NASA Advanced Modeling and Simulation Seminar

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On a new length scale for the buffer zone of turbulent flows

Dr. Svetlana Poroseva

Department of Mechanical Engineering

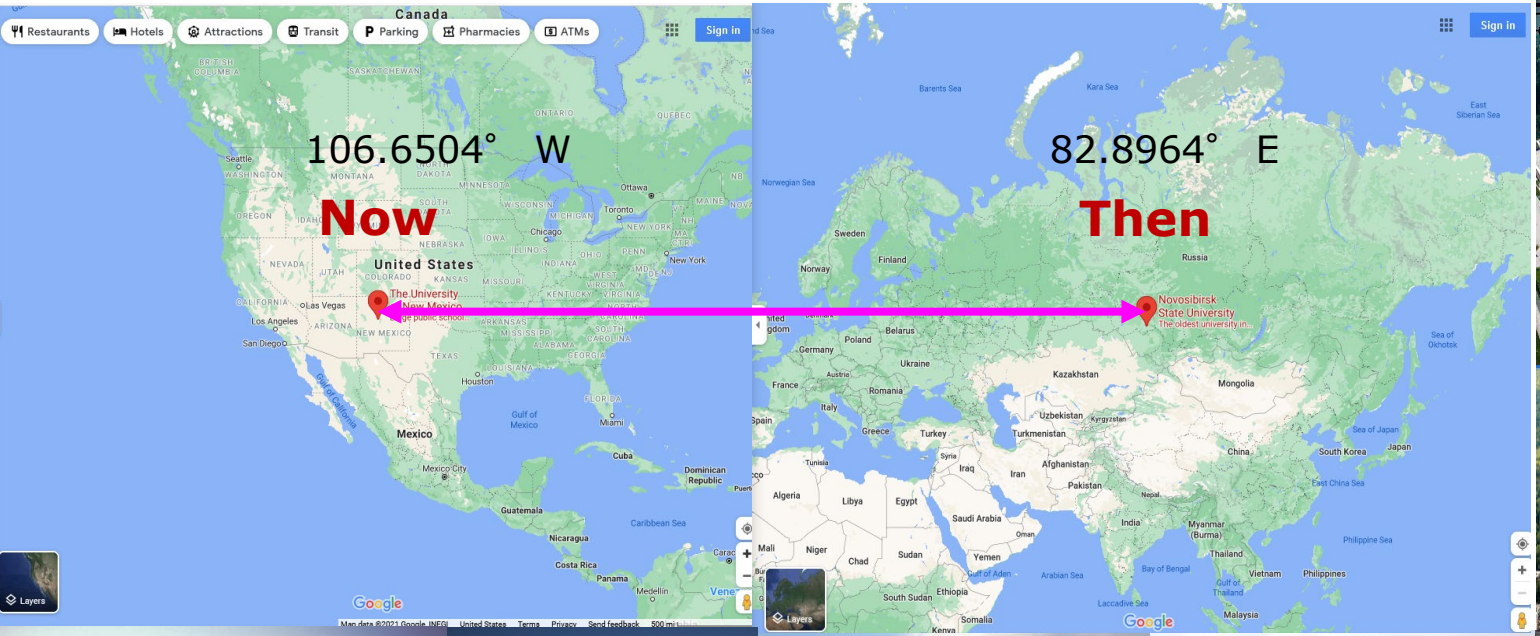
University of New Mexico

Scales in Life

Alma mater: **Novosibirsk State University, Novosibirsk, Russia**

Ph.D. **Fluid & Plasma Mechanics**
M.S. **Physics**, Focus area: **Aerophysics & Gas Dynamics**

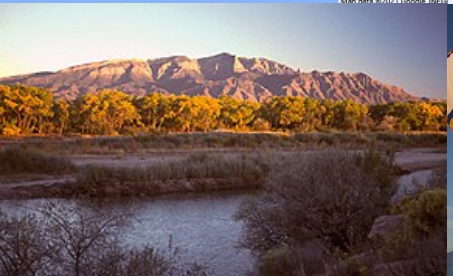
Current: **University of New Mexico, Albuquerque, U.S.A.**
associate professor, Department of Mechanical Engineering, Department of Mathematics and Statistics , Center for Advanced Research Computing





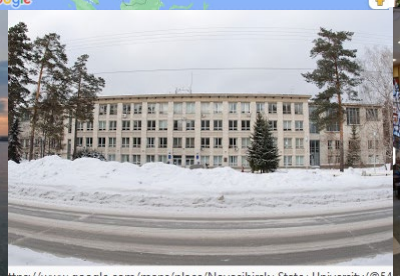














Motivation (initial)

Validation of the truncated Gram-Charlier series expansions (GCSE) as a suitable model for the turbulent flow PDF. This PDF model leads to a turbulent diffusion model in a fourth-order statistical closure (FORANS):

$$\langle u_i^5 \rangle = 10 \langle u_i^3 \rangle \cdot \langle u_i^2 \rangle$$

$$\langle u_i^4 u_j \rangle = 6 \langle u_i^2 u_j \rangle \cdot \langle u_i^2 \rangle + 4 \langle u_i u_j \rangle \cdot \langle u_i^3 \rangle$$

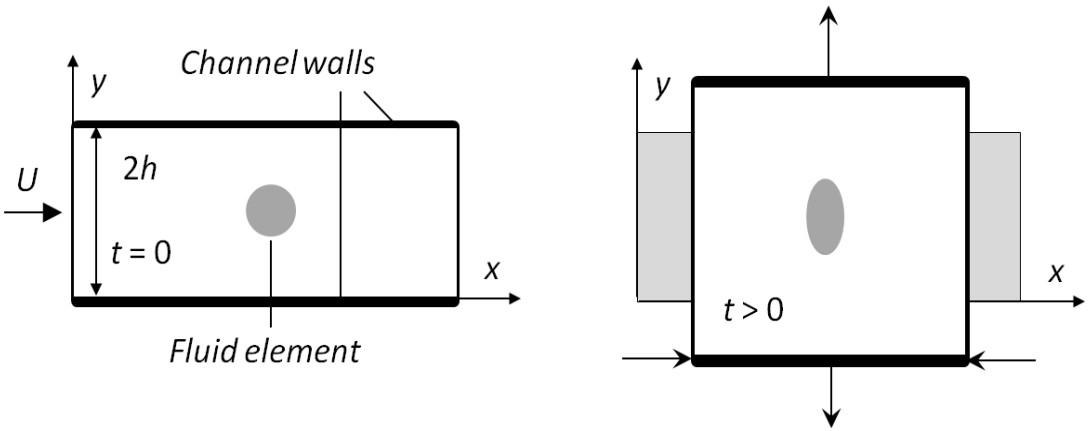
$$\langle u_i^3 u_j^2 \rangle = 6 \langle u_i u_j \rangle \cdot \langle u_i^2 u_j \rangle + \langle u_i^3 \rangle \cdot \langle u_j^2 \rangle + 3 \langle u_i u_j^2 \rangle \cdot \langle u_i^2 \rangle$$

Cartesian coordinates

Int. J. Heat Fluid Flow, 2021, 89 (strained channel)
Int. J. Heat Fluid Flow, 2015, 56 (zero pressure gradient boundary layer over a flat plate)
AIAA2014-2207 (planar wall-bounded flows)
NASA grant NNX12AJ61A Final Report, 2016 (planar wall-bounded flows)
High Temperature, 1997, 35(3) and 1995, 33(5) (rotating cylindrical pipe)
Ph.D. Thesis, High-order turbulence closure in a fully-developed flow in a cylindrical pipe,1996.

Strained channel case

DNS data: Jeyapaul, Coleman & Rumsey, Int. J. Heat Fluid Flow, 2015, 54.

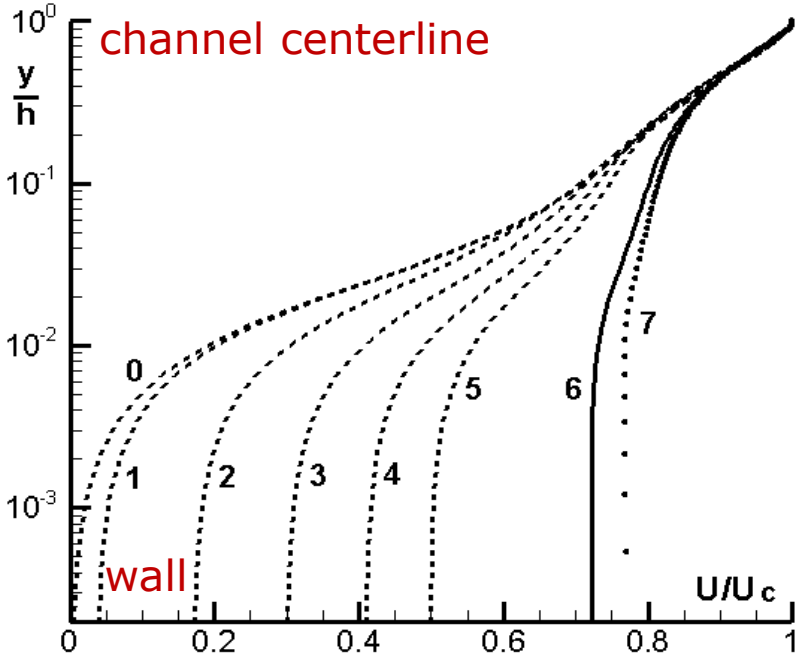


This flow reproduces features of the adverse pressure gradient turbulent boundary layer including the flow separation.

