11th International ERCOFTAC Symposium on
Engineering Turbulence Modelling and Measurement
Palermo, Sept. 21-23, 2016

Direct Numerical Simulation of Drag Reduction with Uniform Blowing over a Rough Wall

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Background

Turbulence

- **Huge drag**
- **Environmental** problems
- High operation **cost**
- **How to control**?

Flow control classification

(M. Gad-el-Hak, *J. Aircraft*, 2001)

- Flow control strategies
  - Active
    - Feedback
    - **Feedforward**
  - Passive

- Uniform blowing

Uniform blowing (UB)

(Sumitani & Kasagi, *AIAA J.*, 1995
Kametani & Fukagata, *J. Fluid Mech.*, 2011)

- **Drag contribution in a channel flow with UB(/US)**

$$C_f = \frac{12}{\mathrm{Re}_b} + 12\int_0^2 (1-y)(-\overline{u'v'})dy \; -12V_w \int_0^2 (1-y)\bar{u}dy$$

V_w: Blowing velocity

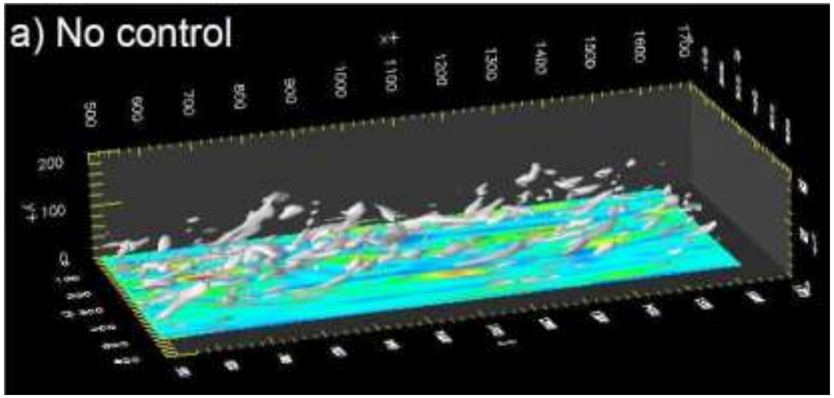
Viscous Contribution (= laminar drag, **const.**)

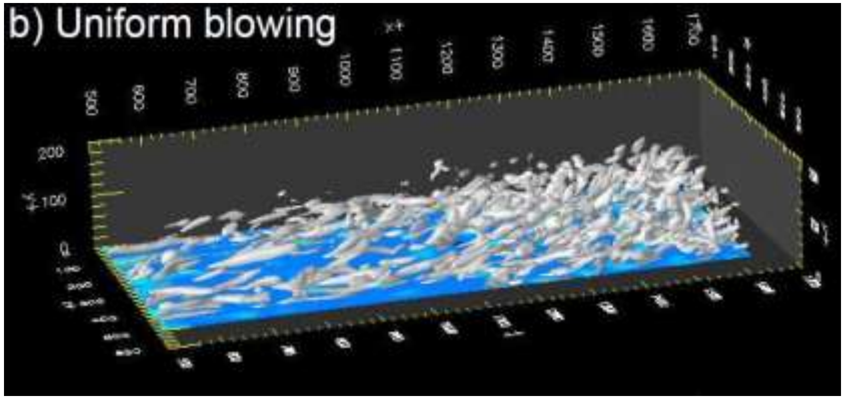
Turbulent contribution

Convective (=UB/US) contribution

(Fukagata et al., *Phys. Fluids*, 2002)

- **Excellent performance** (about **45%** by $V_w = 0.5\%U_\infty$)
- **Unknown over a rough wall**





On a boundary layer, White: vortex core, Colors: wall shear stress

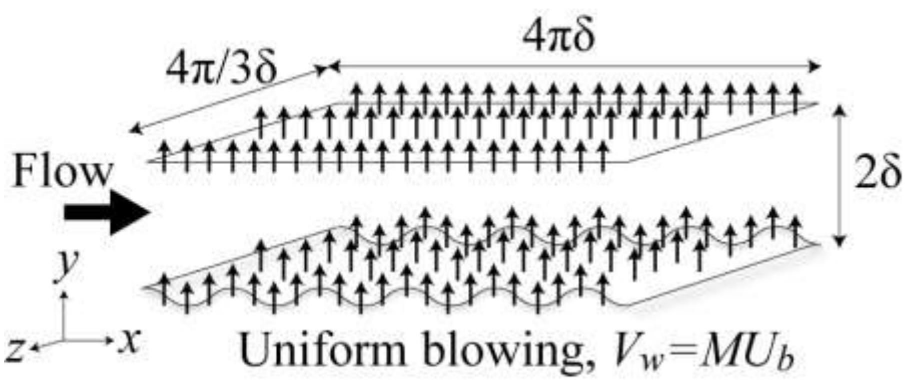
Goal

Investigate the interaction between roughness and UB for drag reduction

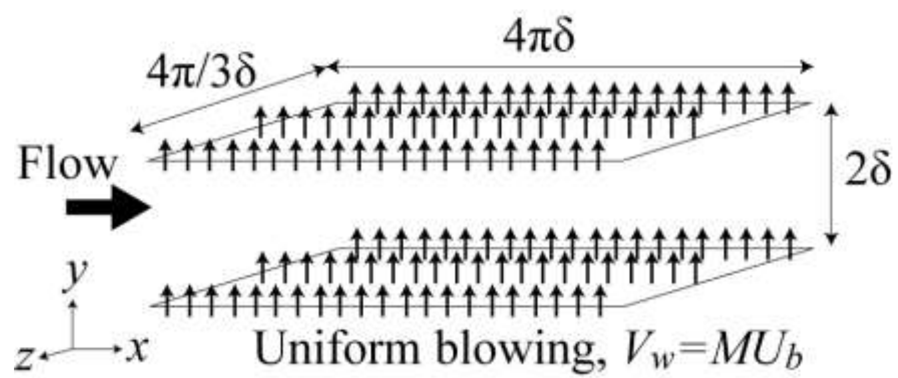
- DNS of turbulent channel flow
- Focus on drag reduction **performance** and **mechanism**

Numerical procedure

- **Based on FD code** (for wall deformation)
  (Nakanishi et al., *Int. J. Heat Fluid Fl.*, 2012)
- **Constant flow rate,** $\mathbf{Re}_b = 2U_b\delta/\nu = 5600$
  - so that $\mathbf{Re}_\tau \approx 180$ in a plane channel (K.M.M.)
- $\Delta x^+ = 4.4, 0.93 < \Delta y^+ < 6, \Delta z^+ = 5.9$
- **UB magnitude:** $M = 0, 0.001, 0.005$



ROUGH CASE



SMOOTH CASE

Model of rough wall

(E. Napoli et al., *J. Fluid Mech.*, 2008)

Roughness displacement

$$d(x) = \delta \sum_{i=1}^{4} A_i \sin\left(\frac{2^i \pi x}{L_x/2}\right)$$

δ: channel half height
L_x: Channel length, $4\pi\delta$
A_i: Amplitude of each sinusoid

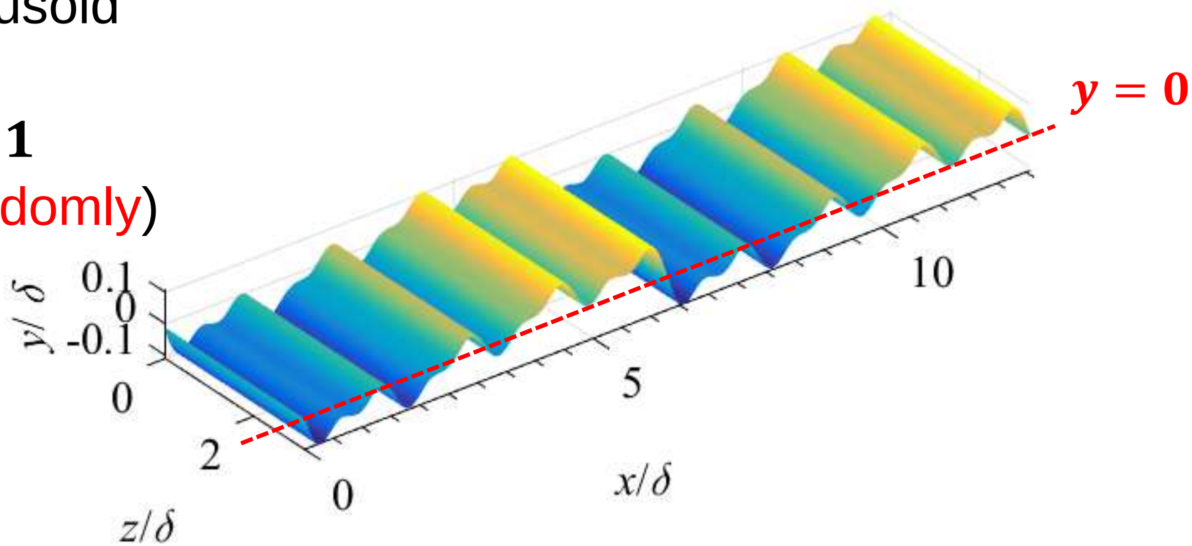
$$A_i = \begin{cases} 1, & \text{for } i = 1 \\ [0, 1], & \text{for } i \neq 1 \end{cases}$$

