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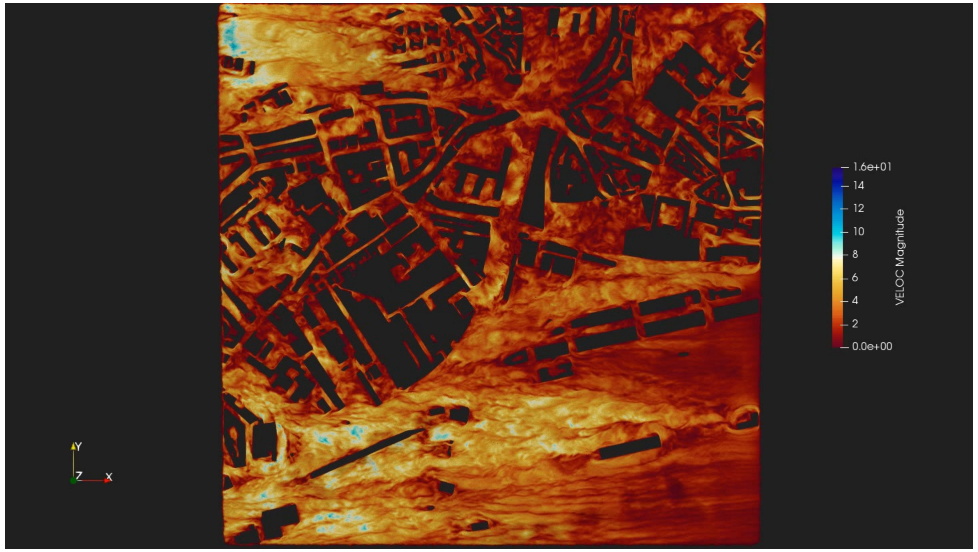
Latest turbulence modelling activities in the Large-Scale Computational Fluid Dynamics group at BSC

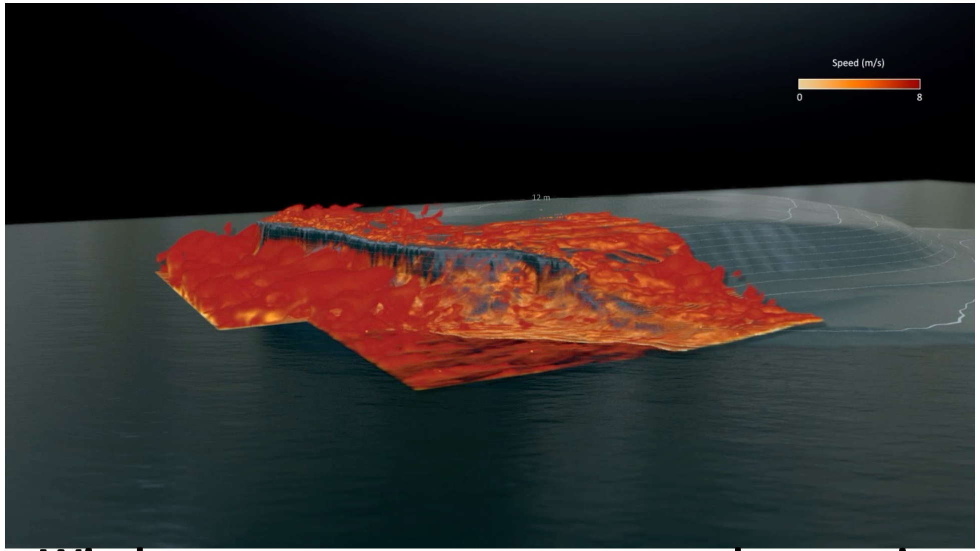
Matías Avila, Oriol Lehmkuhl

16/05/2024

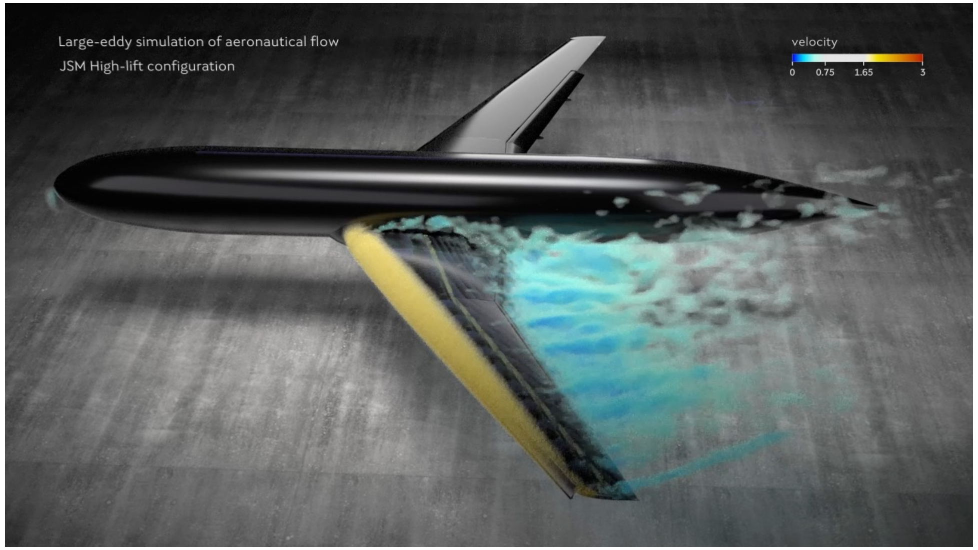
Aerodynamical applications



Urban flows



Wind resource assesment on complex terrain



Full aircaft aerodynamics

External aerodynamics of road vehicles

Main research applications in the LS/CFD team

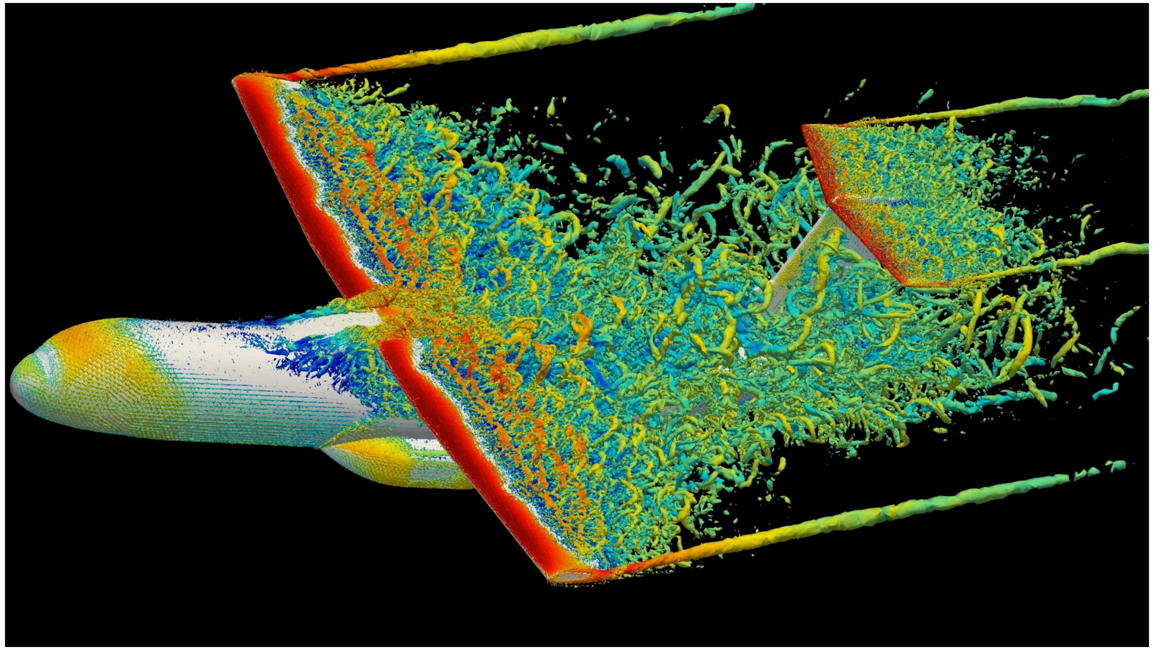
Research founding obtained by LS/CFD:

- CODA: Next generation of industrial aerodynamic simulation code (**NEXTSIM**), EUROPEAN COMMISSION + AEI, 956104; PCI2021-121962, 3.978.096,75 euros, 01/03/2021 - 29/02/2024.
- Development of high-resolution digital twins to fast prediction of air pollutants distribution and the odour impact in cities based on the application of artificial intelligence to CFD models (**APPWIND**), AEI, PLEC2021-007943, 780.694,5 euros, 01/11/2021 - 31/05/2025.
- Towards the design of cleaner aircrafts: MAchine lEarning for flow Solvers, flow conTrol and aeROacoustics (**MAESTRO**), AEI, PID2020-116937RB-C21, 266.200,00 euros, 01/09/2021 - 30/08/2024.
- Groundbreaking tools and models to reduce air pollution in urban areas (**MODELAIR**), EUROPEAN COMMISSION, PE115600, 2.736.115,20 euros, 01/01/2023 - 31/12/2025.
- Towards a digital twin for forecasting of power production to wind energy demand (**WindTwin**), EUROPEAN COMMISSION, PE139900, 5.998.768,87 euros, 01/06/2024 - 31/05/2027.
- Tecnologías Inteligentes para la Fabricación, el diseño y las Operaciones en entornos iNdustriales (TIFON), AEI, PLEC2023-010251, 1.417.823,36 euros, 01/01/2024 - 31/12/2026.
- Participation in EuroHPC CoE: CEEC, Excellerat 2 and EoCoE3 (more than 750k euros in total)
- Private contracts with Airbus, ITPAero, Iberdrola Renovables, and OceanWinds (more than 1.5M euros in execution).