Time

0	1	2	3	4	5	6	7
0	0.02	0.1	0.191	0.285	0.365	0.675	0.772

Before separation



$Re_{\tau 0} = 392$

Validation of the GCSE-based models

Poroseva & Murman, Int. J. Heat Fluid Flow, 2021, 89

$$\vec{x} = (x, y, z), \vec{u} = (u, v, w), \vec{U} = (U, V, 0)$$

u, v – velocity fluctuations in streamwise and normal-to-wall directions

Solid lines: models

DNS data

$$\langle u^5 \rangle = 10 \langle u^2 \rangle \cdot \langle u^3 \rangle$$

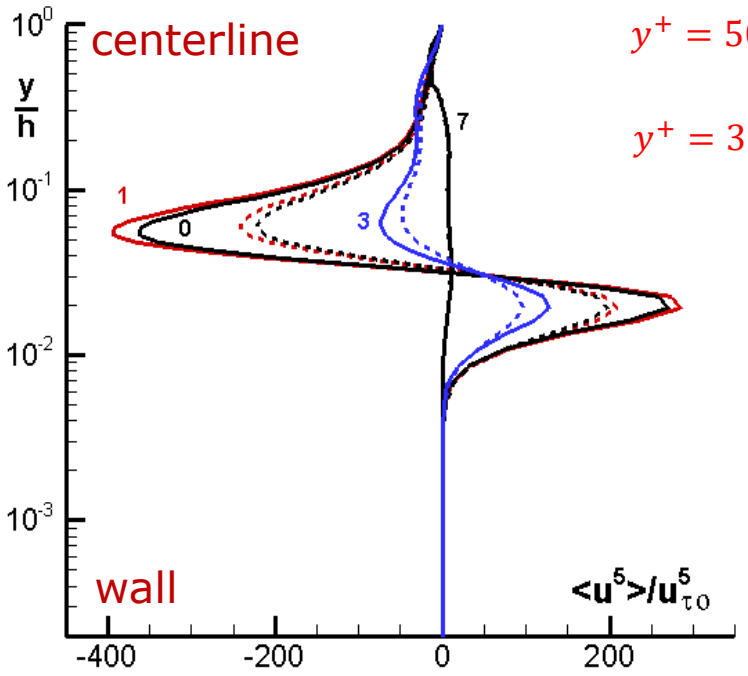
$$\langle u^4 v \rangle = 6 \langle u^2 \rangle \cdot \langle u^2 v \rangle + 4 \langle u^3 \rangle \cdot \langle uv \rangle$$

• • •

$$\langle uv^4 \rangle = 6 \langle v^2 \rangle \cdot \langle uv^2 \rangle + 4 \langle v^3 \rangle \cdot \langle uv \rangle$$

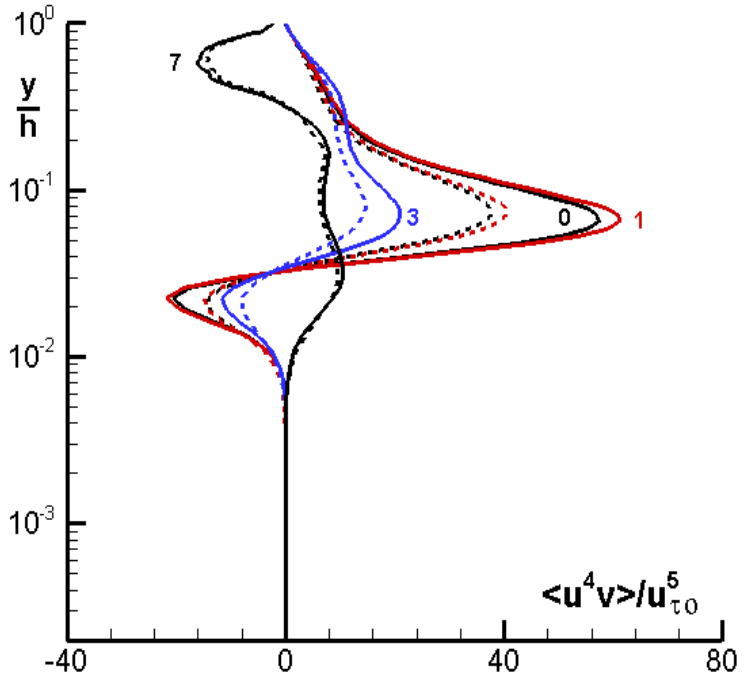
$$\langle v^5 \rangle = 10 \langle v^2 \rangle \cdot \langle v^3 \rangle$$

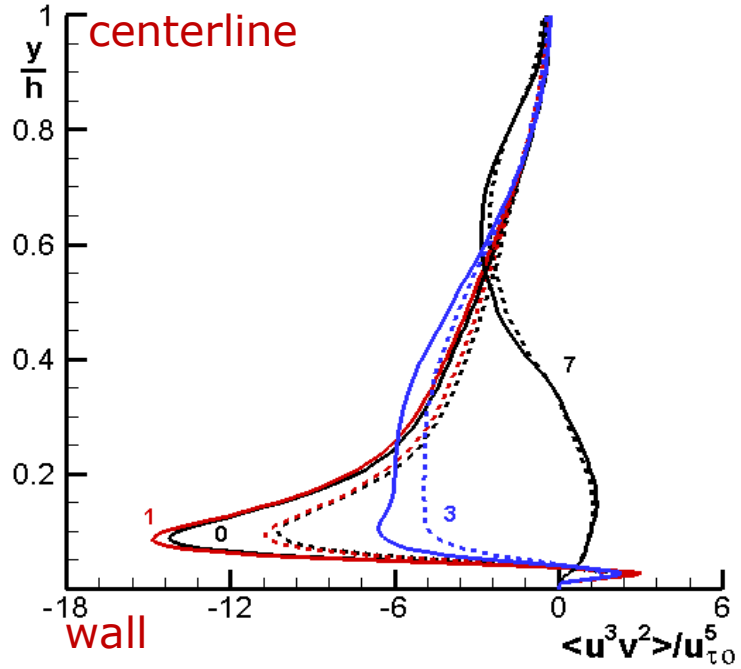
Dashed lines: DNS data $\langle u^5 \rangle, \langle u^4 v \rangle, \ldots, \langle uv^4 \rangle, \langle v^5 \rangle$