(Defined randomly)

with rescaling so that

$$\overline{|d(x)|} = 0.05\delta$$

$|d(x)|_{max} = 0.11\delta$



Coordinate transformation

(S. Kang & H. Choi, *Phys. Fluids*, 2000)

Calculation grids: ξ_i (Cartesian with extra force)

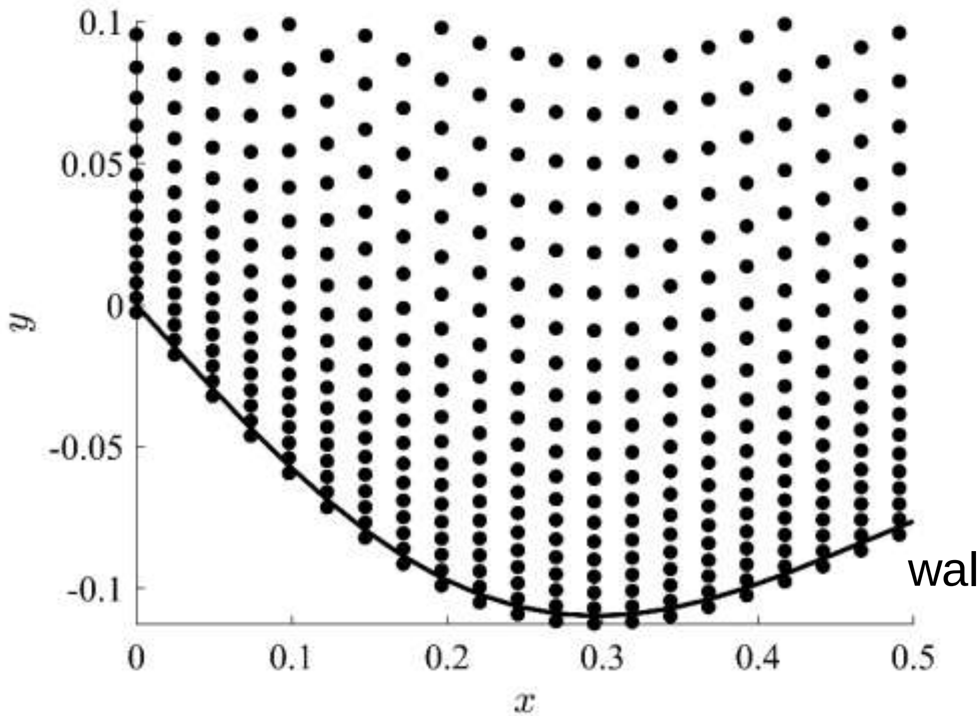
$$\begin{cases} x = \xi_1 \\ y = \xi_2(1+\eta) + \eta_d \\ z = \xi_3 \end{cases}$$

(x, y, z: physical coordinate)

$$\eta \equiv (\eta_u - \eta_d)/2$$
$$= -d(x)/2$$
$$\eta_d = r(x), \eta_u = 0$$

η_d, η_u: displacement of lower/upper wall

Actual grid points allocation



Post processing

- **Drag coefficient decomposition for rough case**

$$C_{Duf} = \frac{8}{\mathrm{Re}_b}\frac{d\bar{u}}{dy}\bigg|_{\xi_2=2}$$

$$C_{Dlf} = \frac{8}{\mathrm{Re}_b}\overline{\left(\frac{du}{dy}\bigg|_{\xi_2=0} + \frac{dv}{dx}\bigg|_{\xi_2=0}\right)}$$

(Friction component)

$$C_{Dlp} = -16\frac{dP}{d\xi_1} - \left(C_{Dlf} + C_{Duf}\right)$$

(Pressure component)

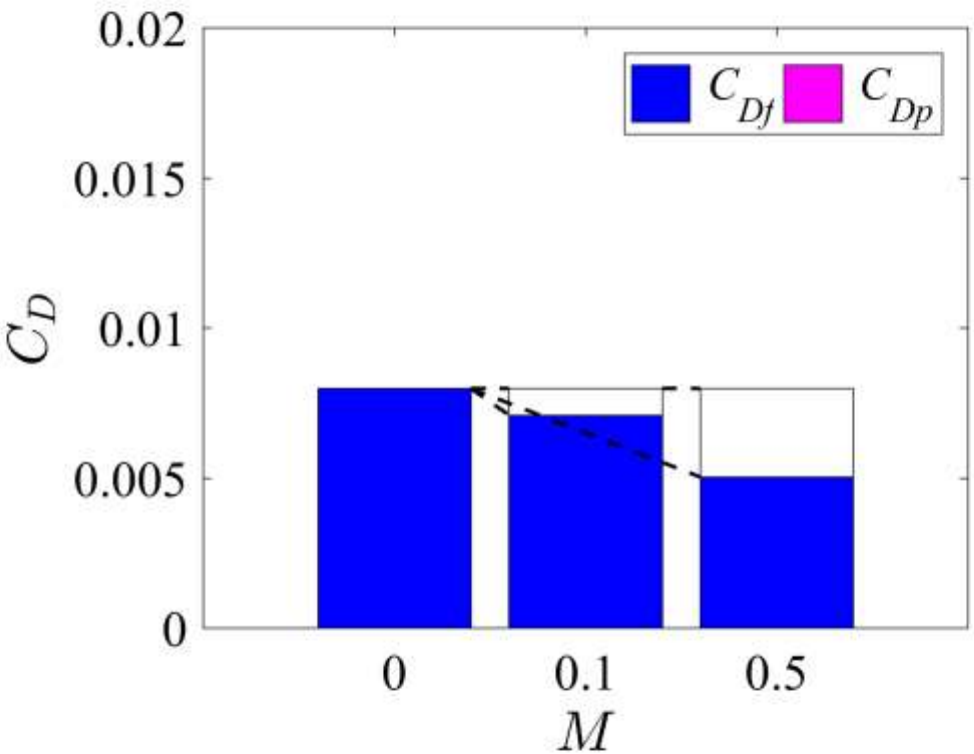
- **Drag reduction rate**

$$R_{Dl} = \frac{\Delta C_D}{C_{D,M=0}} \times 100\ [\%]$$

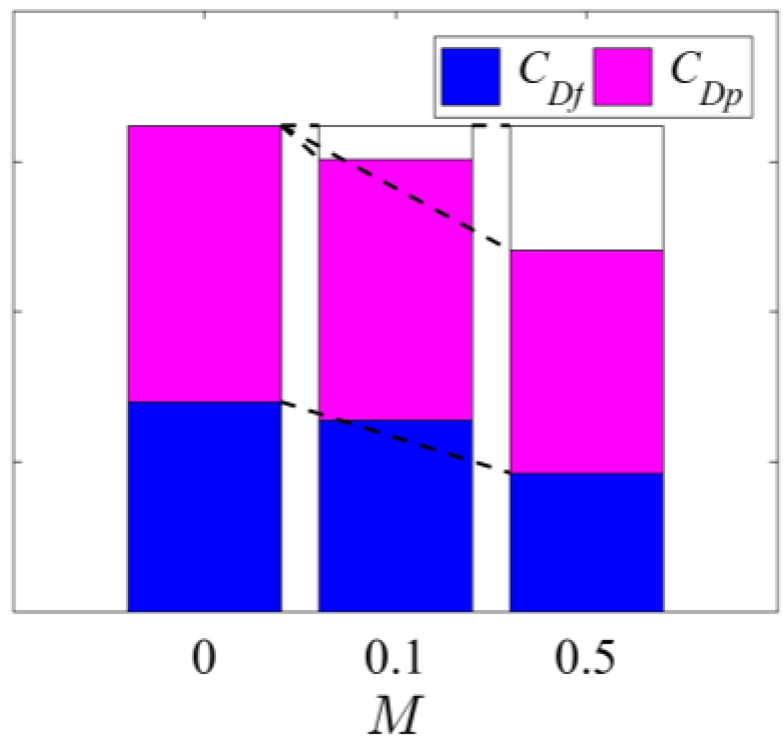
Only focusing on lower side,
subscript “l” omitted hereafter

