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Stochastic sensitivity analysis to grid resolution and closure modeling in large-eddy simulation

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Background and Motivation

- ✓ **Large-eddy simulation:** the motion of turbulence large scales is directly simulated, while the effect of the small unresolved scales is provided through a subgrid scale (SGS) model.

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- ✓ Nowadays, large-eddy simulation (LES) is increasingly applied to complex flow configurations of interest in technological or environmental applications.

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- ✓ In this context, the assessment of the quality and reliability of LES results has become a topic of increasing interest.

This task is particularly complex for LES

Why?

Motivation

Main sources of error/uncertainty in LES

Discretization errors

- Numerical accuracy
- Grid resolution

SGS modeling errors

~~Boundary conditions (mainly inlet/outlet conditions)~~

- ✓ **RANS**: grid convergence can be often achieved and the dominating error is that due to turbulence modeling
- ✓ **LES**: different errors may be of the 'same order' and they may interact in a non-linear way leading to counterintuitive results:
  - ✧ for given scheme and SGS model, accuracy deteriorating with grid refinement,
  - ✧ for given grid and SGS modeling, lower-order schemes giving better results than higher-order ones,
  - ✧ for given grid and numerical scheme, no model simulations giving better results than LES with SGS modeling.

Discretization and SGS modeling uncertainties can not be considered separately

Controversial ideas in the LES community on how to manage numerical errors

- ✓ The numerical errors should be made negligible and all the 'burden' should be on the SGS modeling.

High-order schemes (e.g. Ghosal (1996), Kravchenko and Moin (1997))

Explicit filtering of width significantly larger than the grid size (e.g. Geurts and van der Bos (1995), Bose et al. (2010))

Both solutions are unpractical for complex flows of practical interest

- ✓ Get rid of 'physically based' SGS models and use numerics to provide a 'SGS-like' dissipation → ILES, MILES (e.g. Boris et al., 1992), SVV (Karamanos & Karniadakis (2000))....

Results highly dependent on the numerics, not well adapted to numerical methods employed for practical applications

Controversial ideas in the LES community on how to manage numerical errors

- ✓ Compromise: keep a 'physically based' SGS model and a 'not perfect' numerics.

The importance of different errors and their interactions should be assessed →this is difficult for complex applications, because this implies a simultaneous analysis of the sensitivity to (some of the) parameters characterizing numerical discretization and SGS modeling → it requires a huge number of simulations → only a few examples of such analyses for academic flows (e.g. Meyers et al. (2003, 2006, 2010), Kempf et al. (2011), Geurts (2009)) .

In general, sensitivity analysis is difficult for LES because of the large costs of each simulation

Discretization and SGS modeling uncertainties can not be considered separately

- ✓ A possible way is to consider some of the simulation parameters as random variables and to generate a continuous response surface in the uncertainty space.
- ✓ However, the number of deterministic simulations must be low → a possible way is to use simple surrogate models allowing the response surface to be generated from a few deterministic simulations.