Main software for CFD in LS/CFD team

SOD2D

- SOD2D: **S**pectral high-**O**rder coDe **2** solve partial **D**ifferential equations
  https://gitlab.com/bsc_sod2d/sod2d_gitlab
- Based on Spectral Continuous Finite Elements Method
- Simulations of turbulent compressible and incompressible flows over complex geometries
- Fully accelerated using OpenACC
- Used in aeronautical and wind energy applications
- Developed at BSC-CASE as an Open-Source in different EuroHPC projects (NextSim, CEEC, EcoE3 and Excellerat 2)



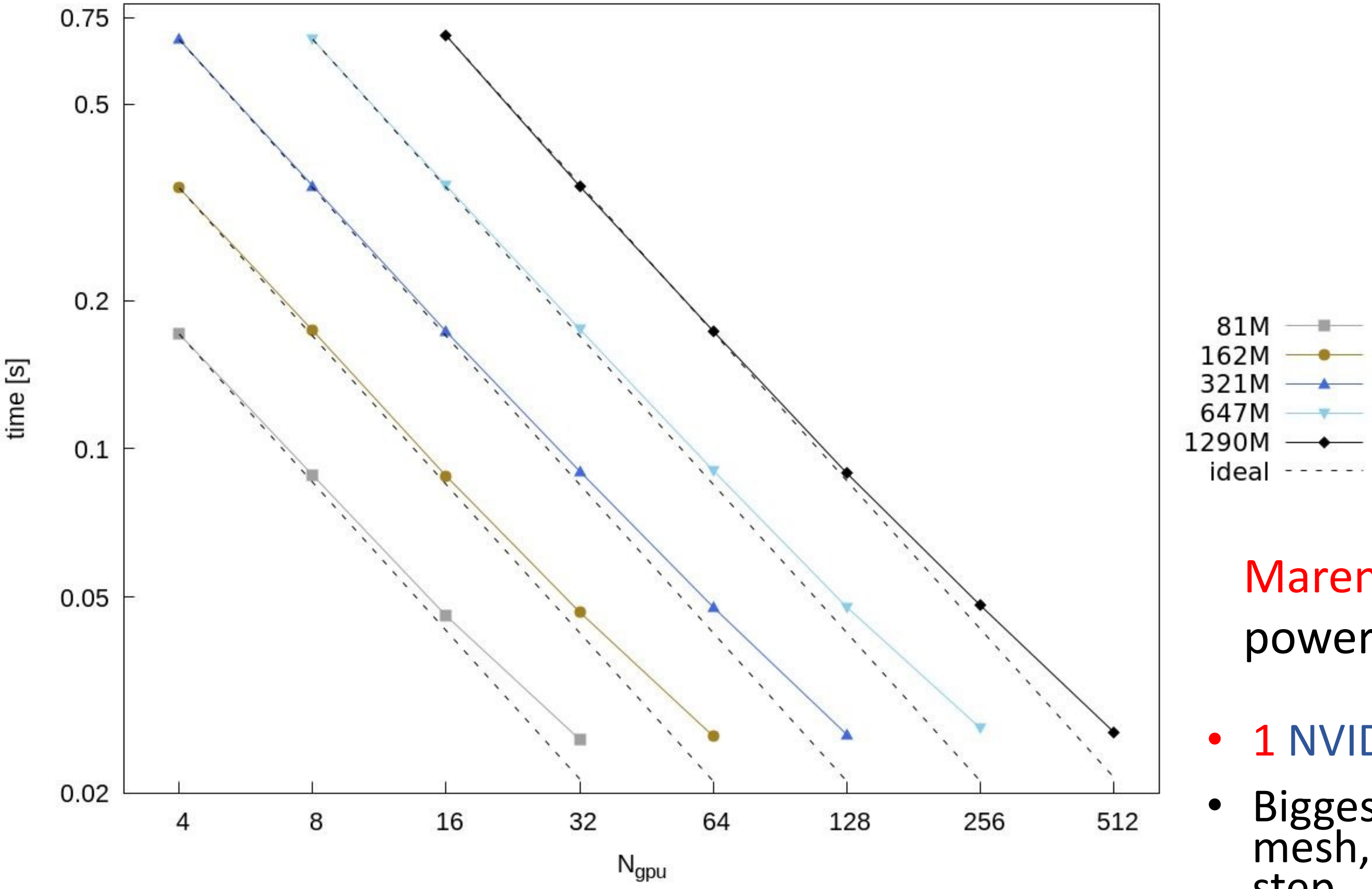
WMLES simulation of a new concept Aircaft from Airbus, using 32 H100 and 200M DoF.

Simulations carried out in the CDTI PTA 2023 (CETACEO) under the collaboration agreement between BSC and Airbus

SOD2D: **S**pectral high-**O**rder co**D**e **2** solve partial **D**ifferential equations

Paper: https://doi.org/10.1016/j.cpc.2023.109067

Main software for CFD in LS/CFD team

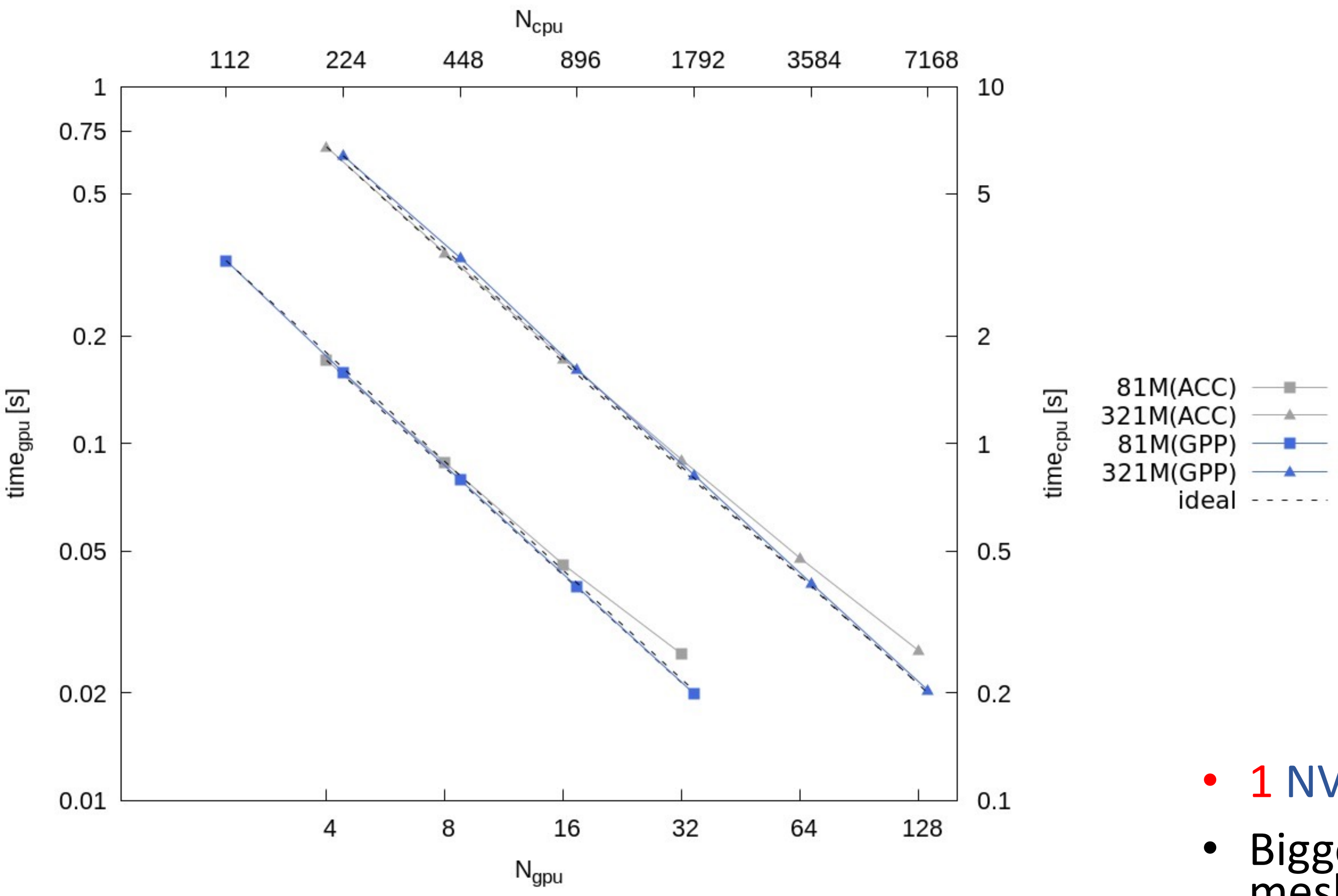


Scalability of SOD2D in MN5, 4th order, several mesh sizes. Compressible, explicit RK4.