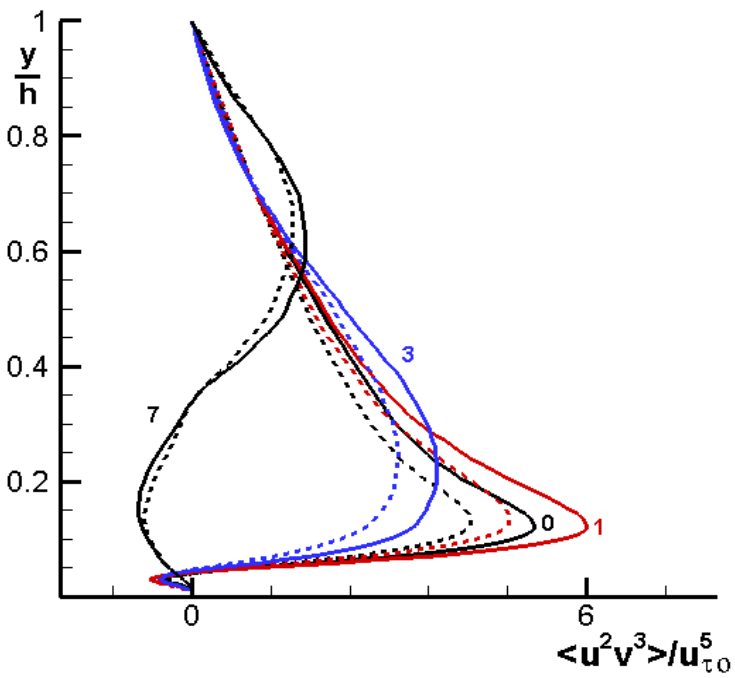


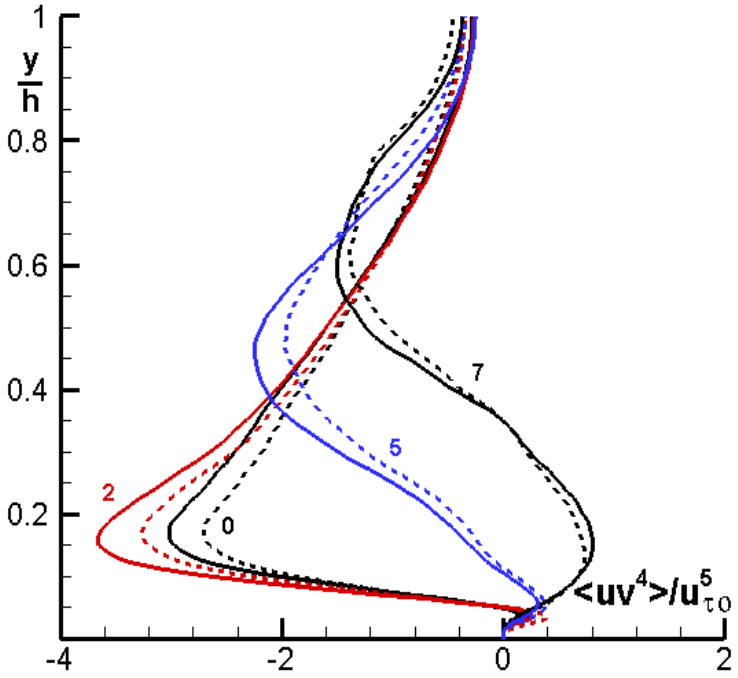
$y^+ = 50 \sim \frac{y}{h} = 0.13$

$y^+ = 3.5 \sim \frac{y}{h} = 0.01$



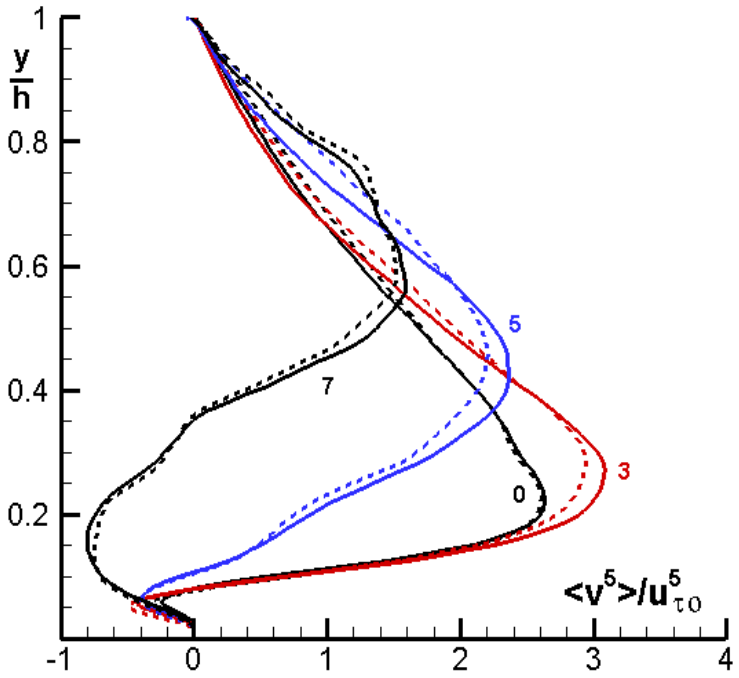






centerline

wall



Observations

- The GCSE-based models are in a good agreement with DNS profiles.
- The agreement improves with time and is excellent when the flow separates.
- Locations of max/min values and zeros are all well reproduced.
- There is a discrepancy sensitive to *u* (magnitude, power), *y*, and *t*.

  This was also observed in Poroseva et al., Int. J. Heat Fluid Flow, 2015, 56.

Discrepancy Analysis

$$\Delta = \frac{\left|\langle u^m v^n \rangle^{(M)} - \langle u^m v^n \rangle\right|}{\left|\langle u^m v^n \rangle\right|_\infty}$$

Max Δ for different moments

Time

	$\langle u^5 \rangle$	$\langle u^4 v \rangle$	$\langle u^3 v^2 \rangle$	$\langle u^2 v^3 \rangle$	$\langle u v^4 \rangle$	$\langle v^5 \rangle$
0	0.68	0.57	0.43	0.25	0.12	0.06
1	0.67	0.56	0.42	0.25	0.12	0.06
2	0.62	0.54	0.43	0.27	0.14	0.06
3	0.32	0.49	0.41	0.24	0.17	0.06
5	0.26	0.24	0.18	0.19	0.18	0.11
6	0.12	0.17	0.14	0.16	0.14	0.12
7	0.13	0.17	0.15	0.17	0.15	0.11

separation

- The high the power of *u*, the larger is max Δ.
- The higher the power of *v*, the less is max Δ.
- With time, max Δ reduces for the *u*-dominated velocity moments and so are the moments themselves.

