

Assessment of Large Eddy Simulation for Flow Dynamics in Urban-like Environments

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From WMC to Urban simulations: plan

- 1- Channel flow: WMC validation. LES and no model.
- 2- Boundary layer: WMC.
- 3- Changing obstacles: Barcelona's illa de l'Eixample inspired shape.
- 4- Urban canopy. Comparison with CEDVAL (wind tunnel datasets), Universität Hamburg
- 5- Real ABL. Introduction of pollutants. Dispersion.

Some properties of S3PQR models

S3PQR: a combination of two invariants of GG^T (Trias, 2015), giving PQ, PR, QR, LES models. Properties:

- 0) $\nu_e \geq 0$, locality and frame invariant;
- 1) $\mathcal{O}(y^3)$ near-wall behavior;
- 2) $\nu_e = 0$ for 2D flows (PR, QR);
- 3) $\nu_e \approx 0$ for the canonical axisymmetric flow (< 0.076)
- 4) Well-conditioned and low computational cost.

Current status: so far, assessment done for channel flow, homogeneous isotropic turbulence (both forced and decaying), boundary layer, and wind farm (with forces).

Some algorithm details

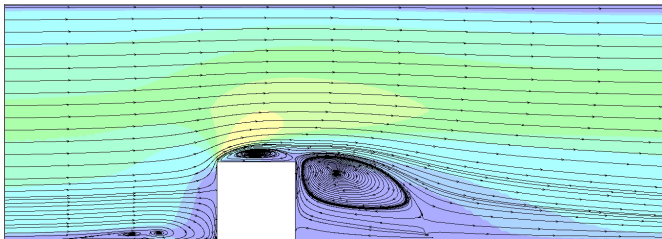
LES models: Smagorinsky, Verstappen, WALE, Vreman, and all S3PQR models.

Previous computations: in-house pseudospectral code. For the periodic boundary layer, Spalart's growing terms.

Now: FVM (TFA). For the periodic boundary layer, body force (Wynn et al, 2025).

WMC reference: Trias, 2009

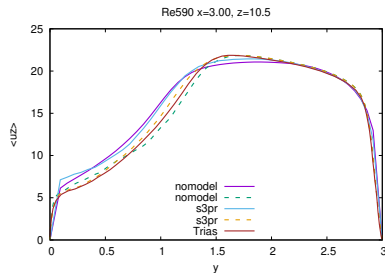
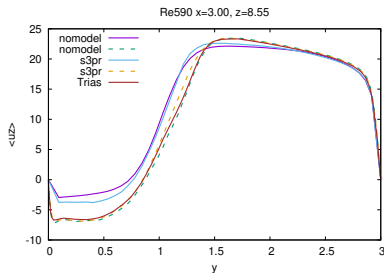
400x200x196 mesh, $Re_\tau = 590$, channel flow



Domain dimensions: $6 \times 3 \times 17$. WMC height $h = 1.0$

WMC in a channel flow

Mesh dependence. Average velocity profile

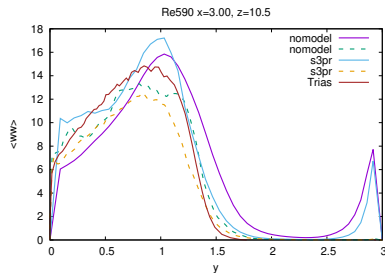
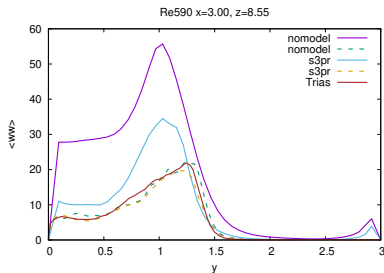


$Re_\tau = 590$; solid line: $50 \times 50 \times 100$; dashed line: $200 \times 200 \times 400$ no model, $100 \times 100 \times 200$ s3pr; brown line: Trias, 2009.