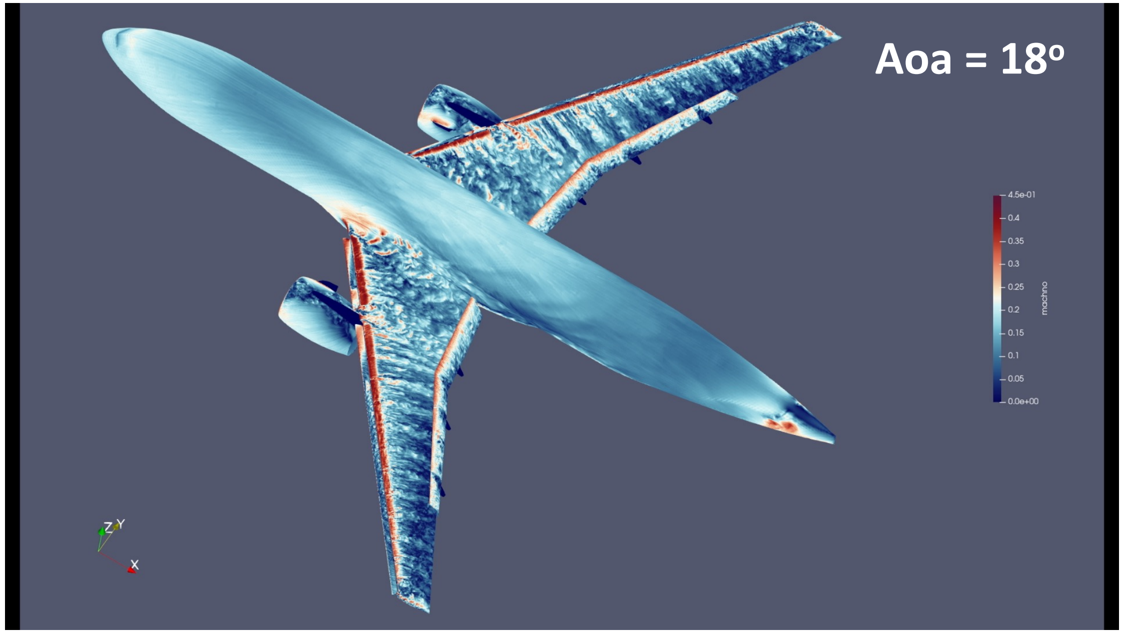
Marenostrum 5 supercomputer with a computational power of 314 Pflops (265.5 from GPUs (85%))

- 1 NVIDIA H100 behaves like 560 Intel Sapphire Rapid cores
- Biggest test carried out: 768 GPUs, with 2Billion node mesh, at 83% of parallel efficiency doing 0.02s per time step.
- Full Aircraft in 12h using 100 H100 GPUs. In the previous MN4 we needed the 70% of the machine and several days.

Main software for CFD in LS/CFD team



[CPU vs GPU] :: Compressible RK4, p=4



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Main software for CFD in LS/CFD team

ANL-23/59

Argonne NATIONAL LABORATORY

Turbulence Modeling with Nek5000/RS, SOD2D and Alya

prepared by

Vishal Kumar[1], Oriol Lehmkuhl[2], Ananias Tombouldies[3], Paul Fischer[1,4,5], and Misun Min[1]

[1] Mathematics and Computer Science Division, Argonne National Laboratory
[2] Barcelona Supercomputing Center (BSC)
[3] Department of Mechanical Engineering, Aristotle University of Thessaloniki
[4] Department of Computer Science, University of Illinois Urbana-Champaign
[5] Mechanical Science & Engineering, University of Illinois Urbana-Champaign

September 25, 2023

Periodic pipe flow at $Re_b = 37700$

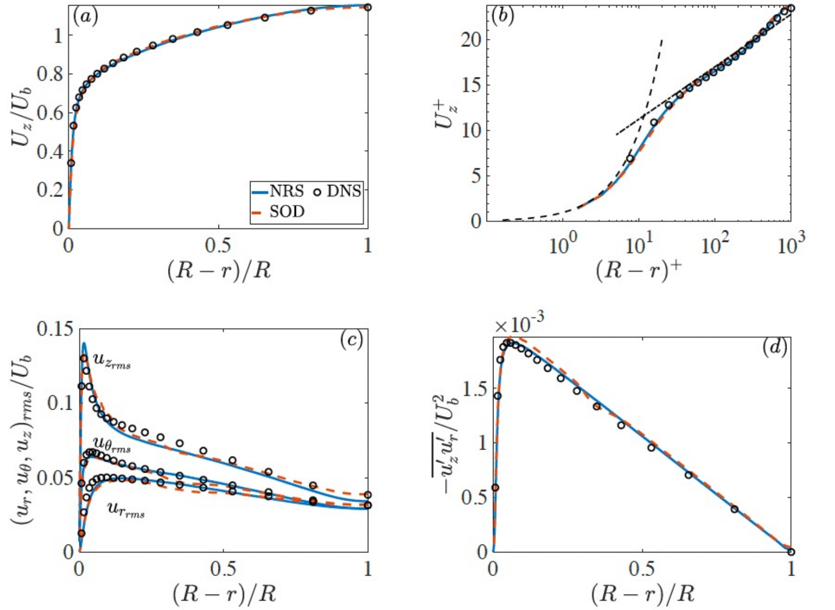
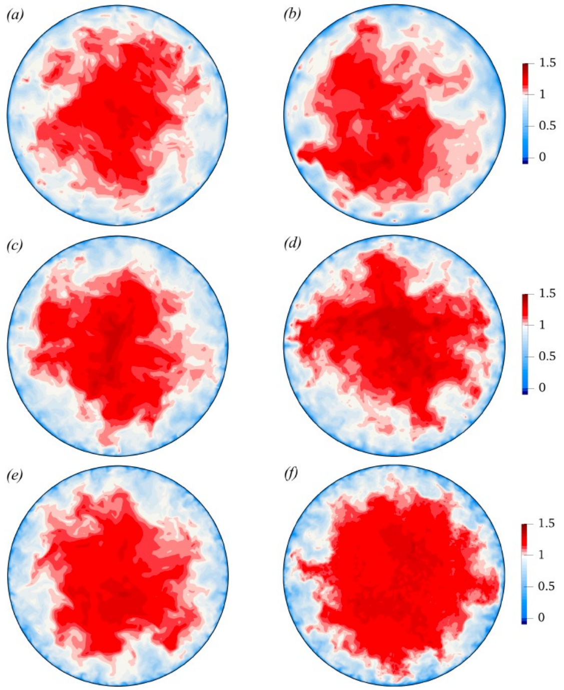


Figure 15: Comparison of turbulent pipe flow results between NekRS and SOD2D at $Re_\tau = 1000$ on the Fine grid resolution; *(a)* axial velocity (U_z/U_b) in outer units; *(b)* axial velocity in inner units; *(c)* normal turbulent stresses; *(d)* resolved Reynolds stress.

- Externals users are already doing research with the miniApp: UPC, Delft, KTH and Argonne are the most notable.
- Example of external applications
- Two spectral element codes (CG, DG) running in GPUs a wall resolved pipe flow

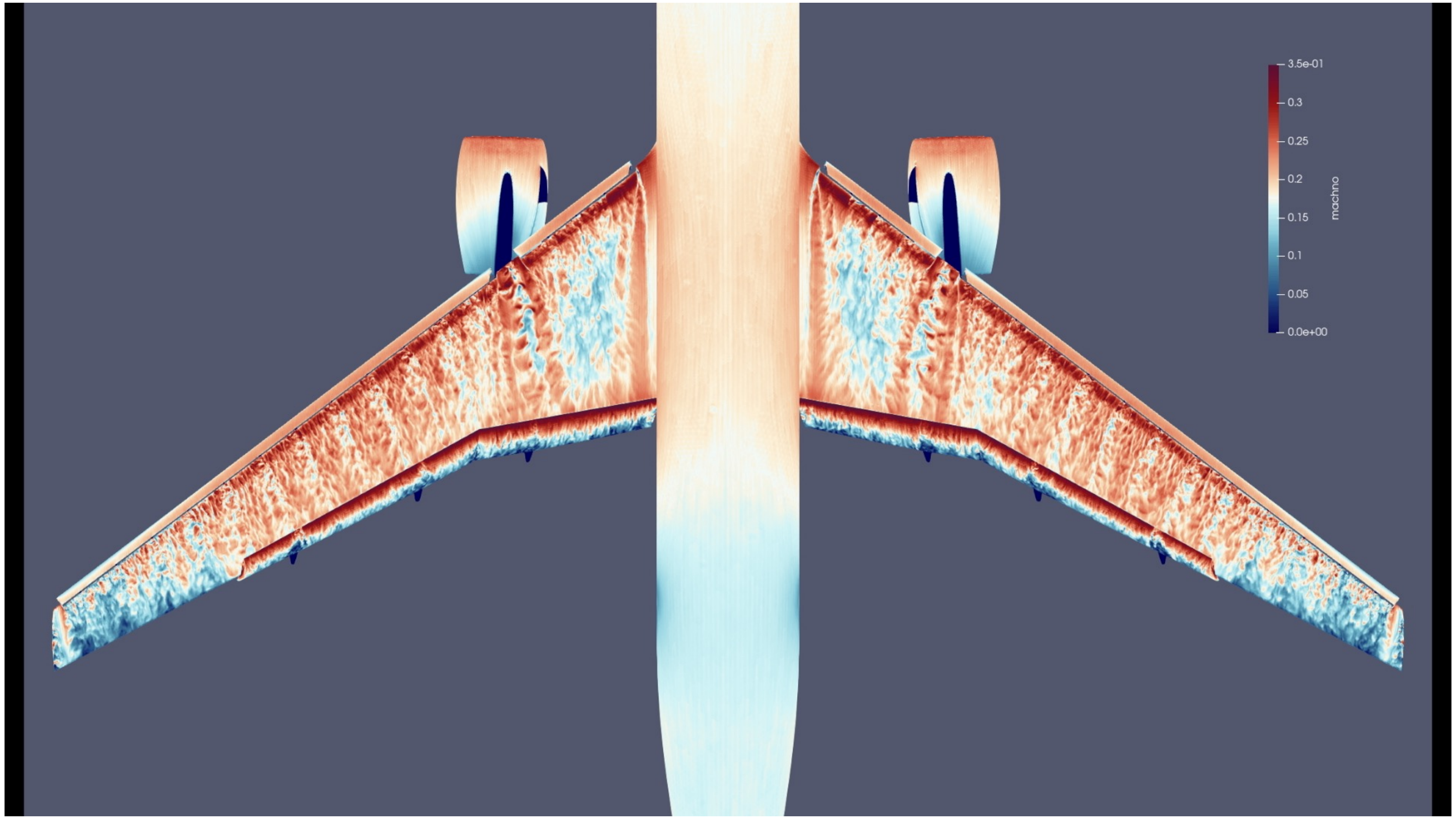


4: Visualization of instantaneous axial velocity (u_z/U_b) for pipe flow at $Re_\tau = 1000$; *(a,c,e)*
; *(b,d,f)* SOD2D; *(a,b)* Coarse resolution; *(c,d)* Medium resolution; *(e,f)* Fine resolution;
olution are indicated in Table 3.

