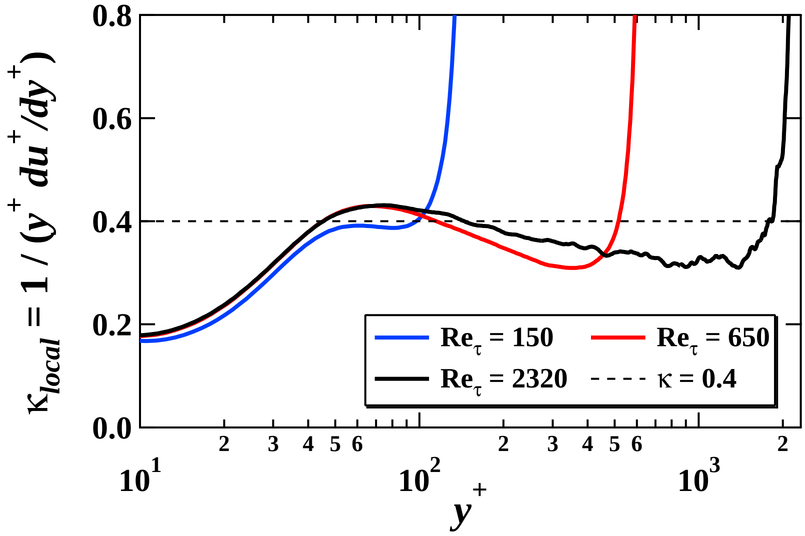
(a)



(b)

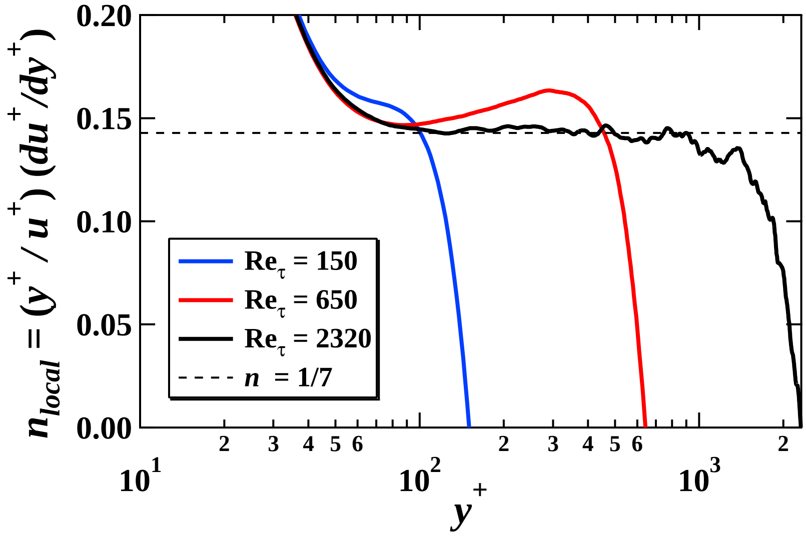


Fig. 2 Diagnostic quantities (a)for a logarithmic law and (b)for a power law at Re_τ = 2320, 650 [12], and 150 [12].