Drag reduction rate, R_D

SMOOTH CASE



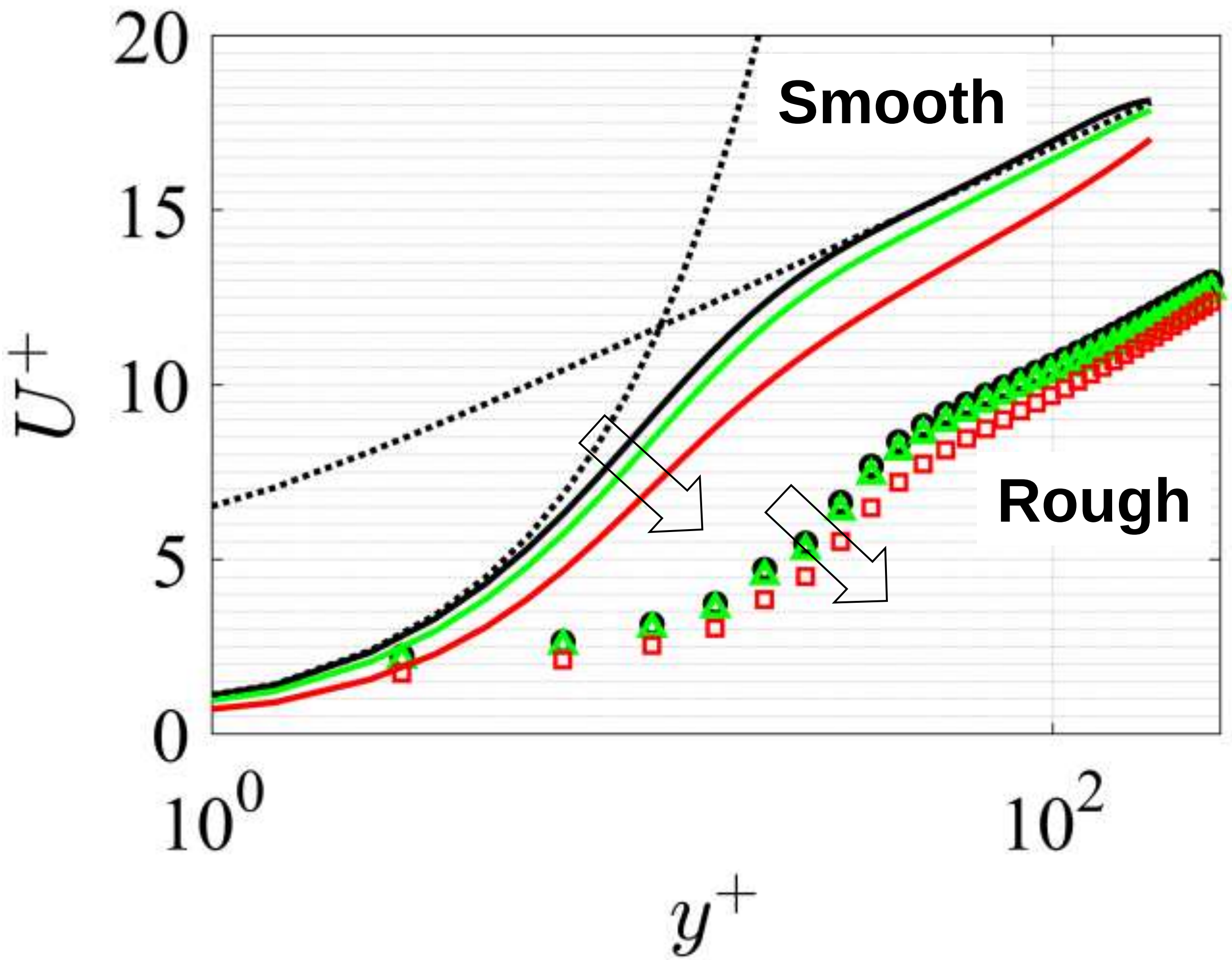
ROUGH CASE



	Smooth $M=0.1$	Smooth $M=0.5$	Rough $M=0.1$	Rough $M=0.5$
Total R_D	↓11%	↓37%	↓7%	↓26%
Friction $R_{D,F}$	↓11%	↓37%	↓9%	↓34%
Pressure $R_{D,P}$	-	-	↓5%	↓19%

How does friction drag decrease?

Bulk mean streamwise velocity



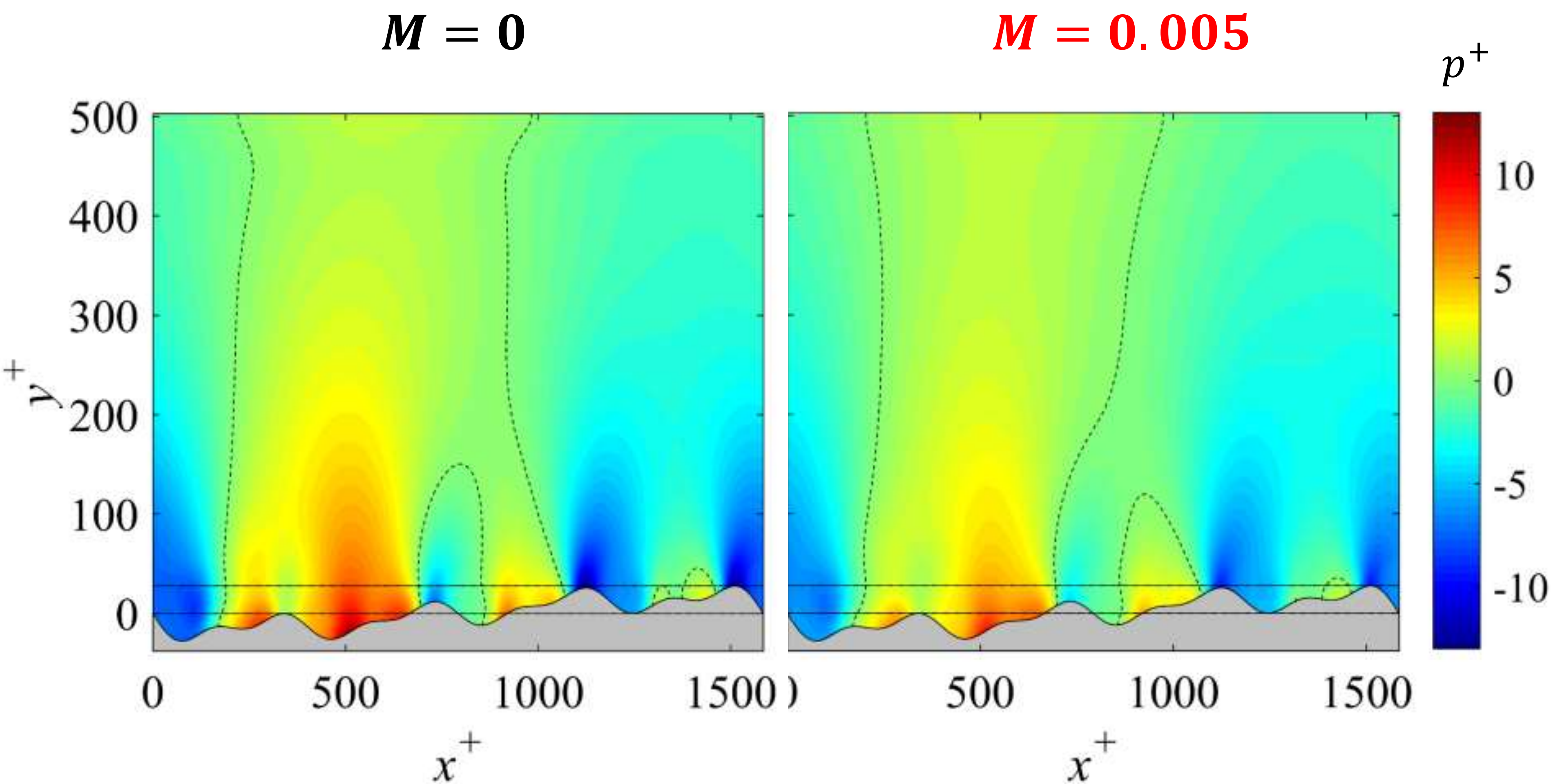
Black: $M = 0$
Green: $M = 0.001$
Red: $M = 0.005$

Normalization based on $M = 0$

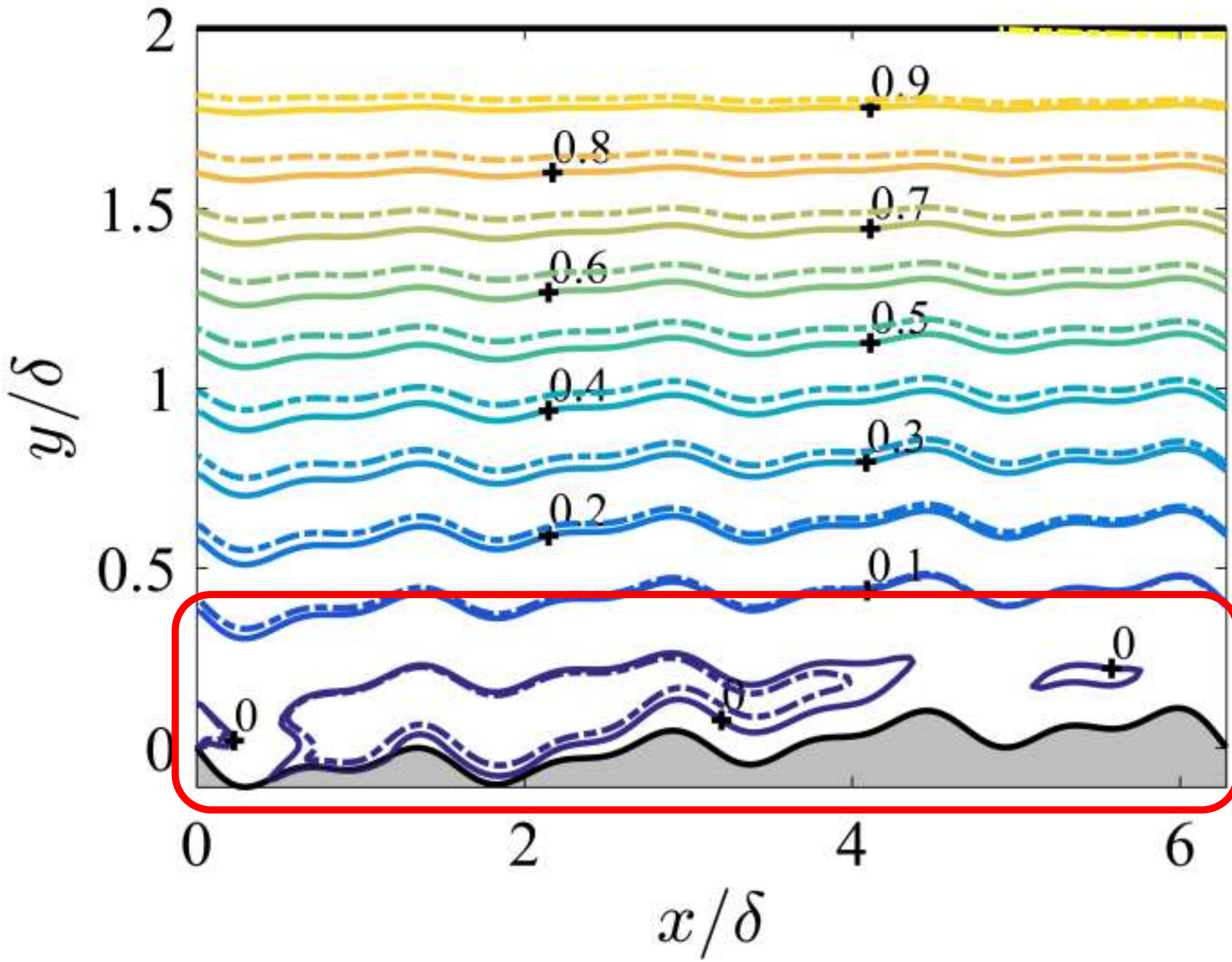
How does pressure drag decrease?