Table 2: Performance of NekRS and SOD2D on Polaris. Tests have been performed for Channe flow at a resolution of $384 \times 384 \times 384$ with $E = 64^3$, $N = 6$, and the total number of grid points o 56 millions. $\Delta t = 1.5\text{e-}03$ $(CFL = 1.7)$ and $\Delta t = 6.5\text{e-}05$ $(CFL = 1.5)$ are used for NekRS anc SOD2D, respectively.

	Performance on Polaris						
Code	nodes	GPUs	dofs/GPU	v_i	p_i	t_{step} (s)	P_{eff}
	2	8	7.0779e+06	2.97	2.13	2.3512e-01	100
	3	12	4.7186e+06	2.97	2.14	1.7690e-01	88.6
	4	16	3.5389e+06	2.97	2.18	1.4138e-01	83.1
Nek5000	5	20	2.8312e+06	2.97	2.09	1.2734e-01	73.8
	6	24	2.3593e+06	2.97	2.16	1.1305e-01	69.3
	8	32	1.7695e+06	2.97	5.16	1.3139e-01	44.7
	9	36	1.5729e+06	2.97	2.13	9.4724e-02	55.1
	2	8	7.0779e+06	-	-	3.4603e-01	100
	3	12	4.7186e+06	-	-	2.4769e-01	93.1
	4	16	3.5389e+06	-	-	1.9941e-01	86.7
SOD2D	5	20	2.8312e+06	-	-	1.6249e-01	85.1
	6	24	2.3593e+06	-	-	1.3526e-01	85.2
	8	32	1.7695e+06	-	-	1.0868e-01	79.5
	9	36	1.5729e+06	-	-	9.6119e-02	80.0

High Lift configurations: HL CRM with SOD2D



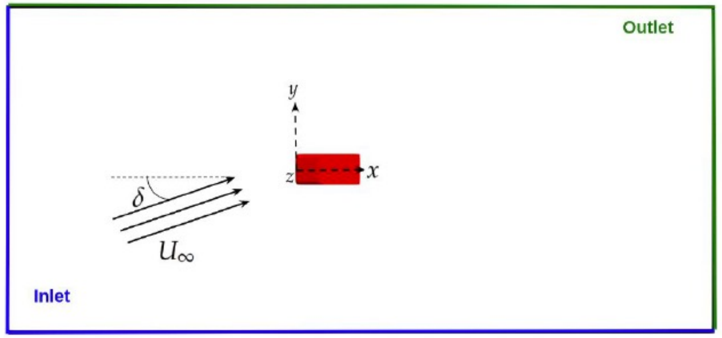
ONERA (Frenc Aerospace)
HLPW5 TC2.4 WT

AoA	CL	CD
6.06	1.649874	0.1753716

P2: 130 M DoF (Re 5.4M)

AoA	CL	CD
6.00	1.636332	0.177894

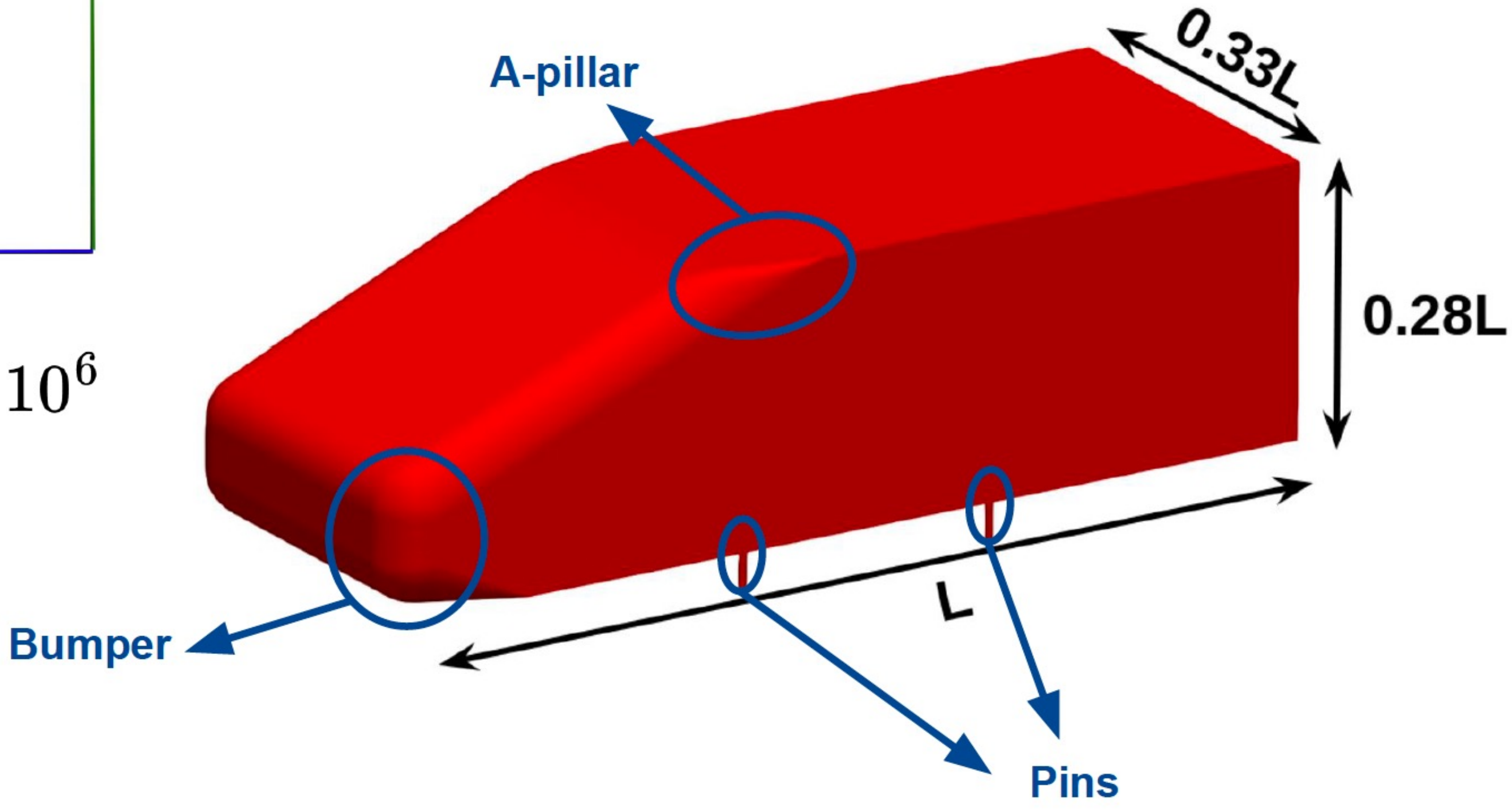
Case definition



$\delta = [2.5^\circ, 5^\circ, 7.5^\circ, 10^\circ, 12.5^\circ]$

$$Re_L = \frac{U_\infty L}{\nu} = 2.9 \times 10^6$$

The Windsor body with 2.5º of yaw is one of the test cases of the AutoCFD workshop [3]



Presented on the last : 14th Direct and Large Eddy Simulation workshop
Authors: Benet Eiximeno, Ivette Rodríguez and Oriol Lehmkuhl

On the wall-modeled large eddy simulations of the Windsor body at different yaw angles

Wall-modeled large eddy simulations (WMLES)

Flow solver: **SOD2D** [4,5]

CG Spectral Element Method
Entropy viscosity stabilization [6]
Running on both GPU & CPU

[4] BSC SOD2D Gitlab https://gitlab.com/bsc_sod2d/sod2d_gitlab
[5] Gasparino, L. et al. 10.1016/j.cpc.2023.109067
[6] Guermond et al. 10.1016/j.jcp.2010.11.043

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

$$\boxed{\frac{\partial \overline{u}_i}{\partial t}} + \boxed{\frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j}} - \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \rho^{-1} \boxed{\frac{\partial \overline{p}}{\partial x_i}} = - \boxed{\frac{\partial \mathcal{T}_{ij}}{\partial x_j}}$$

Convection: 2nd order Adams-Bashforth
Diffusion: Implicit 2nd order Crank-Nicolson

Kennedy-Gruber skew-symmetric splitting [7]

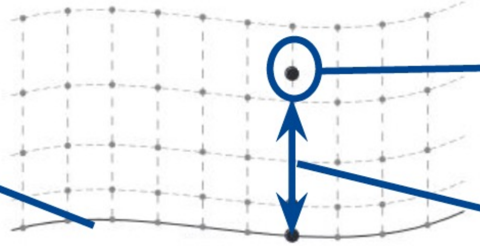
[7] Kennedy, C.A.; Gruber, A 10.1016/j.jcp.2007.09.020

Fractional step method [8]

[8] Codina, R. 10.1006/jcph.2001.6725

ILSA model [9]

[9] Lehmkuhl, O. et al. 10.1016/j.ijheatfluidflow.2019.108422



Exchange location at the 5th node [11]

[11] Lehmkuhl, O. et al Large-eddy simulation of practical aeronautical flows at stall conditions

Slip boundary

Reichard wall law [12]