t0

t7

centerline

$< u^5 >$

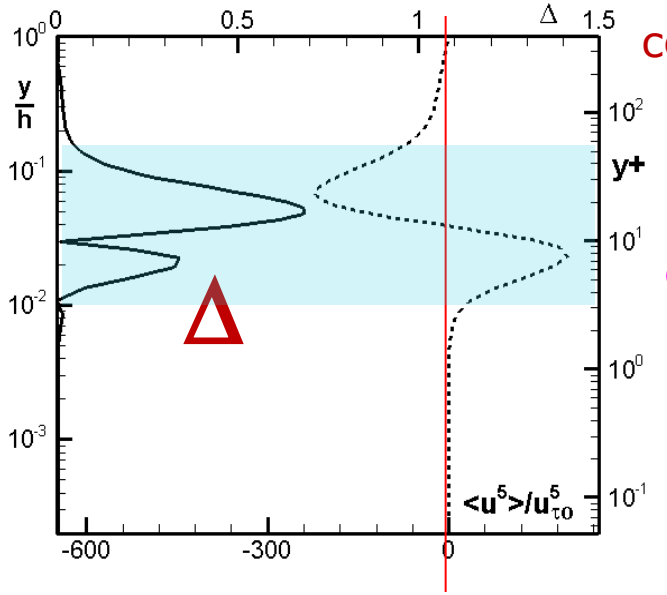
Around extremes

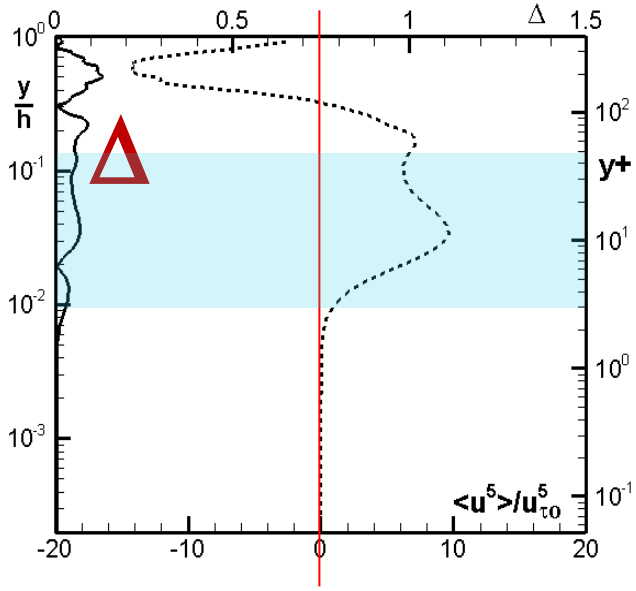
wall

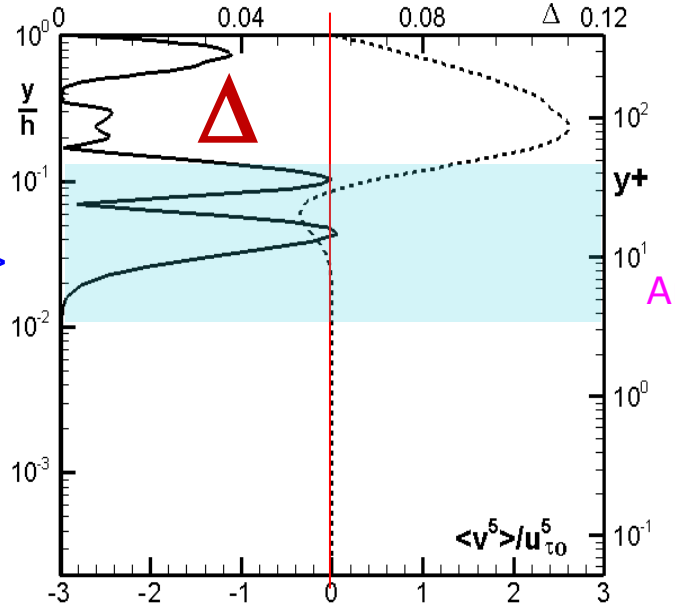
$< v^5 >$

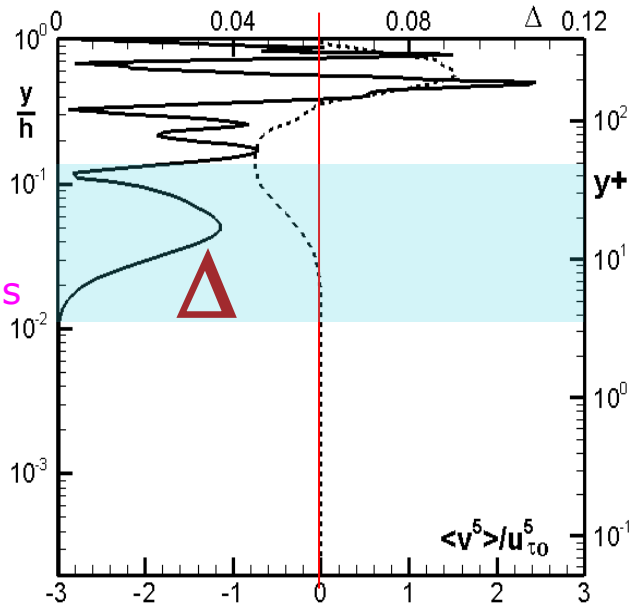
Around zeros

wall









Non-dimensional locations of max Δ and max $|\langle u^5 \rangle|$

Time	0	1	2	3	5	6	7
$y/h(\max\Delta)$	0.05	0.05	0.05	0.02	0.02	0.6	0.5
$y/h(\max\langle u^5 \rangle)$	0.06	0.06	0.02	0.02	0.02	0.55	0.64

Max Δ follows max $|\langle u^5 \rangle|$ with time

The role of production by shear

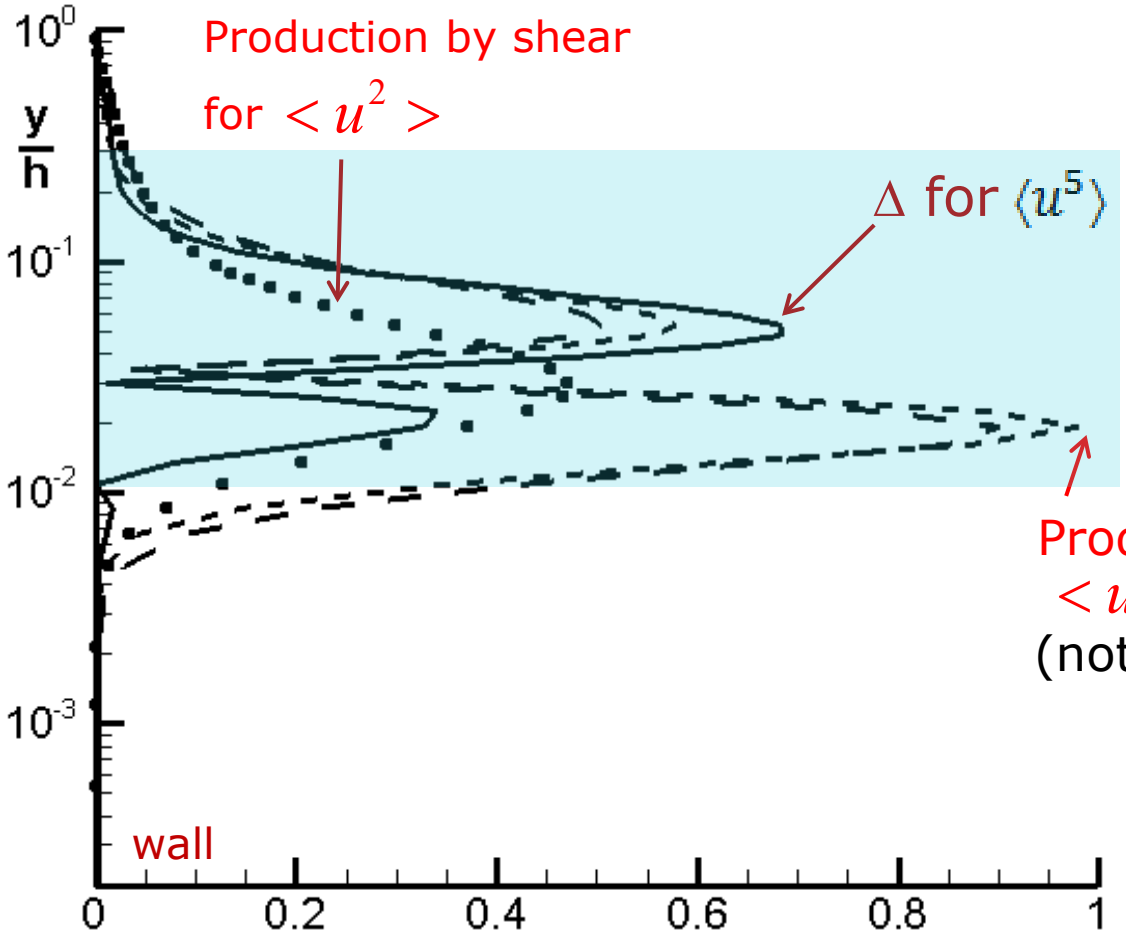
- The production by shear $(-m < u^{m-1}\, v^{n+1} > \partial U/\partial y)$ dominates budgets of $< u^m v^n >$ with $m > n$.
- There is no contribution to $\langle \boldsymbol{v^5} \rangle$ from the production by shear at any t.
- The production by shear is the largest in the flow buffer zone and equal to zero at the channel centerline in the unstrained channel. Its contribution with time reduces and is negligible near a wall.

Dynamics is similar to that of Δ in $< u^m v^n >$ with $m > n$.

The discrepancy between the model and DNS profiles observed in the flow buffer zone can be linked to the production by shear.

Discrepancy Analysis for $\langle u^5 \rangle$ at t0

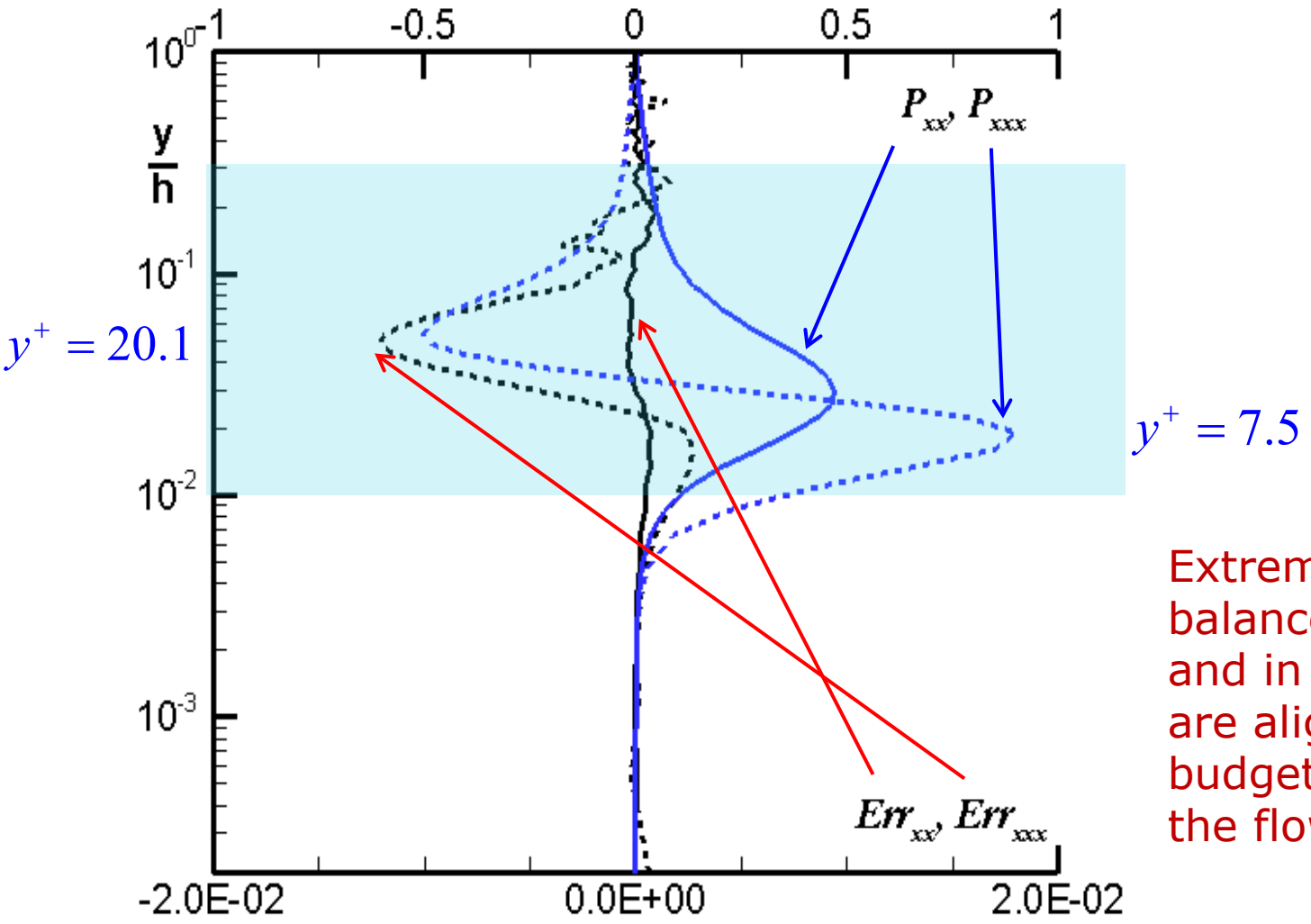
$$\langle u^5 \rangle = 10 \langle u^2 \rangle \cdot \langle u^3 \rangle$$