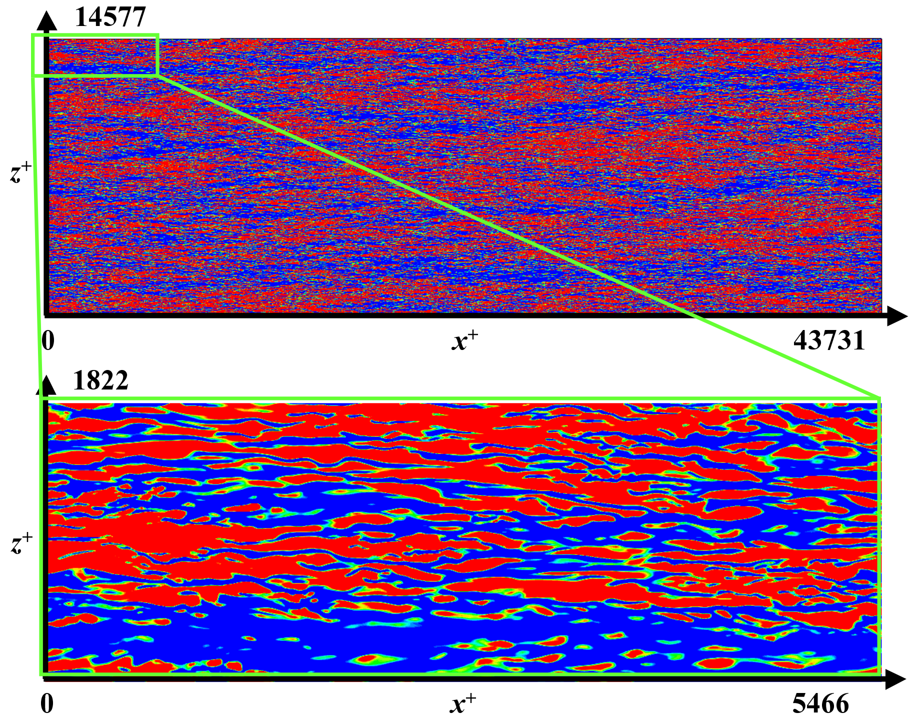


Fig. 3 Plane views of instantaneous near-wall velocity field at $y^+ \approx 11$. Contours of the streamwise velocity fluctuation, blue to red, $u'^+ = -1$ to $u'^+ = 1$. Total computational volume is 43731 and 14577 wall units in the x- and z-directions, respectively.

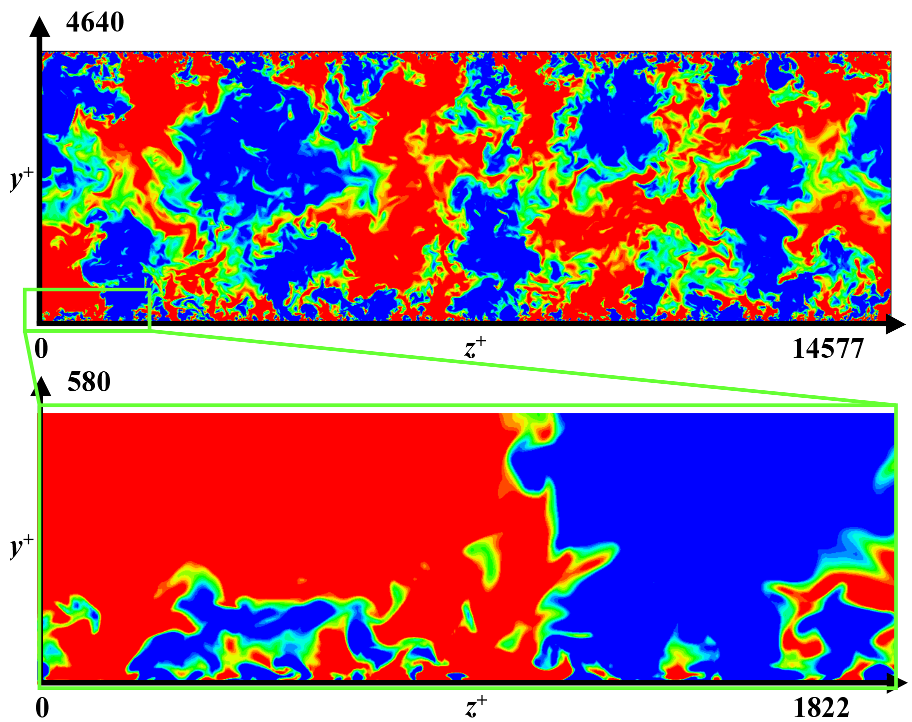


Fig. 4 Cross views of instantaneous velocity field. Contours of the streamwise velocity fluctuation, blue to red, $u'^+ = -1$ to $u'^+ = 1$. Total computational volume is 4640 and 14577 wall units in the y- and z-directions, respectively.