Left: $(3.0, y, 8.55)$ Right: $(3.0, y, 10.5)$

WMC in a channel flow

Mesh dependence. Average Reynolds stress $\langle ww \rangle$

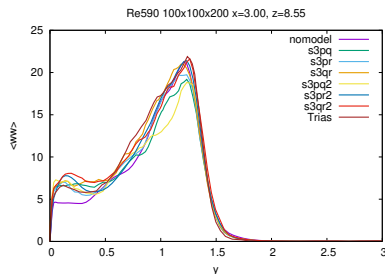
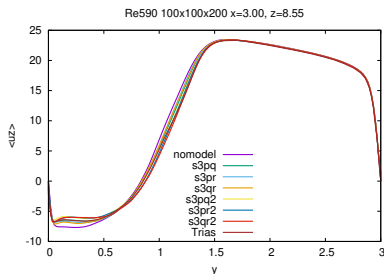


$Re_\tau = 590$; solid line: $50 \times 50 \times 100$; dashed line: $200 \times 200 \times 400$ no model, $100 \times 100 \times 200$ s3pr; brown line: Trias, 2009.

Left: $(3.0, y, 8.55)$ Right: $(3.0, y, 10.5)$

WMC in a channel flow

S3PQR LES comparison $x = 3.0, z = 8.55$

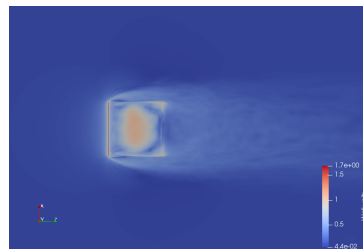
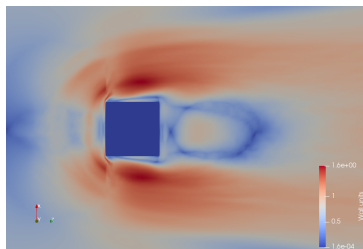


$Re_\tau = 590, 100 \times 100 \times 200$; brown line: Trias, 2009

Left: normalized average streamwise velocity profile Right: $\langle ww \rangle$

WMC channel flow

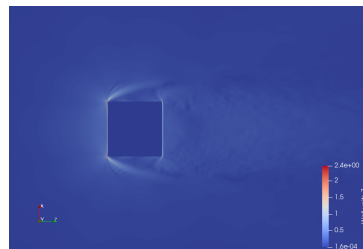
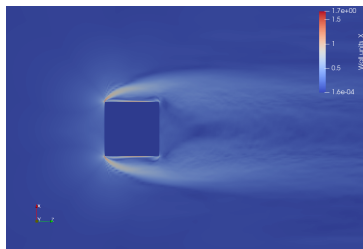
Mesh resolution validation (rough estimate, work in progress) 200x200x400, $Re_\tau = 590$, no model



Left: bottom $\Delta y^+ < 1.6$; Right: WMC roof $\Delta y^+ < 1.7$

WMC channel flow

Mesh resolution validation (rough estimate, work in progress) $200 \times 200 \times 400$, $Re_\tau = 590$, no model, $y = 0.5$



Left: spanwise $\Delta x^+ < 1.7$; Right: streamwise $\Delta z^+ < 2.4$

Boundary Layer: periodic boundary conditions

- Displacement thickness (δ^*):

$$\delta^* = \int_0^\infty (1 - u/u_\infty) dy$$

- Introduction of energy via body force (Wynn, 2025):

$$f(t)y \frac{\partial \mathbf{u}}{\partial t}$$

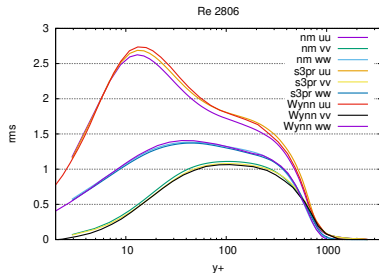
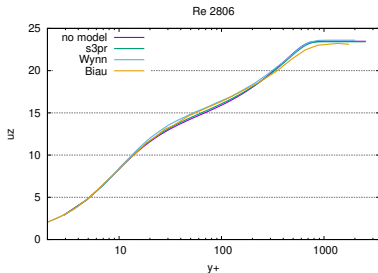
$f(t)$ depends on the desired δ^* , $\delta^*(t)$ and skin friction

$$f(t) := \frac{-k(\delta^* - \delta^*(t)) + \frac{1}{2}C_f(t)}{\delta^*(t)}$$

- "Real" ABL boundary thickness $\delta \sim 600m$, $\delta^* \sim 150m$.
 $Re_{\delta^*} \sim 6 \times 10^7$.