Productions by shear for $< u^5 >, < u^3 >$
(not to scale)

Δ can be linked to the production by shear for $< u^3 >, < u^5 >$.

Balance errors in DNS budgets of $\langle u^2 \rangle$ and $\langle u^3 \rangle$



Extremes in the balance error profile and in the production are aligned in the budget for $\langle u^3 \rangle$ in the flow buffer zone.

In the flow buffer zone…

Extremes in the profiles of the following statistics are aligned:

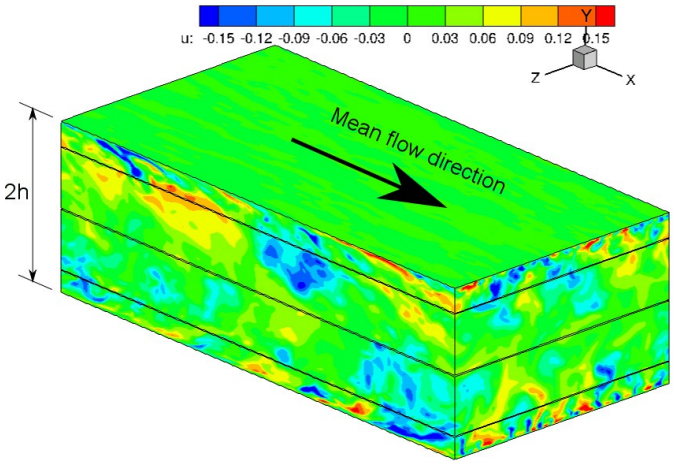
- discrepancy between the GCSE-based models and DNS data;
- odd velocity moments;
- production terms in the budgets of odd velocity moments;
- balance errors (information for the third-order velocity moments).

Statistical errors in DNS data cannot alone explain the balance errors in the flow buffer zone.

Poroseva, Jeyapaul, Murman, Colmenares, "The Effect of the DNS Data Averaging Time on the Accuracy of RANS-DNS Simulations," AIAA2016-3940.

Unstrained channel DNS

Test case: channel flow Re_τ = 392

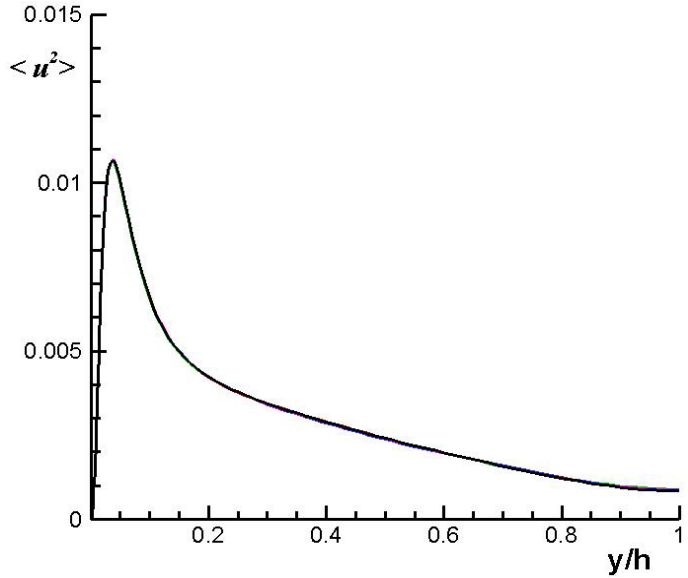


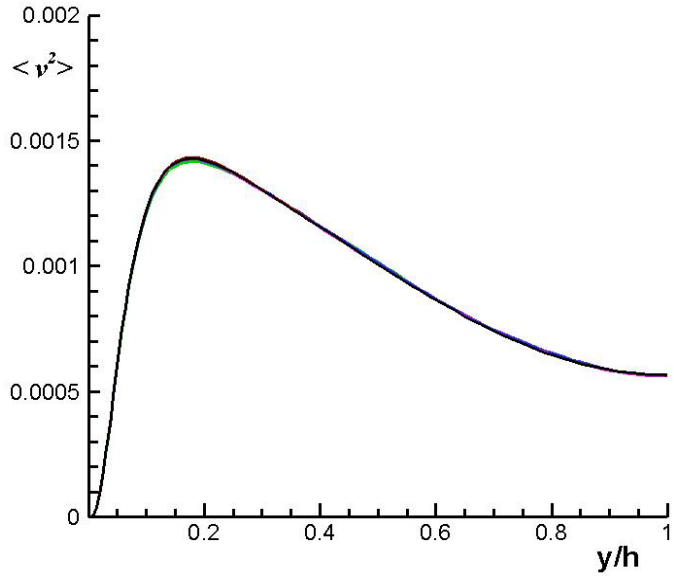
N	t1	t2	t3	t4	t5	t6	t7
realizations	25	50	100	159	200	500	1000
t steps	4.72 X10^6	5.01 X10^6	5.51 X10^6	6.1 X10^6	6.51 X10^6	9.51 X10^6	14.69 X10^6