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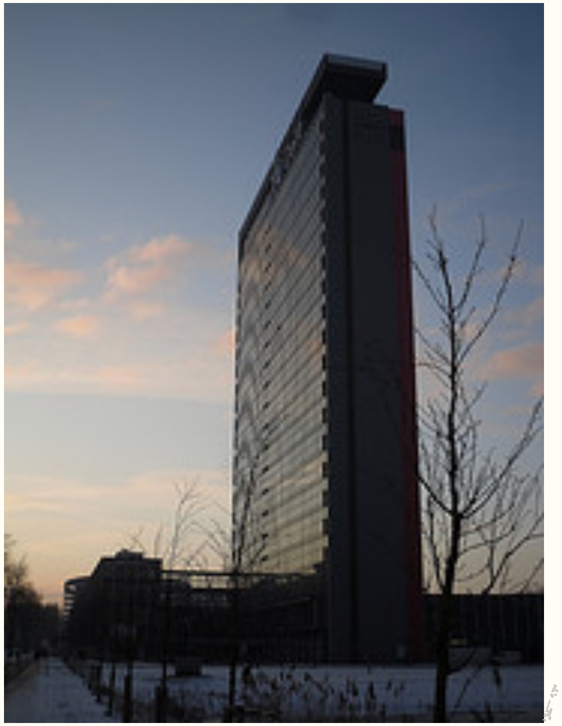
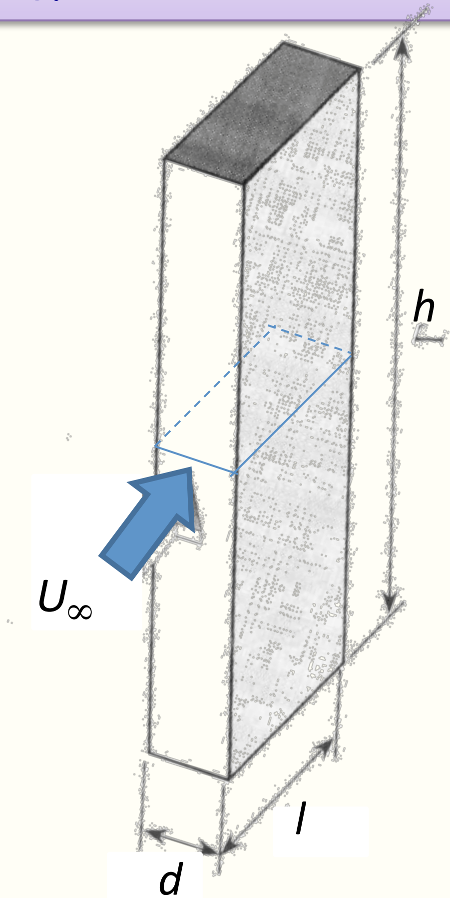
Present work: stochastic quantification of sensitivity to modeling and discretization parameters in LES of the flow over a **5:1 rectangular cylinder**

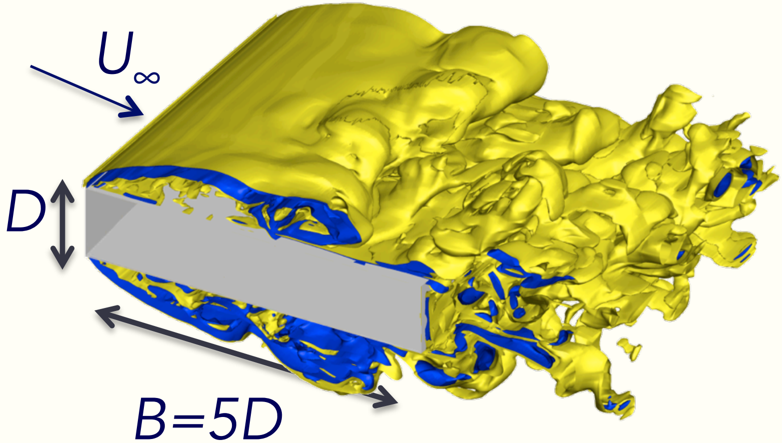
Flow around a 5:1 rectangular cylinder (BARC benchmark)

Tall buildings, towers and bridges can be modeled by a rectangular cylinder, which despite its relatively simple geometry contains most of the difficulties found in realistic bluff bodies.