Boundary Layer $Re_{\delta^*} = 2806$

Validation. Comparison with Wynn, 2025

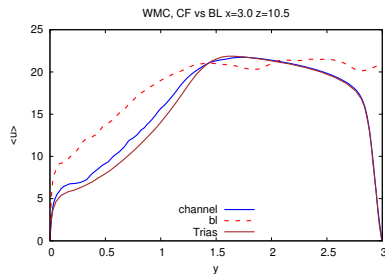
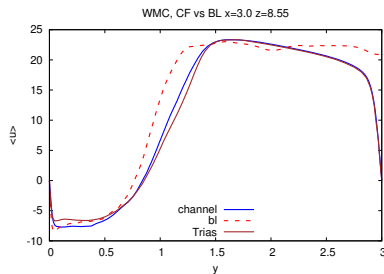


$Re_{\delta^*} = 2806$, $200 \times 400 \times 200$. Left: streamwise average velocity.

Right: rms u^+ ; rms v^+ ; rms w^+ ; Wynn, 2025; Biau, 2023

BOUNDARY LAYER: WMC

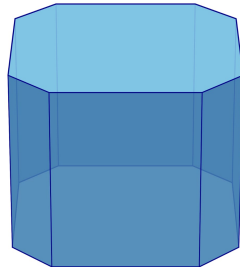
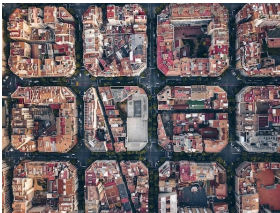
No model, $Re_{\delta^*} = 1741$, $\delta \sim 1.5$, channel $Re_{\tau} = 590$



Average streamwise velocity profile. 100x100x200. Trias, 2009

Left: $x = 3.0, z = 8.55$; Right: $x = 3.0, z = 10.5$

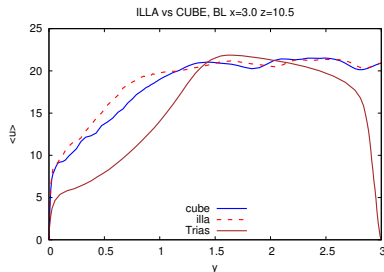
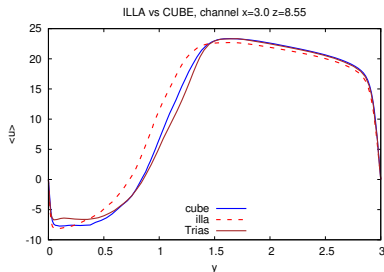
Changing obstacle: Barcelona's illa de l'Eixample inspired shape



Lengths of "real" illa: side (big square), 113 m. Size of the corner (as a square), 14 m. Computation with $side = 1.0$ as in WMC, proportionally.

ILLA vs WMC, channel flow and boundary layer

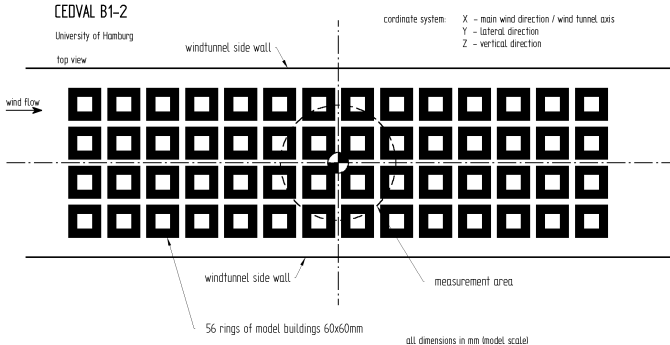
No model, $Re_\tau = 590$, $Re_{\delta^*} = 1741$, $\delta \sim 1.5$



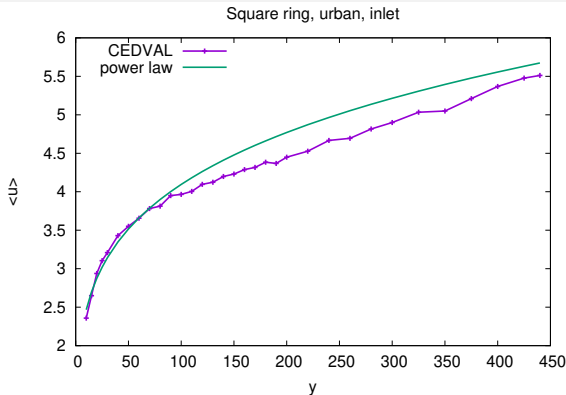
Average streamwise velocity profile. $100 \times 100 \times 200$. Trias, 2009
Left: $x = 3.0, z = 8.55$, channel flow; **Right:** $x = 3.0, z = 10.5$, boundary layer