Pressure contours

averaged in the spanwise and time
dashed lines: zero contour



Stream function

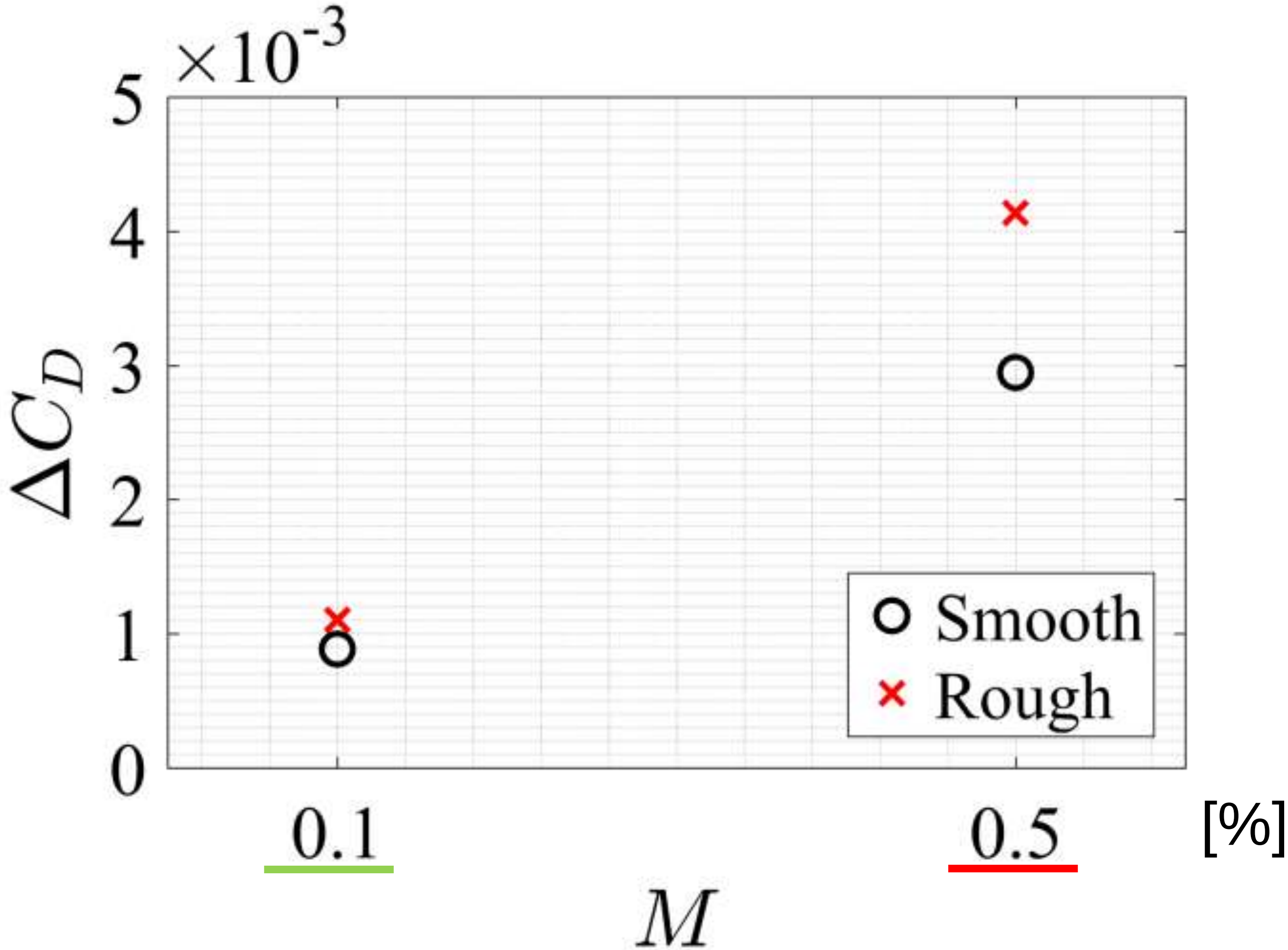


Solid lines:
$M = 0$
Dashed lines:
$M = 0.005$

Uniform Blowing

In practical applications

Drag reduction amount, $\Delta C_D = C_{D,M=0} - C_{D,M=0.1,0.5}$



Concluding remarks

DNS of turbulent channel flow over a rough wall with UB

- **UB is effective over rough walls**
  - Lower drag reduction rate (7%, $\mathbf{26\%}$ / 11%, $\mathbf{37\%}$ in rough / smooth case, with $M = 0.001, 0.005$)
- **Drag reduction mechanism**
  - Friction drag by wall-normal convection (=conventional)
  - Pressure drag by prevention of stagnant flow
- **Outlook toward practical applications**
  - More saving opportunity over rough walls

Future plans

- **Another drag reduction technique on rough surface**
  - Spanwise oscillation (ongoing)
- **Assessment of net energy? (should be external flow)**
- **Calculation at higher Reynolds number?**
- **Other types of rough surfaces (e.g., 3D structure)?**

Uniform blowing (UB)

(Sumitani & Kasagi, *AIAA J.*, 1995
Kametani & Fukagata, *J. Fluid Mech.*, 2011)

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V_w: Blowing velocity

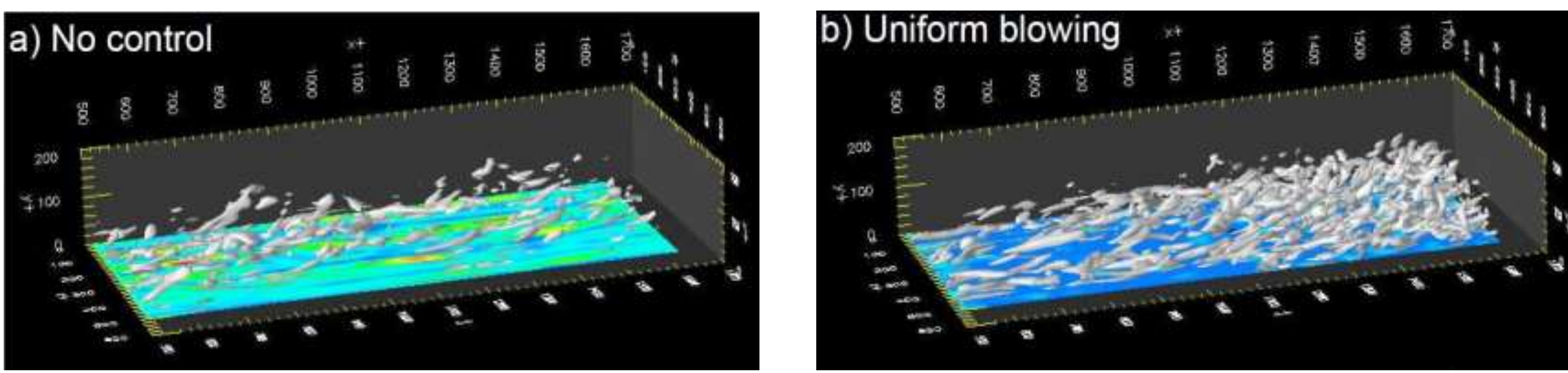
Viscous Contribution (= laminar drag, **const.**)

Turbulent contribution ↑

Convective (=UB/US) contribution ↓ (Fukagata et al., *Phys. Fluids*, 2002)

Blowing side

- **Excellent performance** (about **45%** by $V_w = 0.5\%U_\infty$)
- **Unknown over a rough wall**



White: vortex core, Colors: wall shear stress

Governing equations

(S. Kang & H. Choi, *Phys. Fluids*, 2000)