[12] Reichardt, H. 10.1002/zamm.19510310704

Picture extracted from [10]

[10] Owen, H. et al. 10.1002/fld.4770

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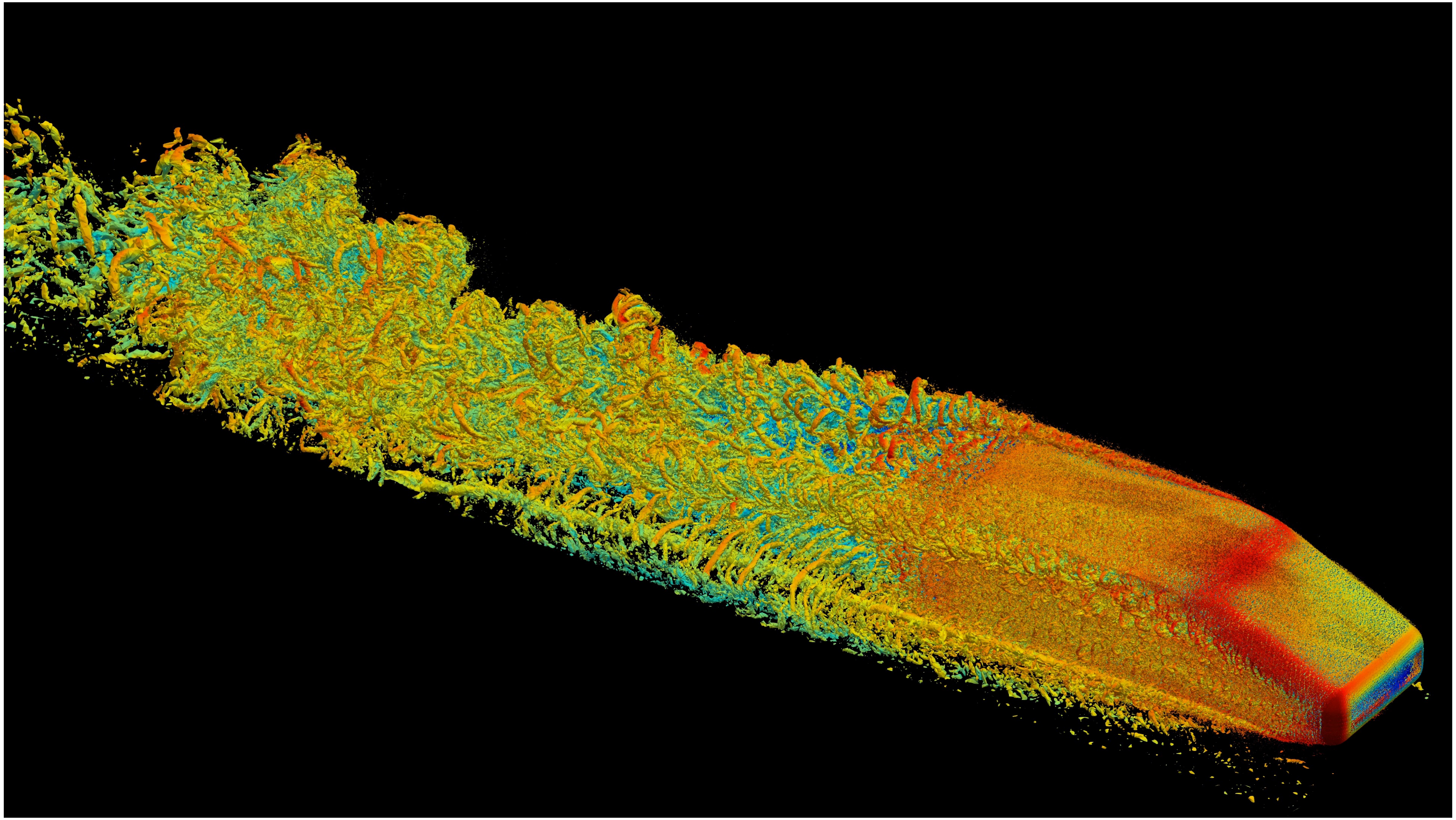

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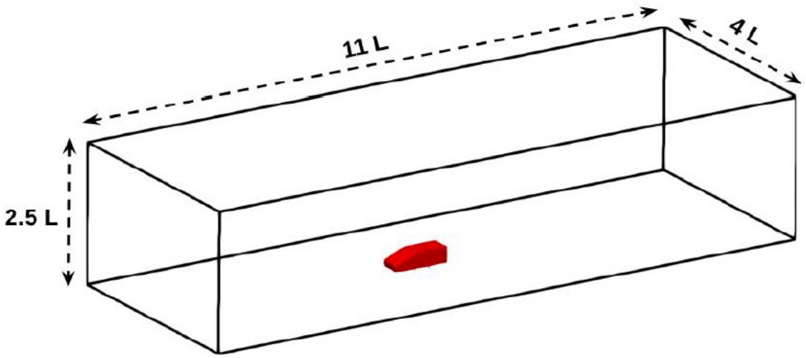
Numerical grid



1.352 x 10^8 grid points
4th order hexahedra (125 nodes each)
Finest AutoCFD [3] grid

Region	x/L	y/L	z/L	Δ/L
A	[-0.15, 5]	[-0.66, 0.66]	[0, 0.025]	0.04
B	[1, 2.8]	[-0.54, -0.54]	[0, 0.4]	0.04
C	[2.8, 5]	[-0.66, 0.66]	[0, 0.4]	0.08

$$\boxed{2 \leq \Delta/\eta \leq 5}$$

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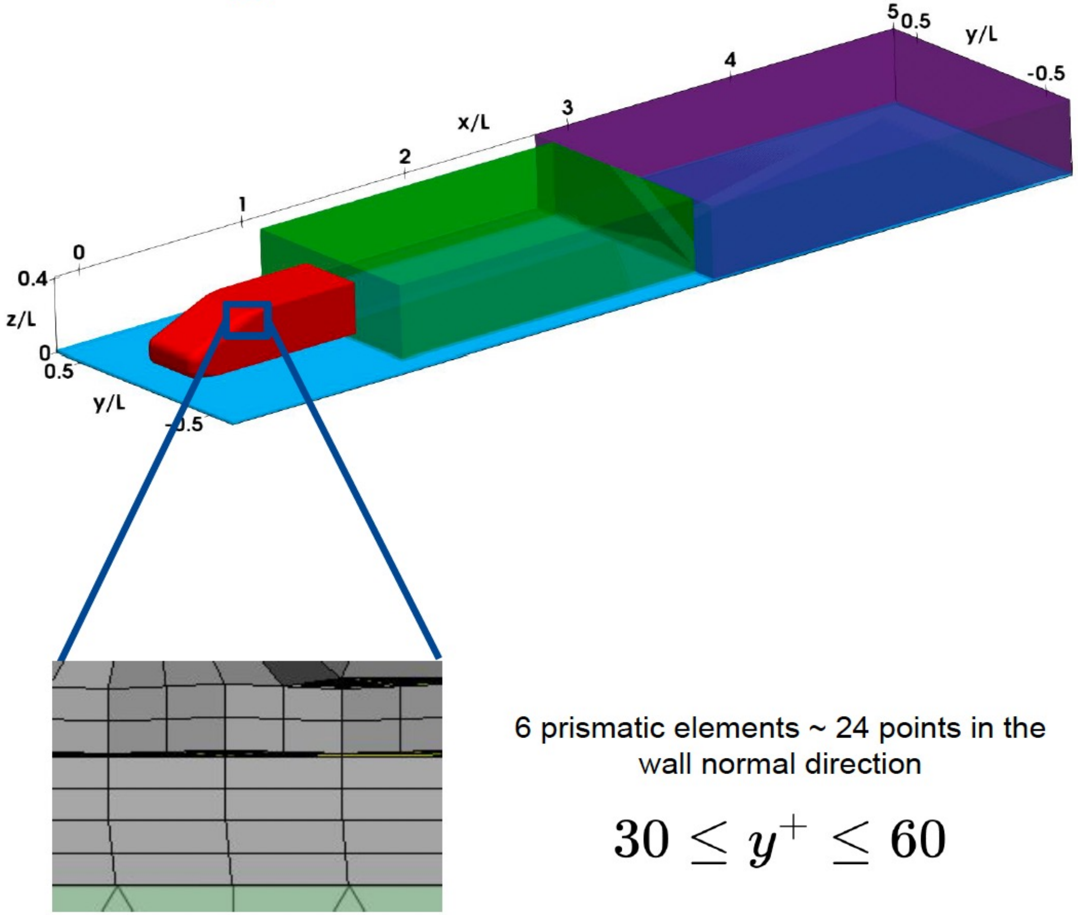
[3] https://autocfd.eng.ox.ac.uk/