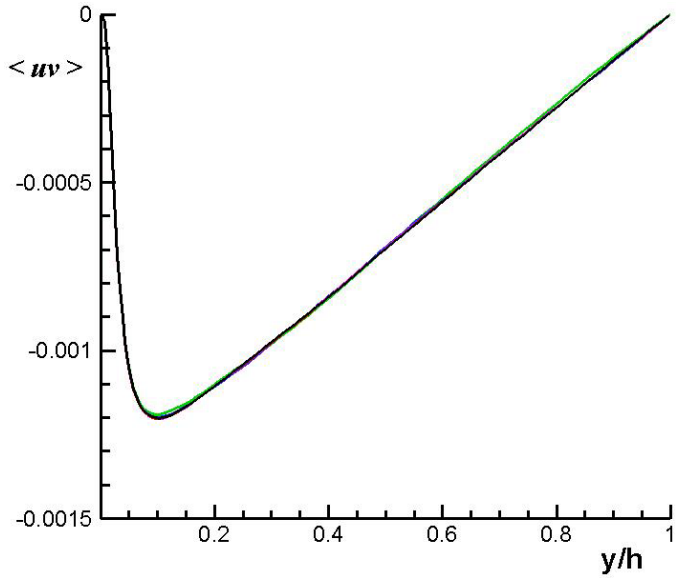
Jeyapaul et al., IJHFF, 2015

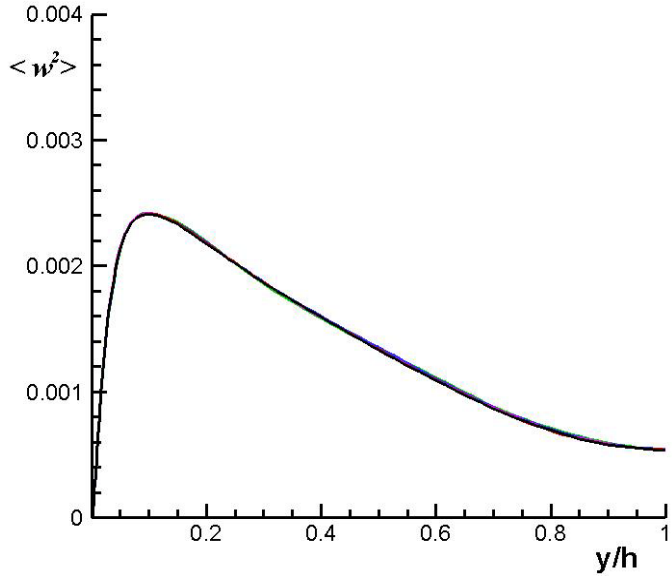
DNS data convergence





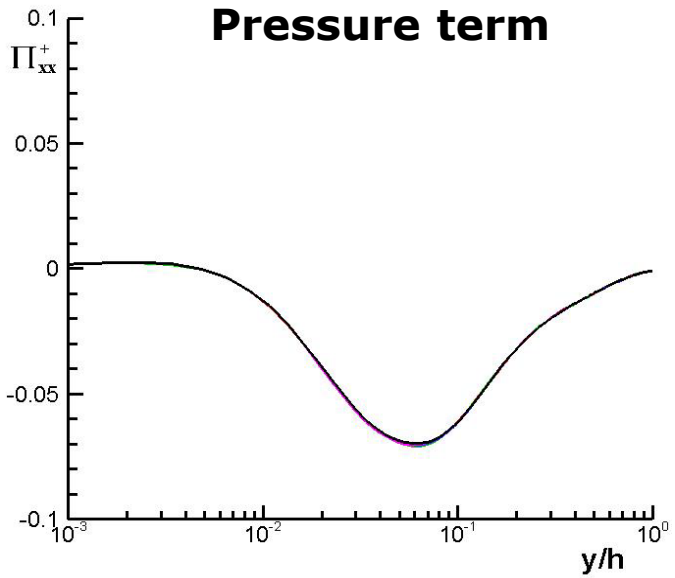


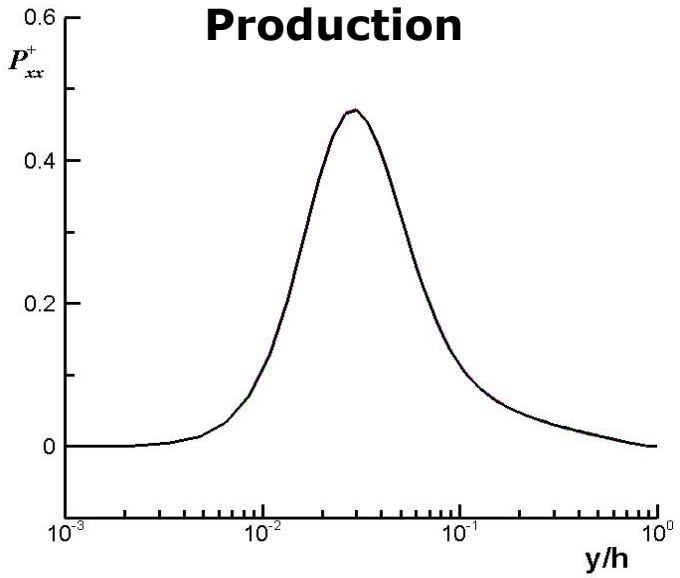


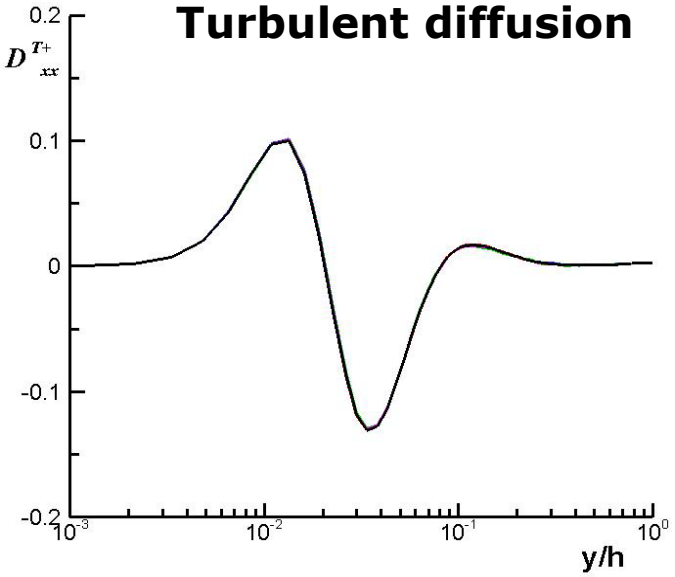


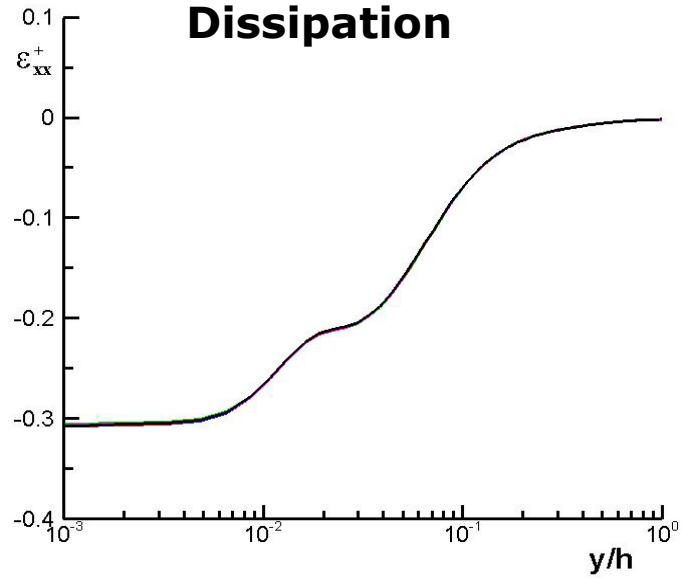
Convergence of $< u^2 >$-budget terms

AIAA2016-3940





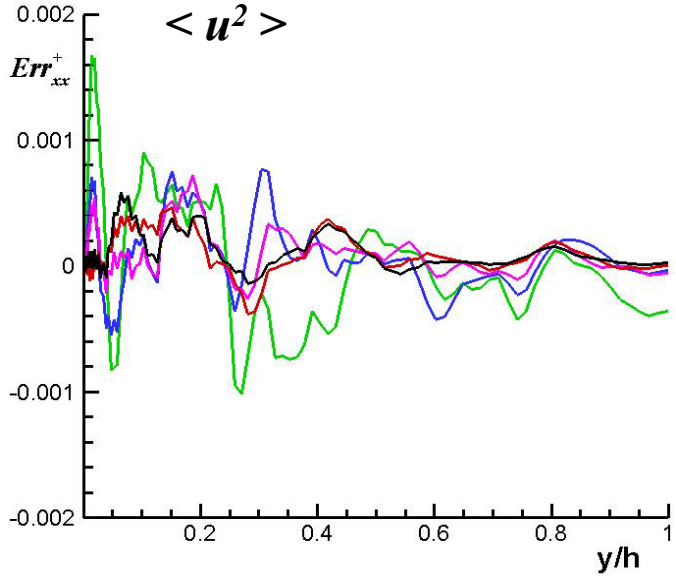


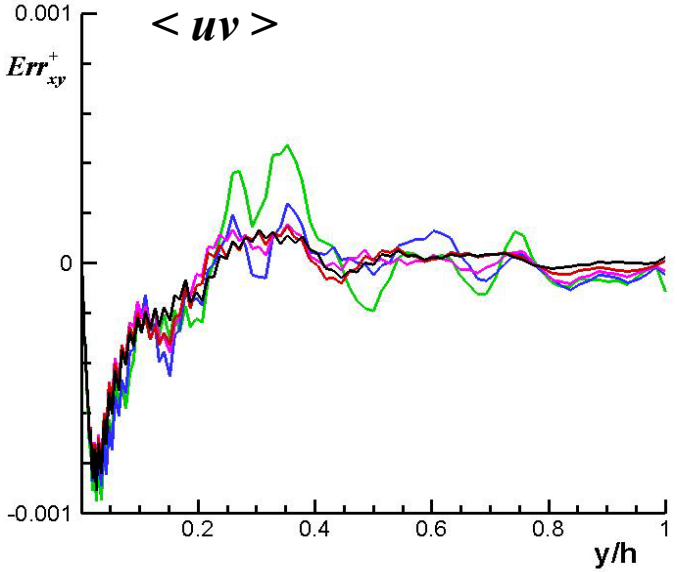


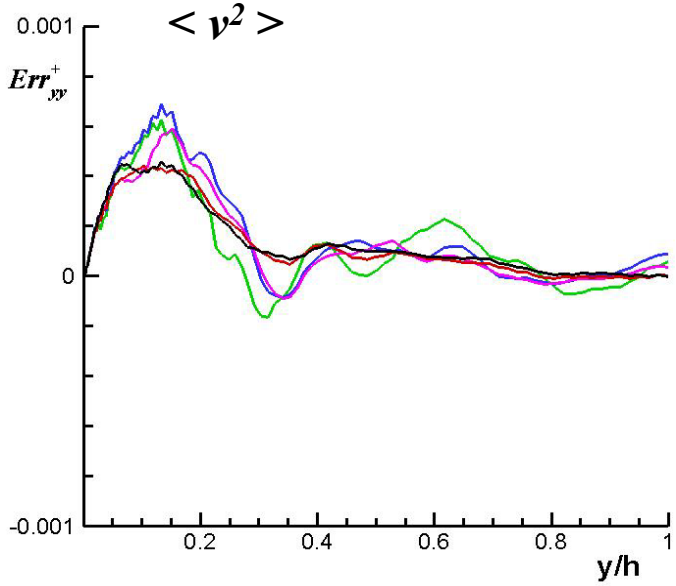
Balance error convergence

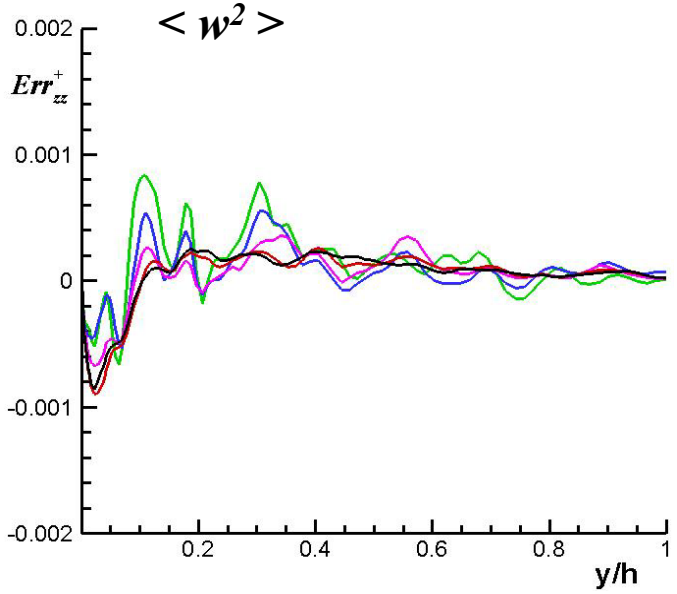
AIAA2016-3940

t2 t3 t5 t6 t7







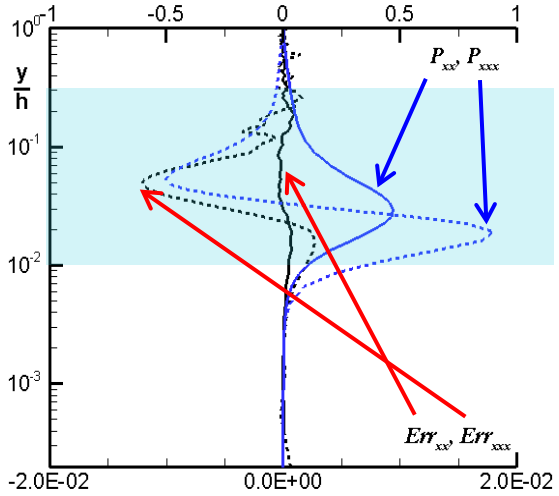


• DNS data (Reynolds stresses and terms in their budgets) do not converge in the statistical sense. **Running DNS longer does not seem to eliminate the systematic error present in the data.**

• The balance errors have a non-uniform distribution in the wall-normal direction, which may indicate issues with the grid resolution.