Incompressible Continuity and Navier-Stokes in ξ_i coordinate

$$
\begin{cases}
\dfrac{\partial u_i}{\partial \xi_i} = -S \\[2ex]
\dfrac{\partial u_i}{\partial t} = -\dfrac{\partial (u_i u_j)}{\partial \xi_j} - \dfrac{\partial p}{\partial \xi_i} + \dfrac{1}{\mathrm{Re}_b} \dfrac{\partial^2 u_i}{\partial \xi_j \xi_j} - \dfrac{dP}{d\xi_1}\delta_{i1} + S_i
\end{cases}
$$

where

$$
S_i = -\varphi_t \frac{\partial u_i}{\partial \xi_2} - \phi_j \frac{\partial (u_i u_j)}{\partial \xi_2} - \phi_j \frac{dp}{d\xi_2}\delta_{ij} + \frac{1}{Re}\left(2\phi_j \frac{\partial^2 u_i}{\partial \xi_j \xi_2} + \phi_j \phi_j \frac{\partial^2 u_i}{\partial \xi_2^2} + \frac{1}{2}\frac{\partial (\phi_j \phi_j)}{\partial \xi_2}\frac{\partial u_i}{\partial \xi_2}\right)
$$

$$
S = \phi_j \frac{\partial u_i}{\partial \xi_2} \qquad \phi_j = \varphi_j - \delta_{j2} \qquad \varphi_j = \begin{cases} -\dfrac{1}{1+\eta}\left(\xi_2 \dfrac{\partial \eta}{\partial \xi_i} + \dfrac{\partial \eta_0}{\partial \xi_i}\right), & \text{for j} = 1,3 \\[2ex] \dfrac{1}{1+\eta}, & \text{for j} = 2 \end{cases}
$$

Discretization methods

- **Energy-conservative second-order finite difference schemes (In space)**

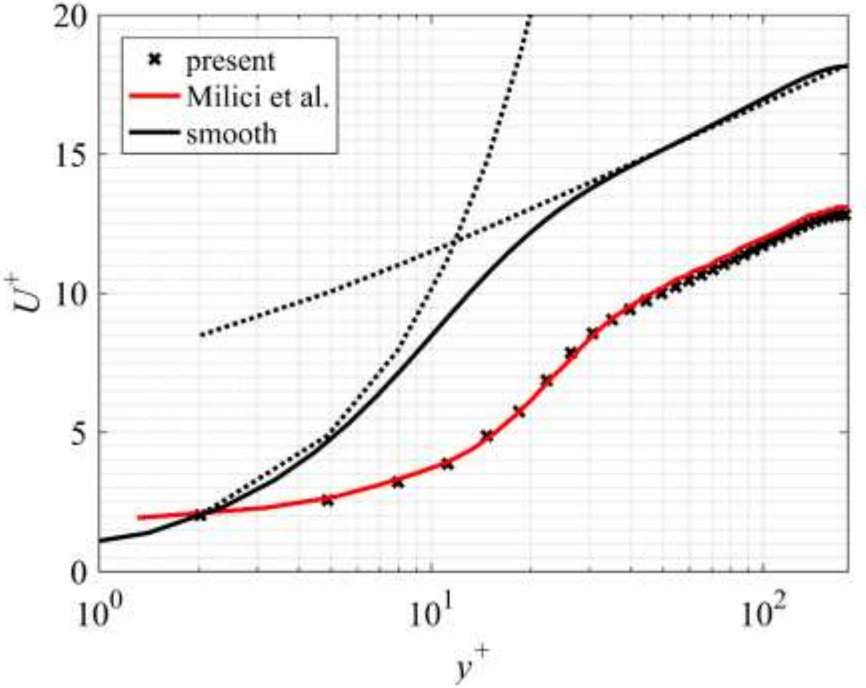
- **Low-storage third-order Runge-Kutta / Crank-Nicolson scheme (In time)**

  + SMAC method for pressure correction

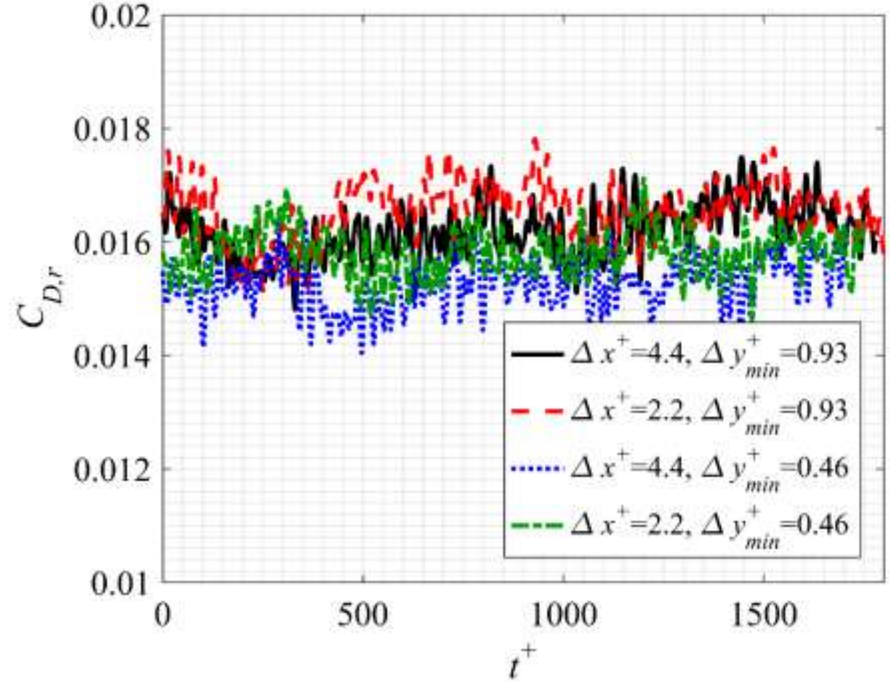
Discretized in the staggered grid system

Validation & Verification

(B. Milici et al., *J. Fluid Mech.*, 2014)



Bulk mean streamwise velocity



Time trace of instantaneous $C_{D,r}$

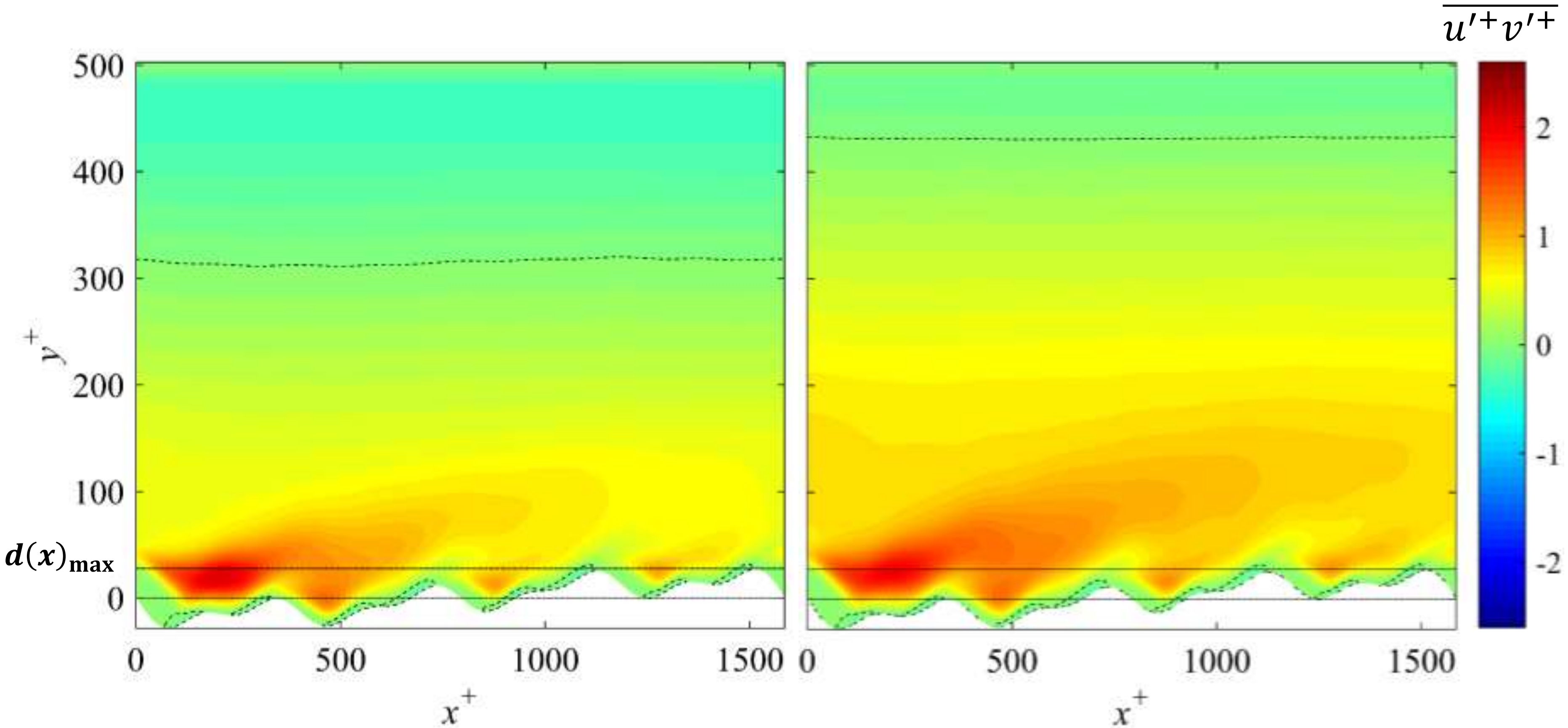
Less than 2% of difference with most resolved one

How does friction drag decreases?