6 prismatic elements ~ 24 points in the wall normal direction

$$30 \leq y^+ \leq 60$$

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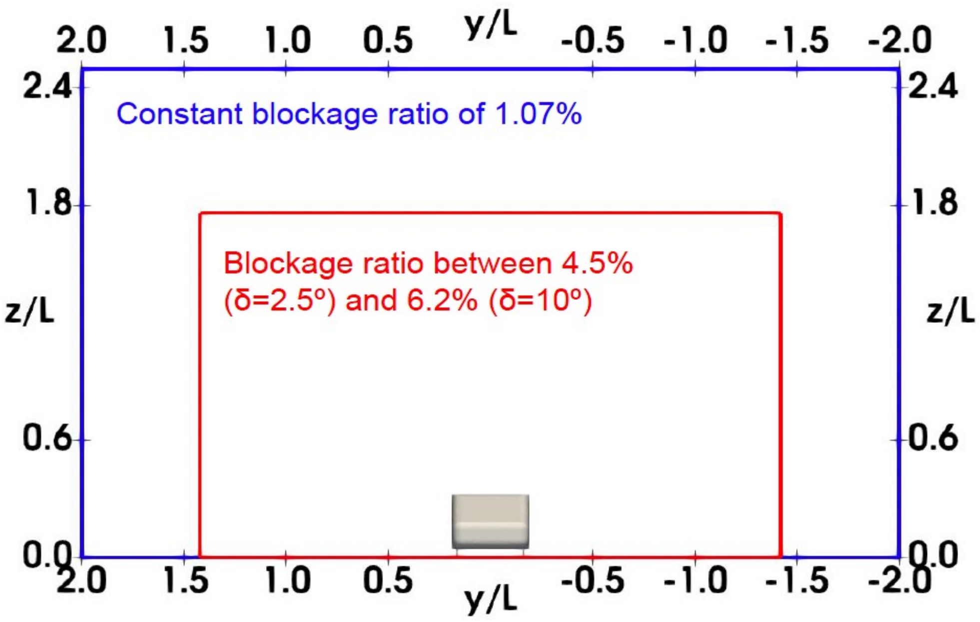
Validation I



Loughborough University's wind tunnel has a smaller test section than the domain used in this study

C_D comparison at δ=2.5º		
WMLES	WMLES	Experiment
0.2895	0.3200	0.3298

Experimental drag is matched when replicating the wind tunnel geometry

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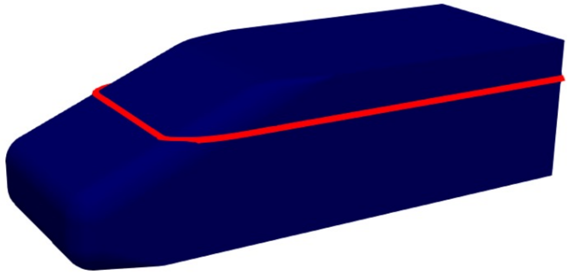
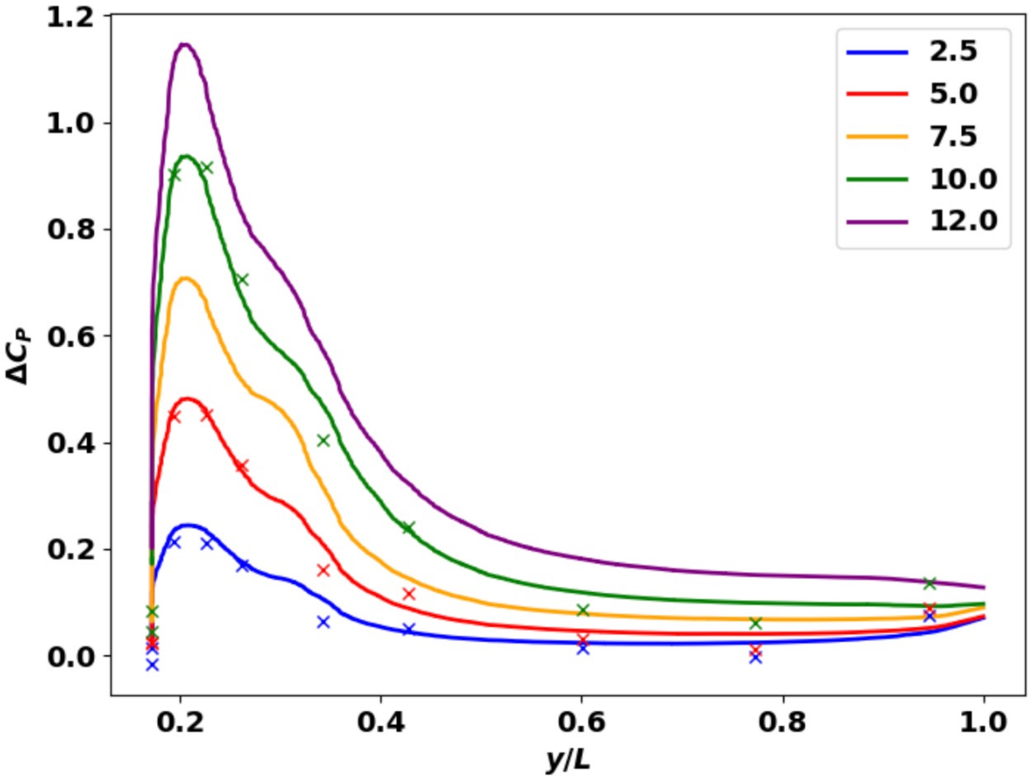
Experimental data extracted from: 10.17028/rd.lboro.13161284

On the wall-modeled large eddy simulations of the Windsor body at different yaw angles

Side pressure II



z/L = 0.24847



The difference with the pressure on the windward face increases rapidly with the angle, leading to a side force augment

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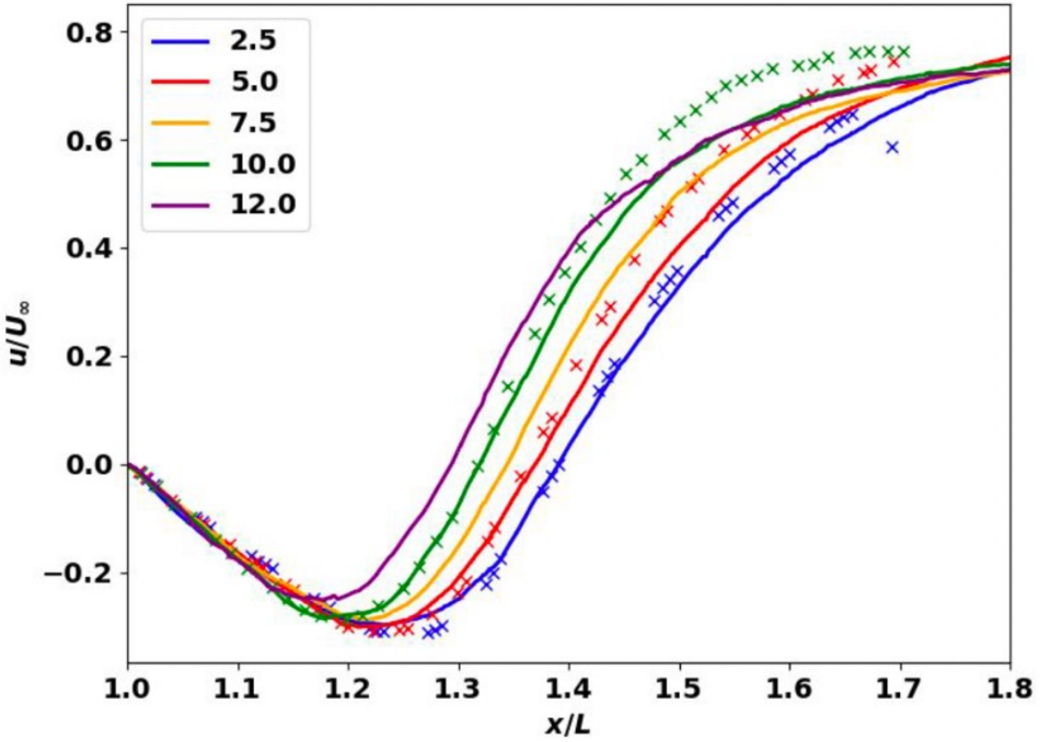
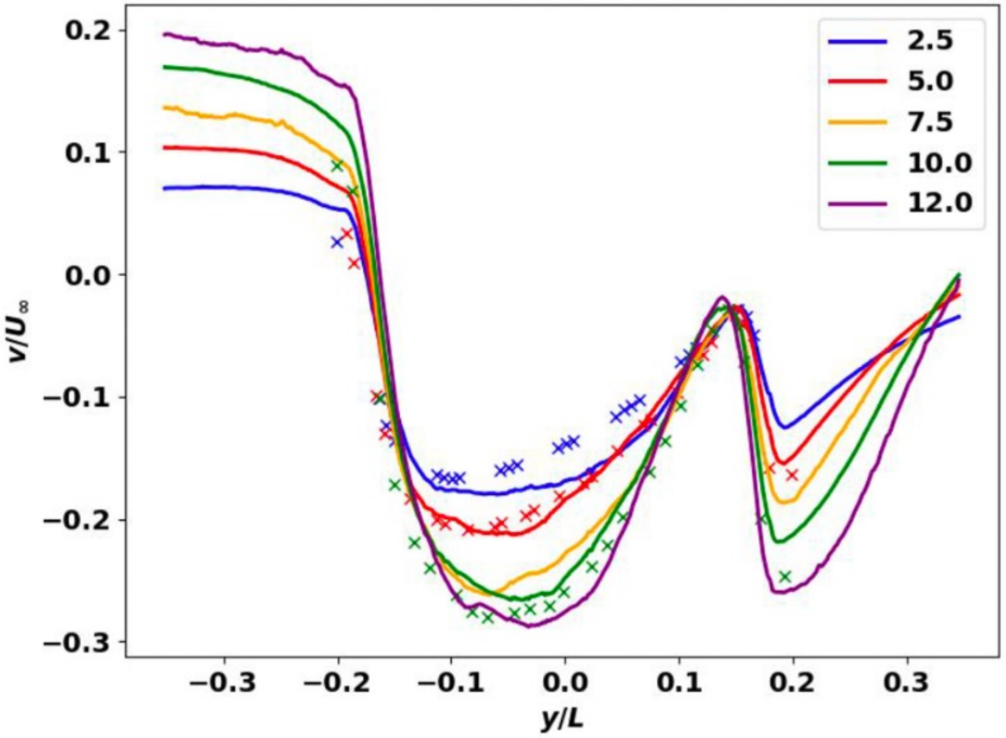
Validation II Wake velocity