It is unlikely for higher-order velocity moments to have a better convergency and particularly for odd moments sensitive to the direction of velocity fluctuations.

More on the error analysis in
Poroseva, Colmenares, Murman,
Physics of Fluids, 2016, 28(11).

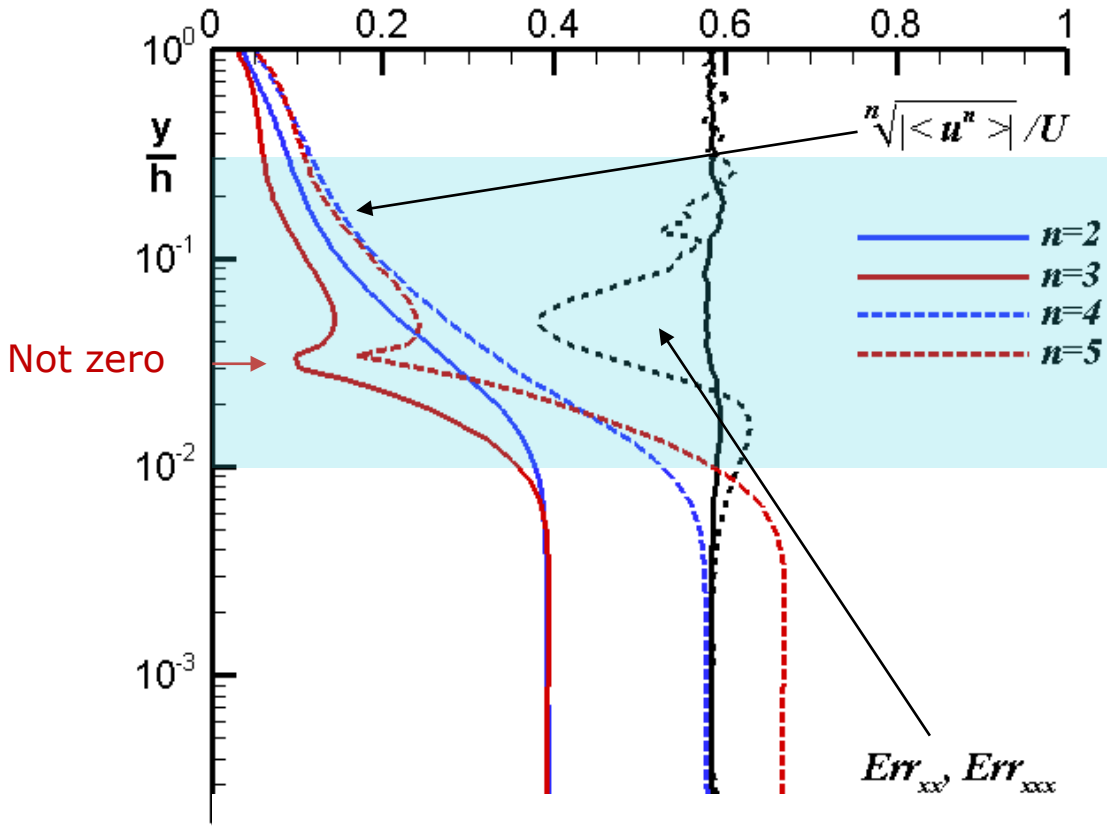


Grid resolution

DNS data used in the study are state-of-the-art with respect to the grid generation procedure.

The Kolmogorov length scale, $\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$, is based on the theory of locally isotropic turbulence. The theory assumes, in particularly, a sufficiently large Reynolds number and small velocity fluctuations.

"The hypothesis of local isotropy is realized with good approximation in sufficiently small domains *G* of the four-dimensional space $(x_1, x_2, x_3.t)$ not lying near the boundary of the flow or its other singularities." A. N. Kolmogorov, Doklady Akad. Nauk SSSR, 1941, 30(4). English translation by Levin, 1991 "Turbulence and stochastic process: Kolmogorov's ideas 50 Years on. Proc. R. Soc. Lond. A, 1980, 434.