Reynolds shear stress contour

*averaged in the spanwise and time
dashed lines: zero contour

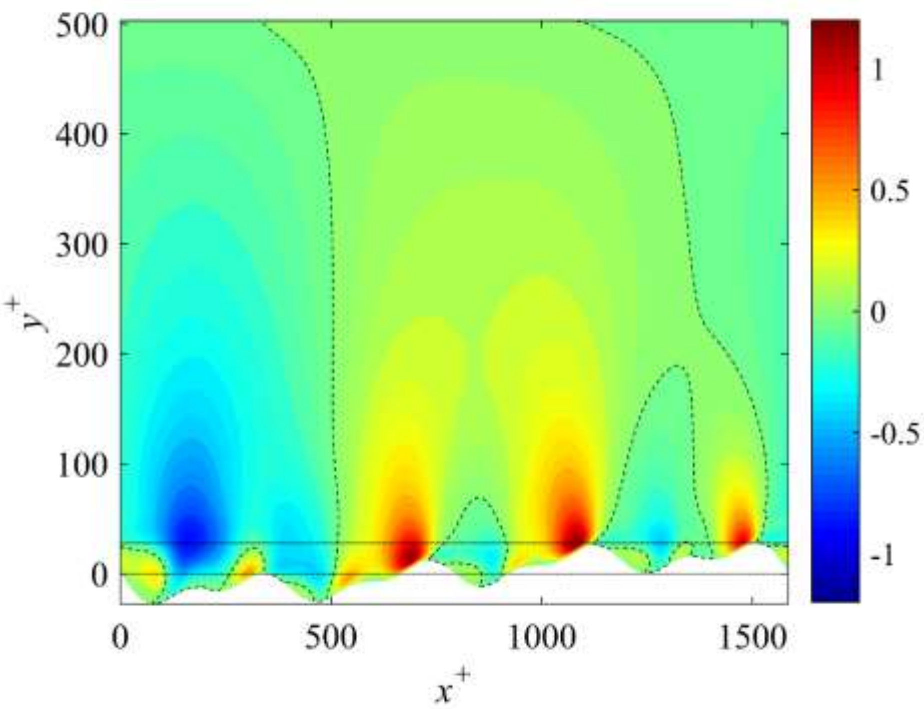
$M = 0$ $M = 0.005$



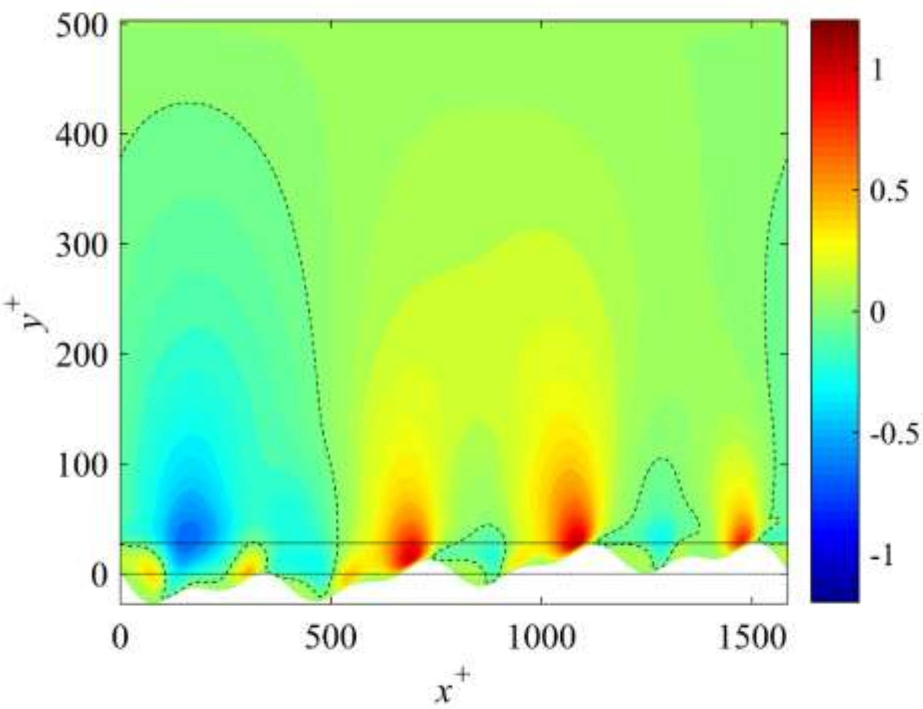
$\overline{v}$ distribution (2D contour)

Based on u_τ in w/o control case

No control case



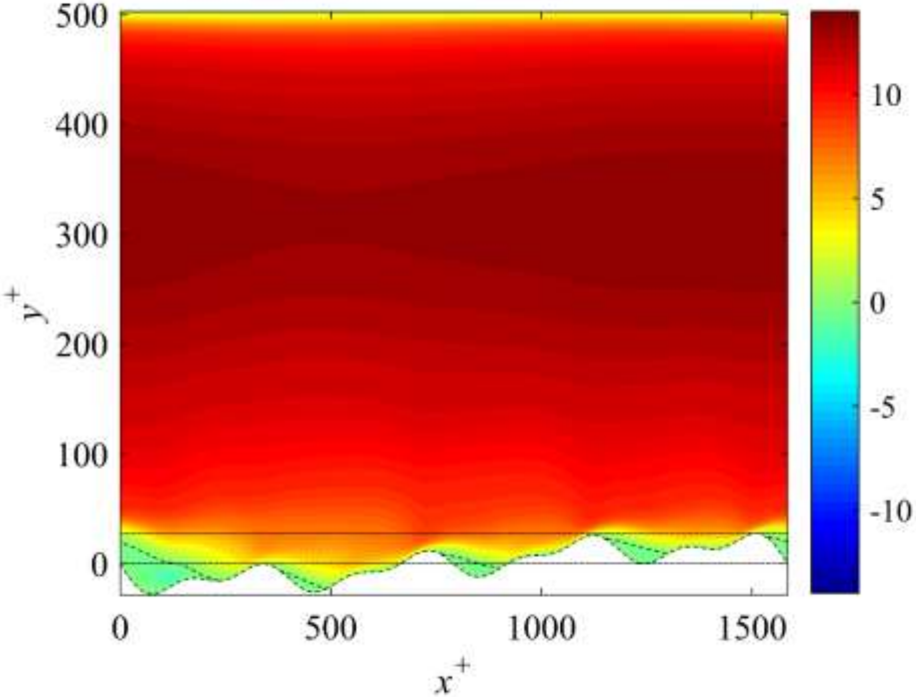
UB 0.5% case



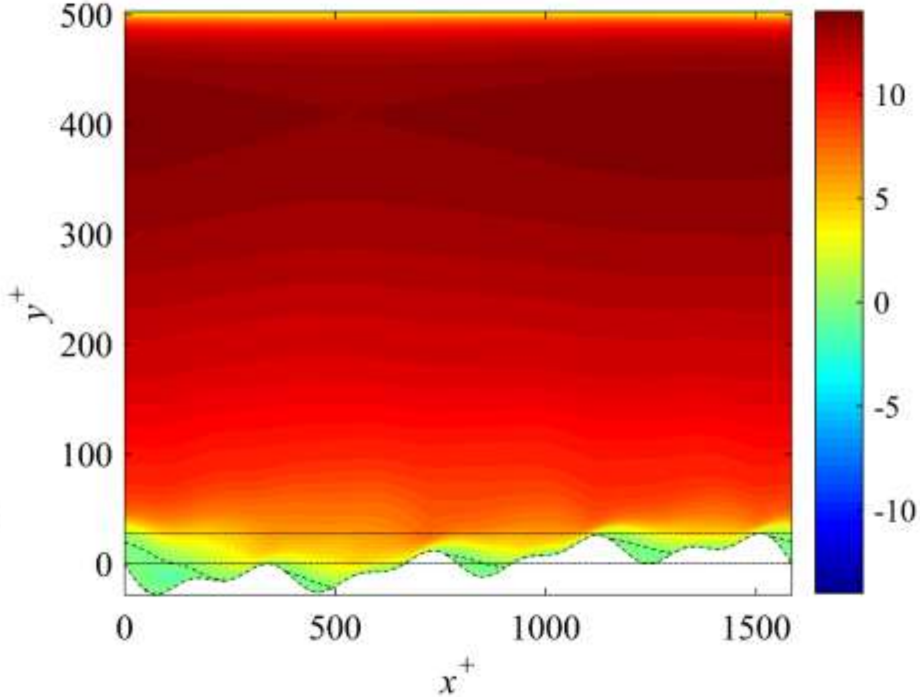
$\overline{u}$ distribution (2D contour)