Experimental data extracted from: 10.17028/rd.lboro.13161284

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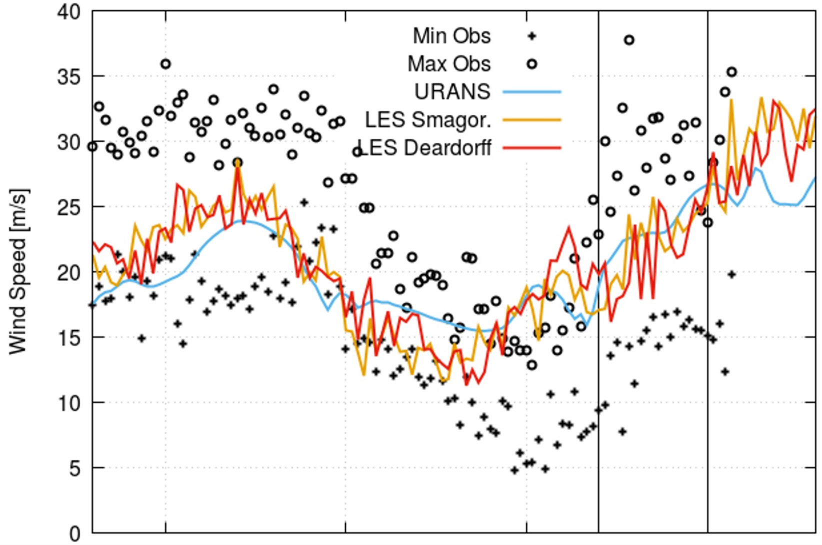
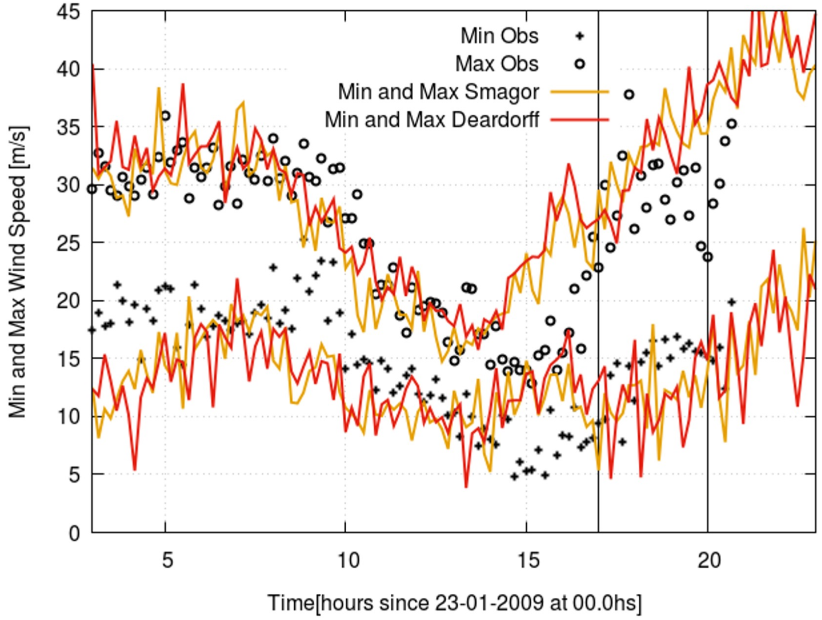
WIND ENERGY DEVELOPEMENTS

Mesoscale driving flows for Wind Energy, using RANS and LES



10 min. averaged wind speed at the *target WT*, *using keps, Smagorinsky and Deardorff models.*



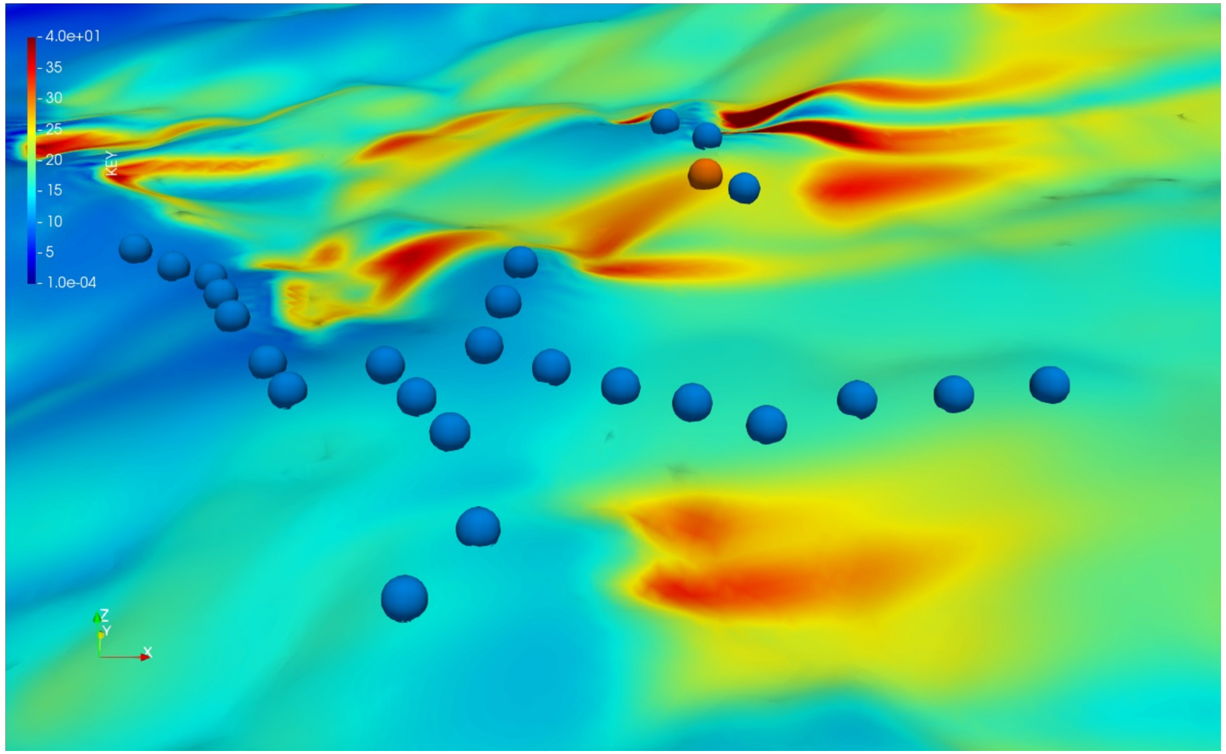
Maximum and minimum wind speed measured (black points) and LES-modelled every 10 minutes intervals.

TORQUE
The Science of Making Torque from Wind

Microscale simulations of extreme events in complex terrain driven by mesoscalar simulations

BSC Barcelona Supercomputing Center
Centro Nacional de Superc

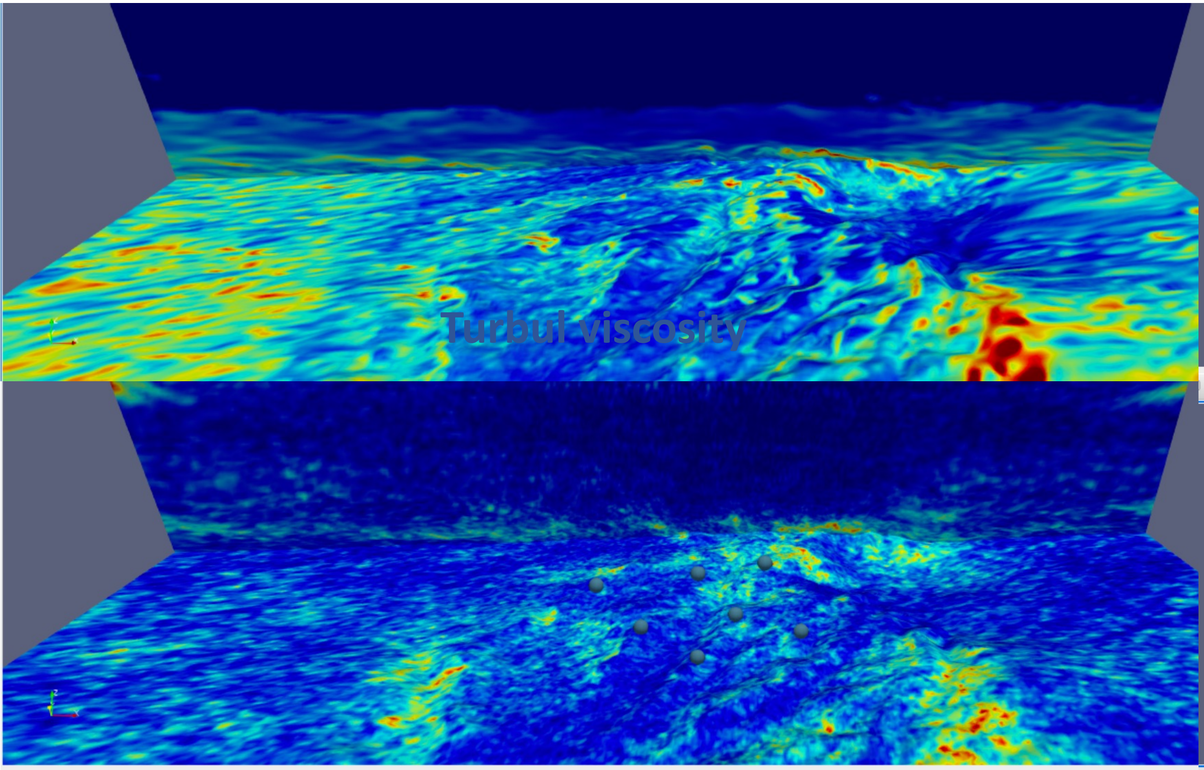
M. Avila[a], H. Owen[a], O. Lehmkuhl[a], J. Navarro[b], J.F. González-Rouco[c], D. Paredes[d] and G. Díaz-Marta[d]
[a]Barcelona Supercomputing Center(BSC), [b]CIEMAT, [c]UCM-CSICC, [d]Iberdrola Renovables Energía