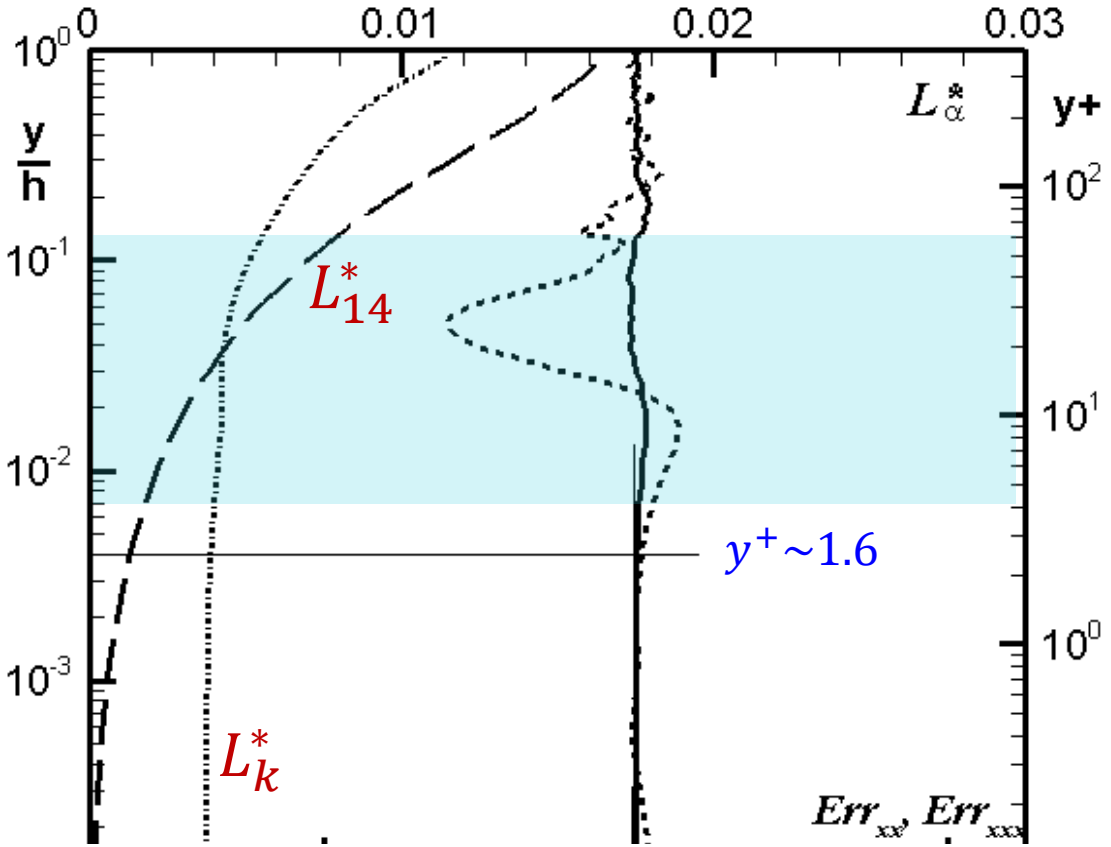


Even velocity moments

Odd velocity moments

Indeed, velocity fluctuations are not small to compare with the mean velocity near a wall. And the local Re is not large.

The ratio also did not converge with respect to *n*.



$L_k^* = \eta/h$ Kolmogorov length scale

$L_{14}^* = \Delta y/h$ Grid cell size in Jeyapaul et al., IJHFF, 2015, 54.

Possible alternatives

Different options were considered for the non-dimensional lengthscale smaller than the Kolmogorov one and independent of the velocity moment order *n*.

$$L^*_{pn} = \frac{L_{pn}}{h} = \frac{1}{Re_{\tau 0}} \left(\frac{1}{|P_n^*|} \right)^{\frac{1}{n+2}}$$

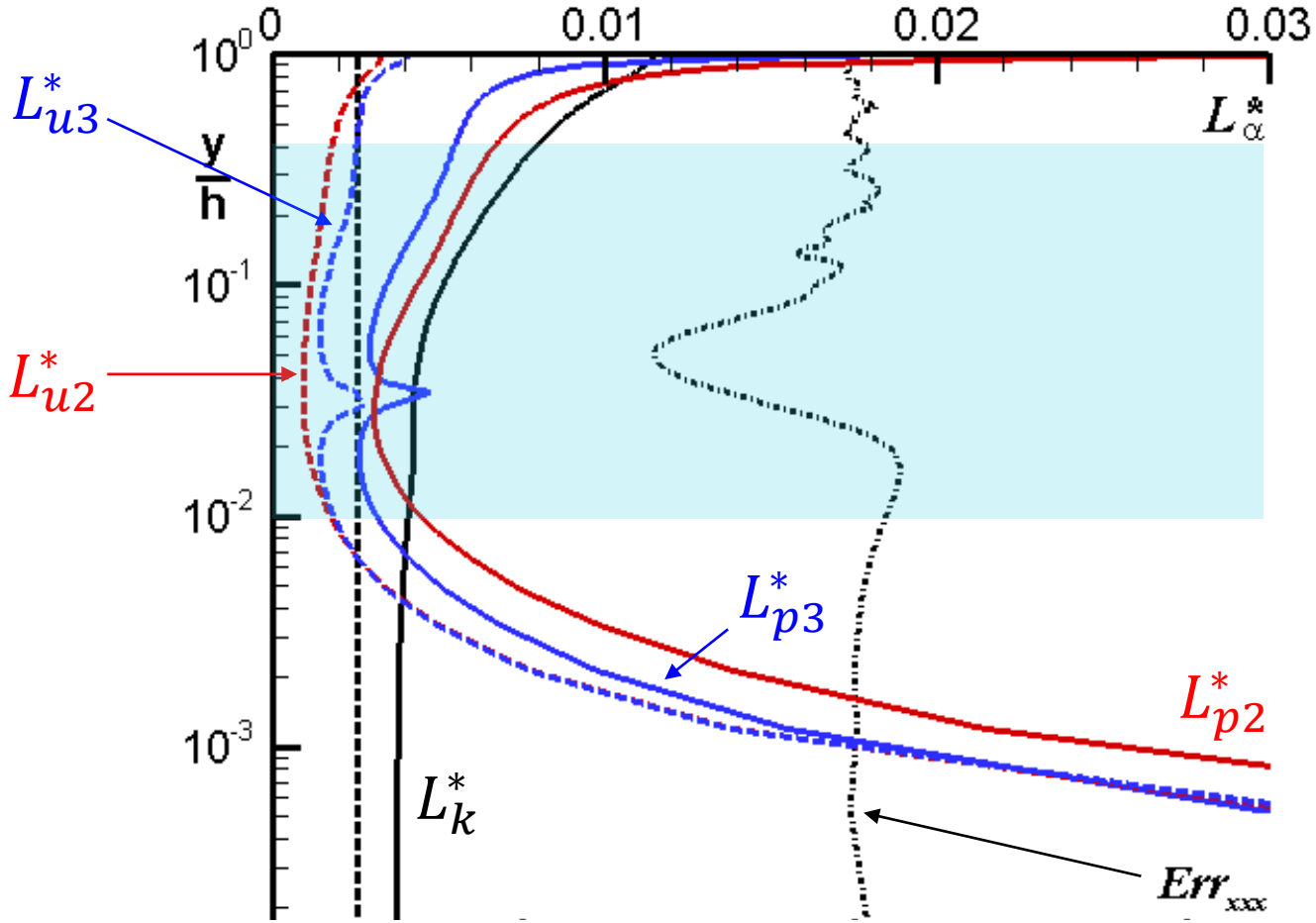
$$L^*_{un} = \frac{L_{un}}{h} = \frac{1}{Re_{\tau 0}} \frac{1}{(|\langle u^{*n} \rangle|)^{1/n}}$$

$n \to \infty$

$$L^*_{inf} = \frac{1}{Re_{\tau 0}}$$

$P_n = P_n^* * u_{\tau 0}^{n+2}/\nu$, P_n - production by shear for $< u^n >$,

$Re_{\tau 0} = \frac{u_{\tau 0} h}{\nu}$, $(\langle u^n \rangle)^{1/n} = u_{\tau 0} (\langle u^{*n} \rangle)^{1/n}$


0
0.01
0.02
0.03
10^0
10^{-1}
10^{-2}
10^{-3}
y/h
L^*_{u3}
L^*_{u2}
L^*_{α}
L^*_{p3}
L^*_{p2}
L^*_k
Err_{xxx}

On the physical meaning…

The physical process is likely to be relevant to formation and dynamics of small-scaled coherent structures in the buffer zone investigated in many previous works. There seems to be a consensus that dynamics of these coherent structures is driven by viscosity and the mean shear, this dynamics is different and independent from the rest of the flow, but common with that observed in statistically stationary homogeneous shear turbulence. That is, the phenomenon is due to the mean shear, not the wall.

More on the buffer zone “life” in e.g., Jiménez, “Coherent structures in wall-bounded turbulence”. JFM, 2018, 842.

Summary

- Discrepancies between model profiles and DNS data reflect not only issues with models, but also inaccuracies in DNS data.
- Inaccuracies in DNS data may not be merely numerical, but also indicators that something is missing in our understanding of the flow physics.
- Odd velocity moments sensitive to the direction of velocity fluctuations have to be collected from DNS and their convergence analyzed (statistical errors, grid sensitivity).
- Budgets (including balance errors) for the mean velocity components are also of interest, but where are they?
- The production by shear and at least some of the velocity moments are likely underestimated in the buffer zone of wall-bounded flows when using current criterion for the grid resolution.
- New lengthscale may be a solution for this flow area.

More detail in Poroseva & Murman, Int. J. Heat Fluid Flow, 2021, 89.

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Thank you!

http://www.unm.edu/~poroseva/

poroseva@unm.edu