Based on u_τ in w/o control case

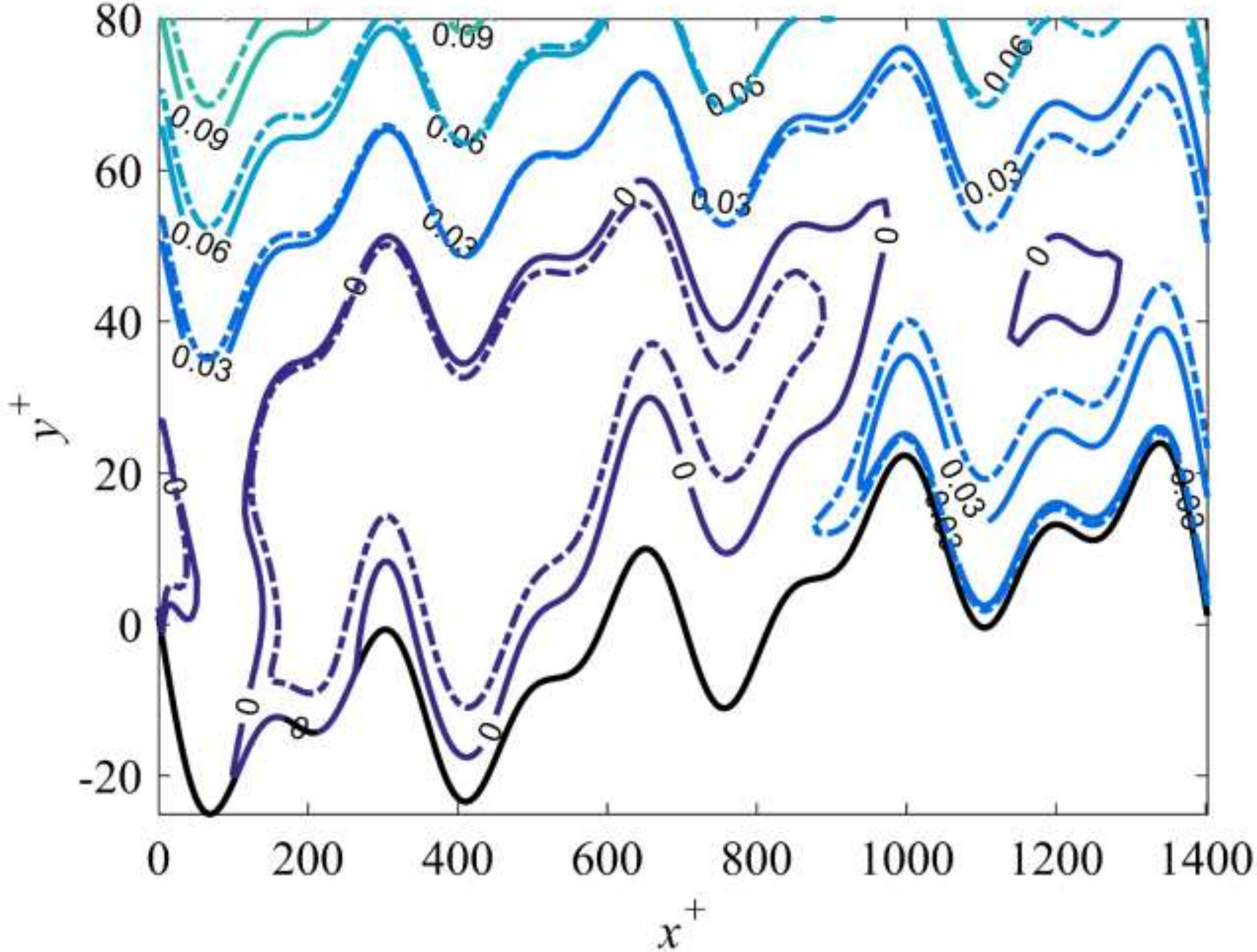
No control case



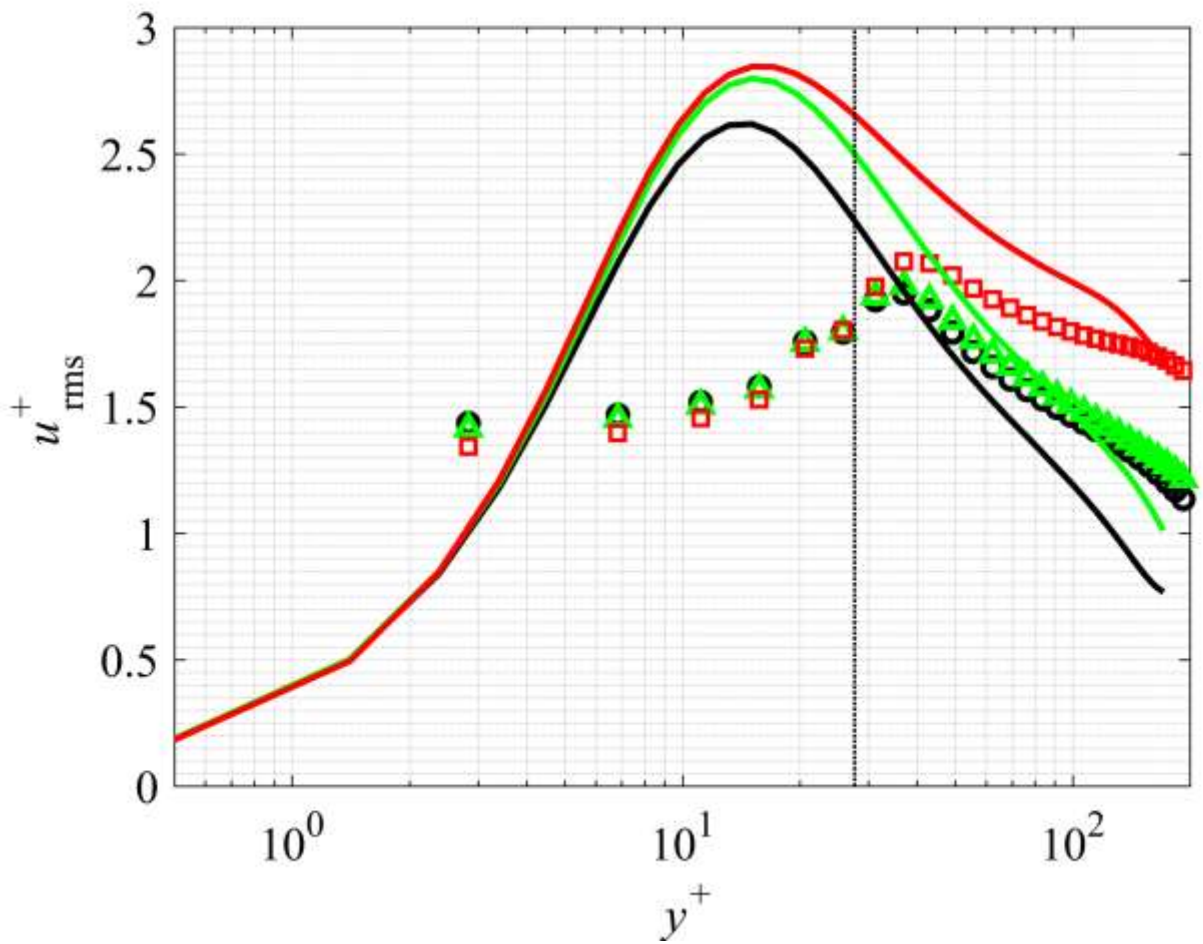
UB 0.5% case



Stream function (detailed)