Urban environment. CEDVAL dataset. Universität Hamburg

Layout and sizes. $Re_h = 14640$ equivalent to $Re_\tau = 37772$

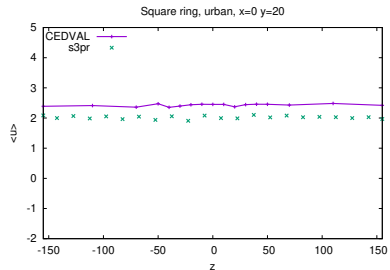
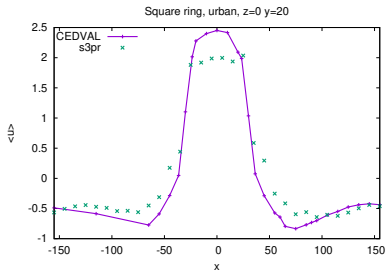


Urban. Channel flow. Domain size: 2m x 3m x 6m.
Velocity inlet. $Re_\tau = 37772$



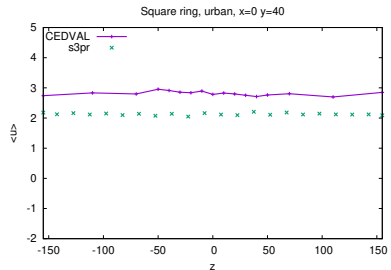
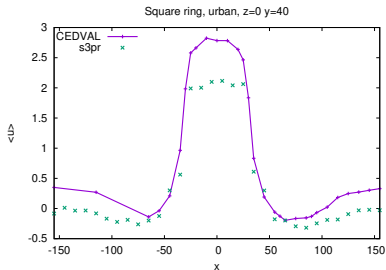
Inlet velocity profile. 200x200x400. CEDVAL profile. Simulation profile, power law: $u_z(y) = 3.66 \cdot \left(\frac{y}{60}\right)^{0.22}$

Urban. Channel flow. Domain size: 2m x 3m x 6m. Velocity profiles. S3PR. $Re_\tau = 37772$. $y = 20mm$



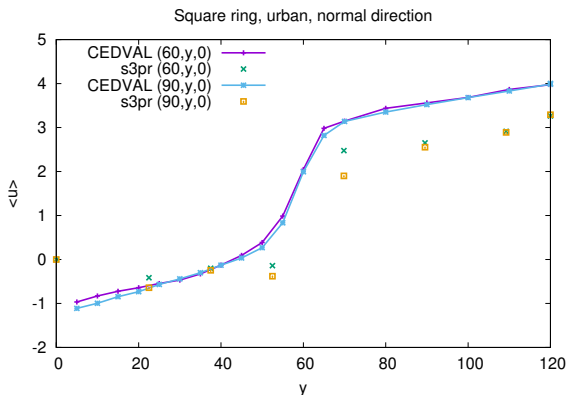
Spanwise (left) and streamwise (right) average u_z velocity profile. 200x200x400. Coordinates: center (0,20,0). Both directions from -155mm to 155mm. CEDVAL and simulation data.

Urban. Channel flow. Domain size: 2m x 3m x 6m.
Velocity profiles. S3PR. $Re_\tau = 37772$. $y = 40\text{mm}$



Spanwise (left) and streamwise (right) average u_z velocity profile. 200x200x400. Coordinates: center (0,40,0). Both directions from -155mm to 155mm. CEDVAL and simulation data.

Urban. Velocity profiles. S3PR. $Re_\tau = 37772$. Normal direction



u_z velocity normal profiles at two locations. $x = 60$ mm, $x = 90$ mm, $200 \times 200 \times 400$. CEDVAL and simulation data.

Conclusions

- Reliability, versatility, and accuracy of TFA and S3PQR LES algorithms on several benchmark cases.
- Possibility of LES improvement based only on invariants of the velocity gradient related tensor.
- Further work: complete the analysis for all the LES models. Introduce pollutant dispersion.

Bibliography. Thank you

- Trias, 2015: Building proper invariants for eddy-viscosity subgrid-scale models. 2015. Physics of Fluids 27(6):065103. F. Xavier Trias, David Folch, A. Gorobets, A. Oliva
- Trias, 2009: F. X. Trias et al. "Turbulent flow around a wall-mounted cube: direct numerical simulation and regularization modeling". In Parallel Computational Fluid Dynamics, 2009
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- CEDVAL dataset: <https://www.mi.uni-hamburg.de/en/arbeitsgruppen/windkanallabor/data-sets.html>