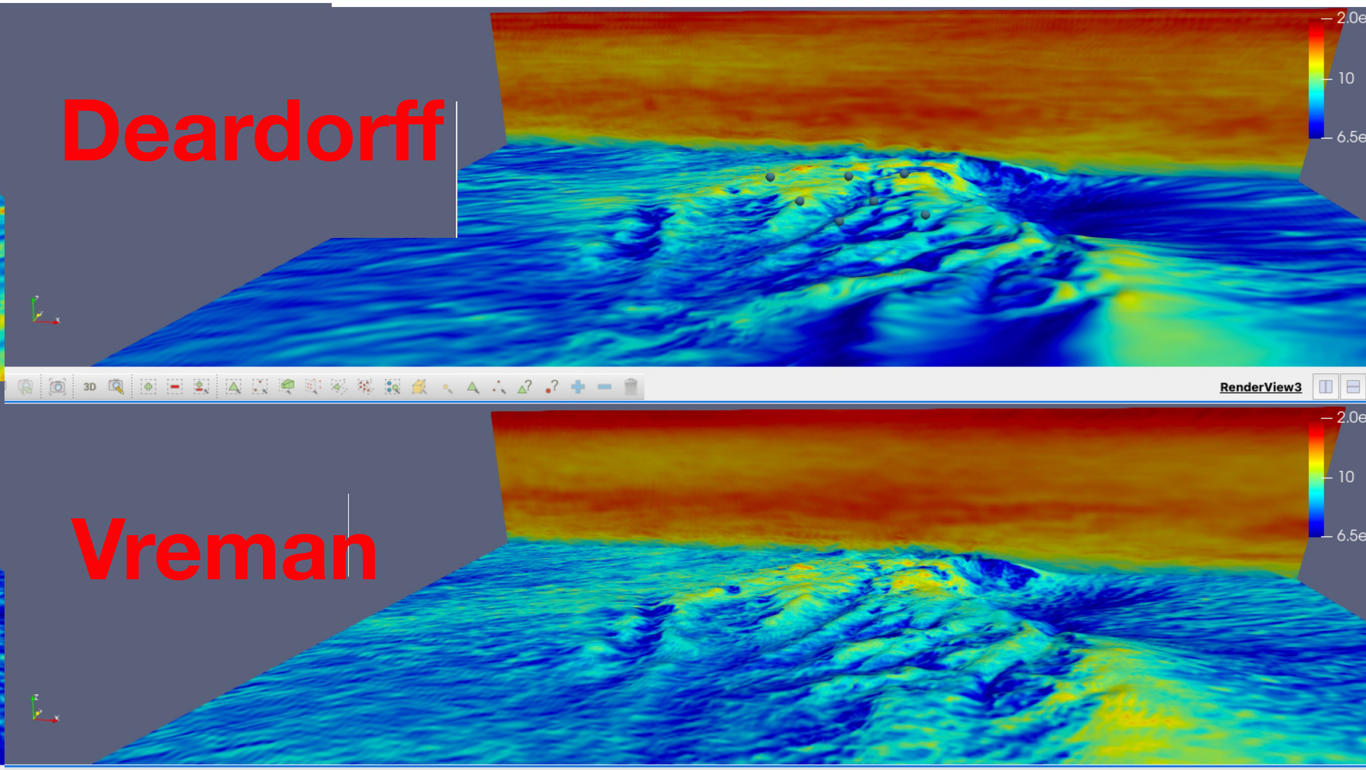
TKE contour plot [m2/s2] at 80m height at 20hs. Target WT is represented in red.

Wind speed at wind farms using LES models

Turbul viscosity



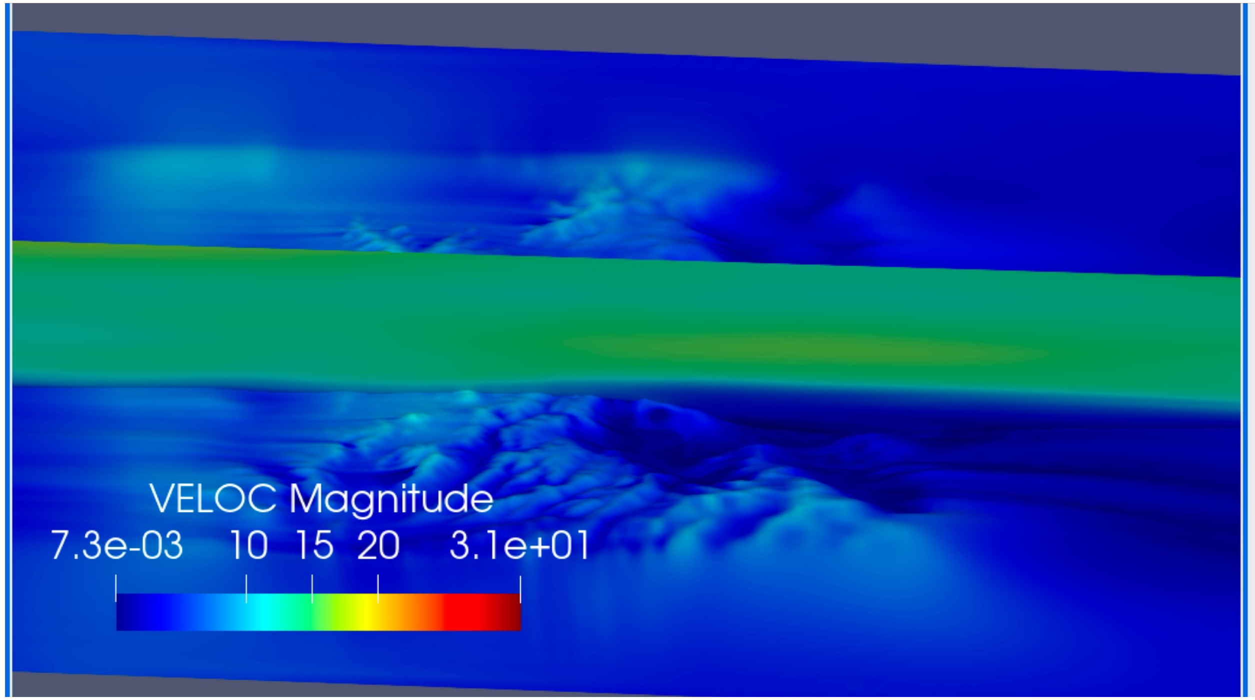
Instantaneous Wind Speed



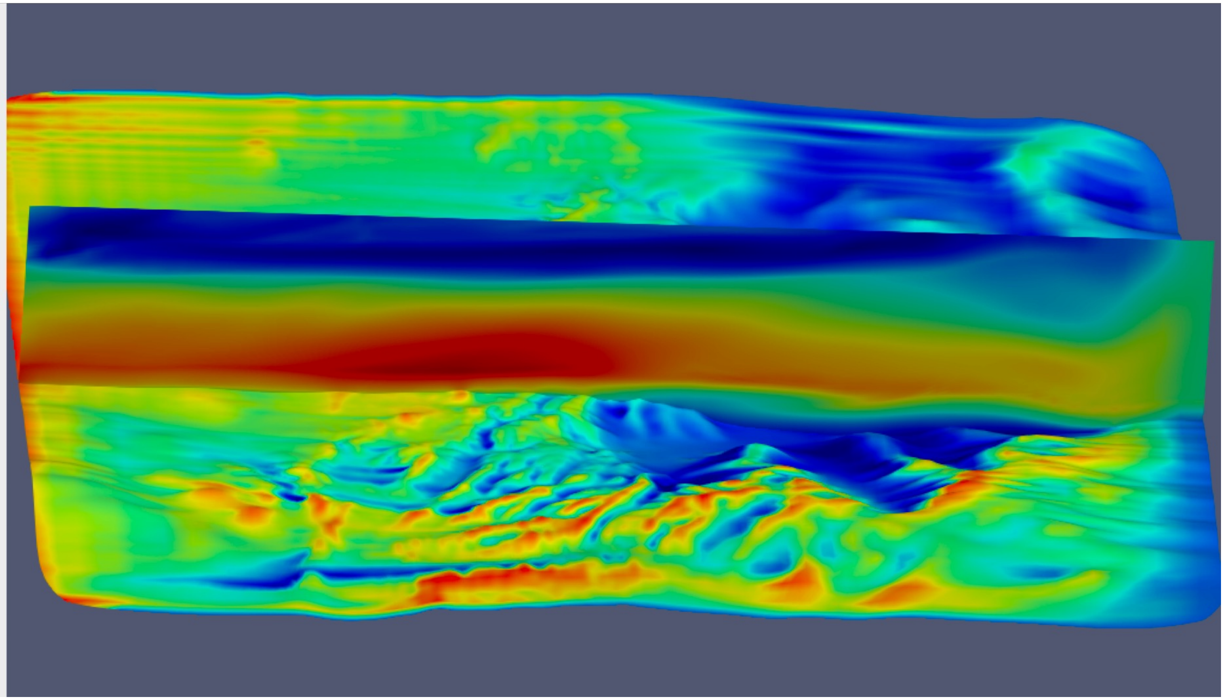
Deardorff model is more diffusive and removes the tubulence viscosity above ABL

Thermally coupled flow in a wind farm

Periodic



Non Periodic



- Same problem case, very different solutions
- Gravity waves reflecting on boundaries when imposing inflow/outflow b.cs.

Thanks!