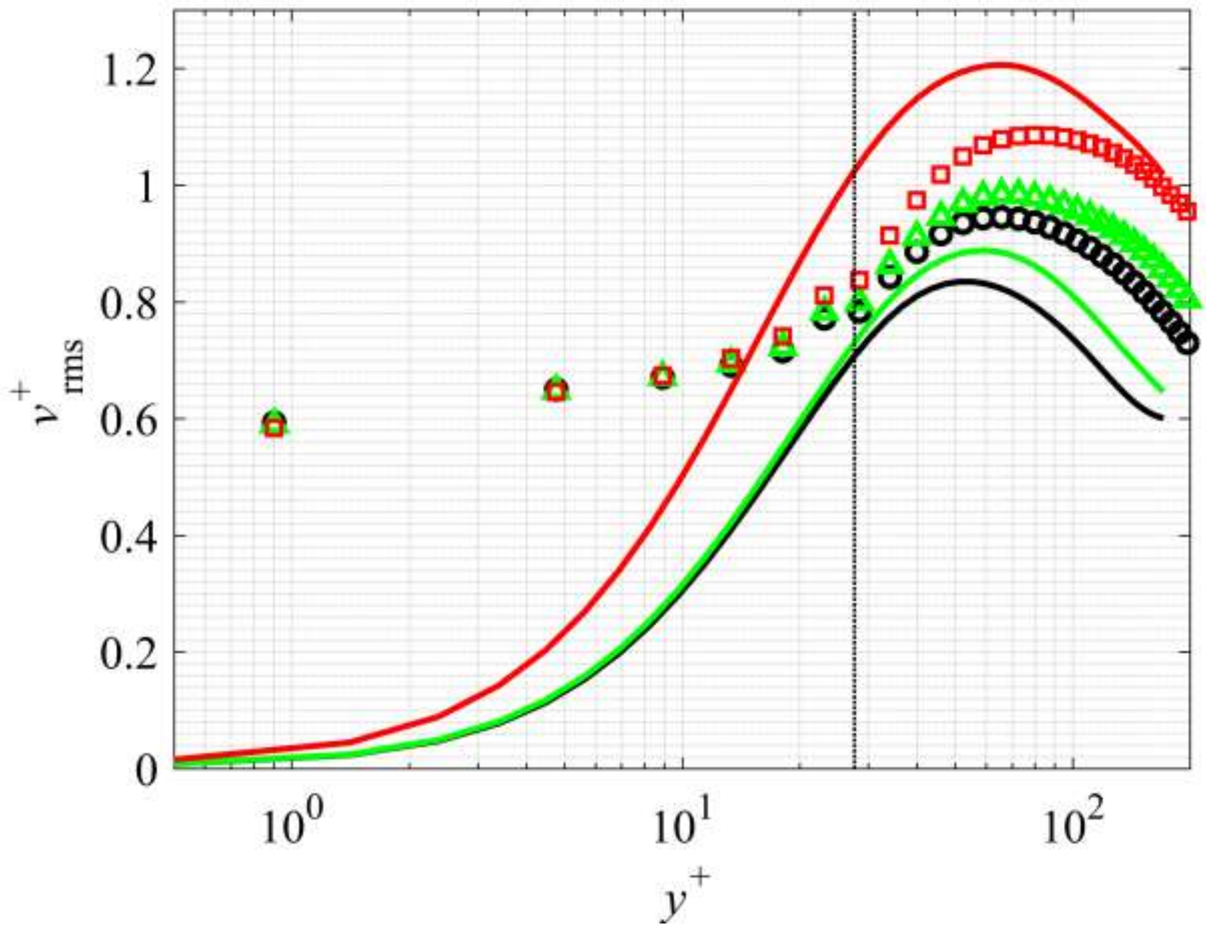
u_{rms} distribution



Black: w/o control
Green: UB 0.1%
Red: UB 0.5%

Normalized by u_τ
in w/o control case

v_{rms} distribution



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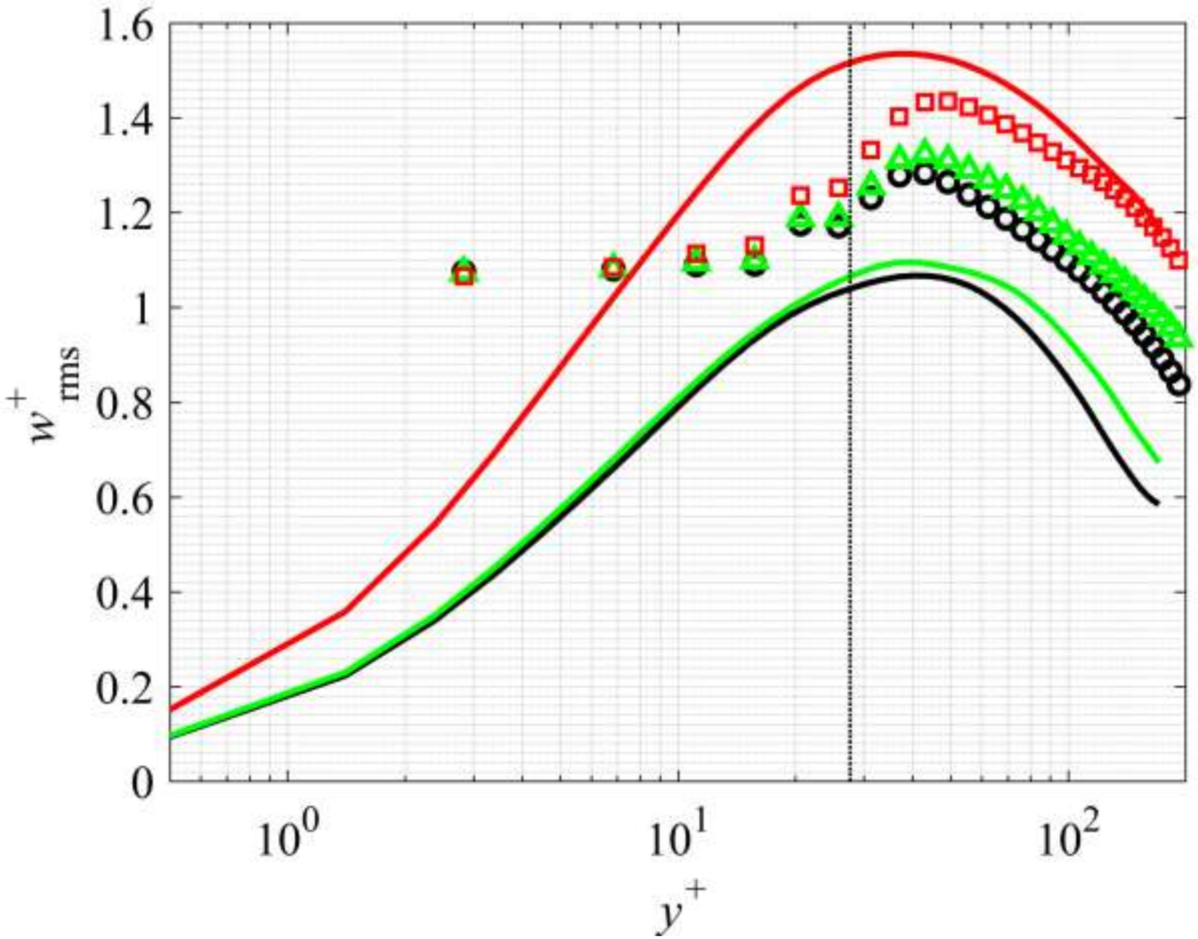
Normalized by u_τ in w/o control case

w_{rms} distribution



Black: w/o control
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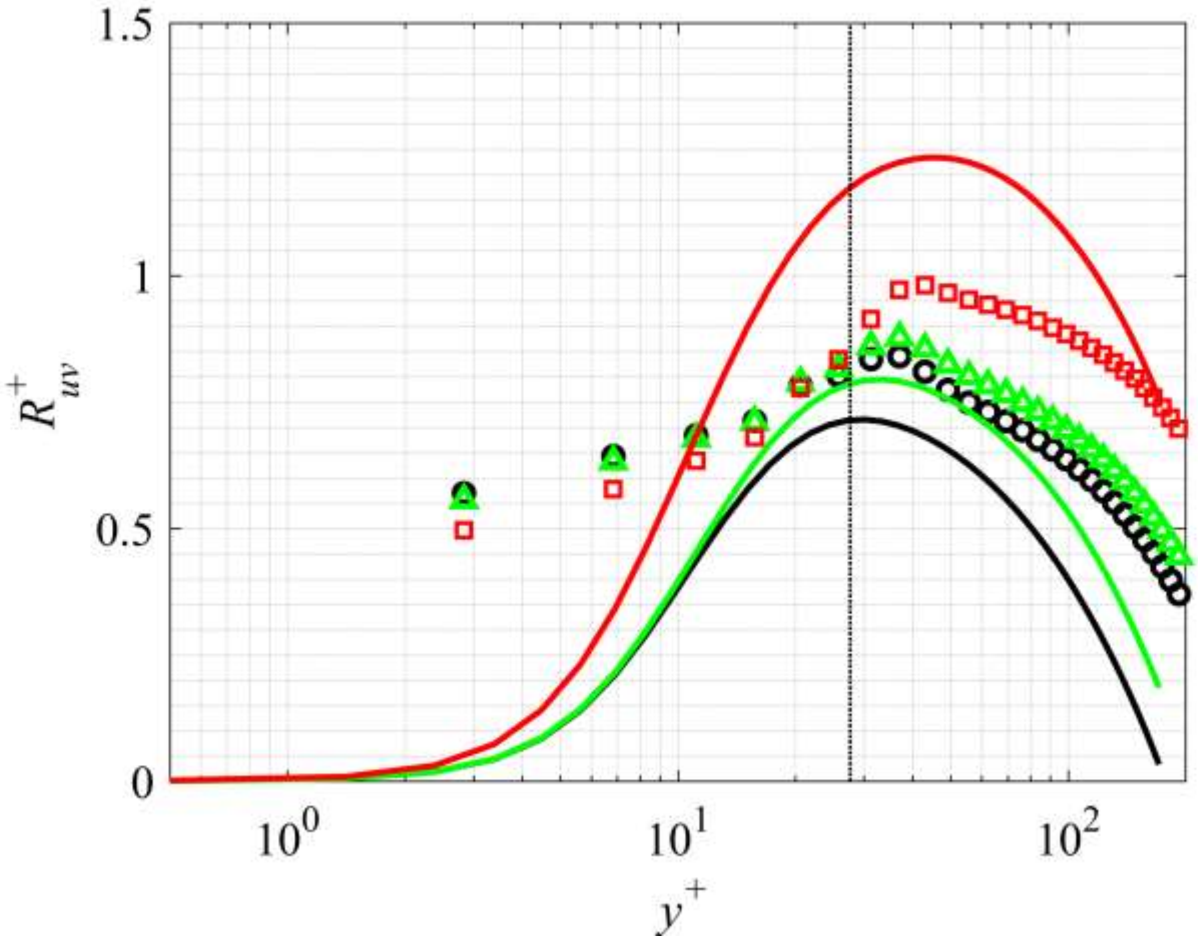
Red: UB 0.5%

Normalized by u_τ in w/o control case

$\overline{u'^+v'^+}$ distribution



Black: w/o control
Green: UB 0.1%
Red: UB 0.5%

Normalized by u_τ
in w/o control case

- **Effective slope = about 0.2**
- **k_rms**
- **Sand grain roughness**
- **3D?**
- **How to calculate skin-friction drag**
- **The history of UB**
- **Pressure component legend (purple) of smooth case should be removed**
- **More time for drag reduction rate slide**