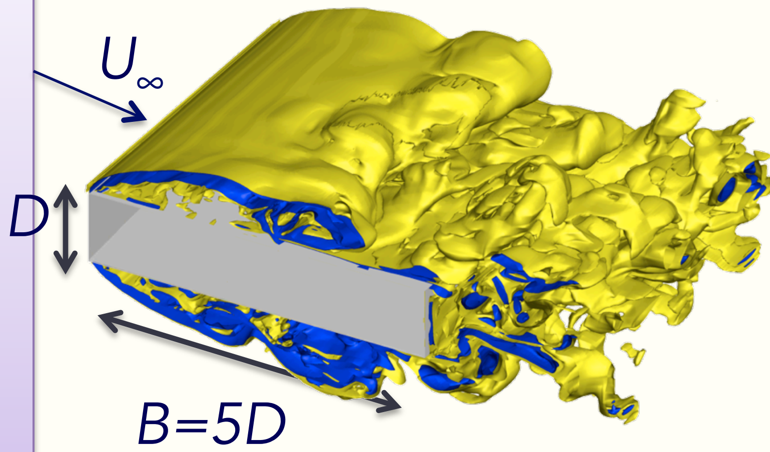
In spite of the simple geometry, the flow is complex, being turbulent with separation from the upstream corners and reattachment on the cylinder side and vortex shedding from the rear corners.

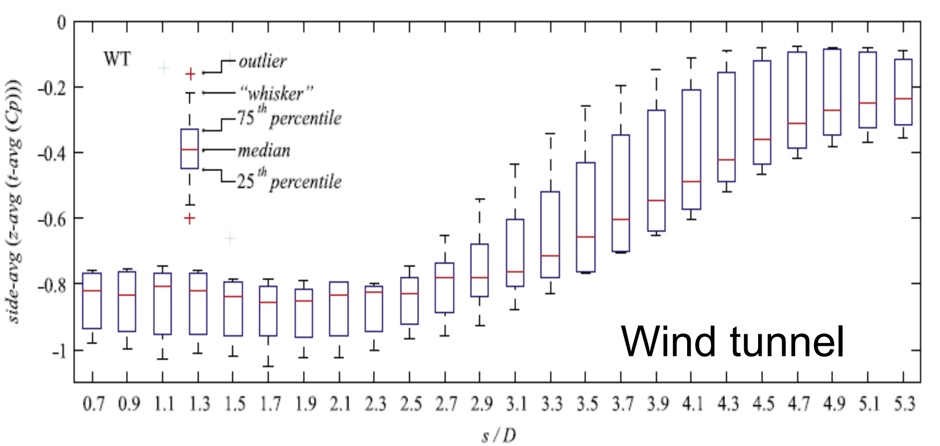


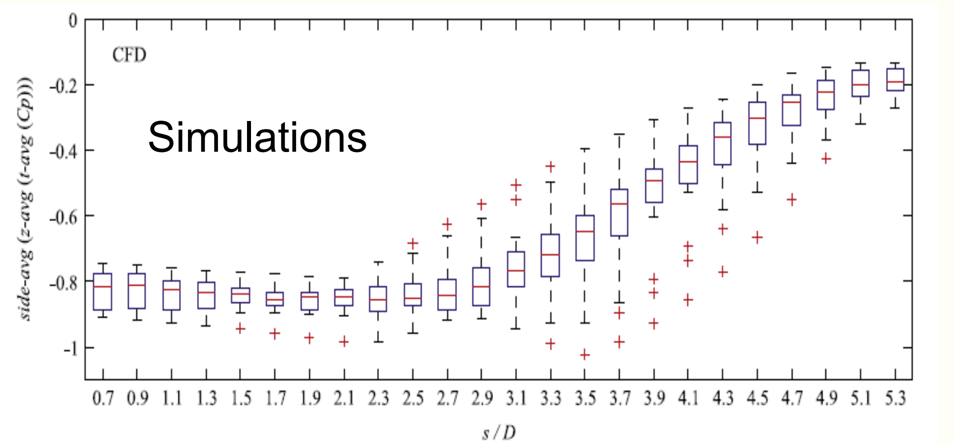
$$\mathrm{Re} = \frac{dU_\infty}{\nu} = 4 \times 10^4$$

Flow around a 5:1 rectangular cylinder (BARC benchmark)

- ✓ Up to 70 numerical and experimental realizations of the BARC flow configuration have been collected. (Bruno, Salvetti, Ricciardelli, JWEIA 2013); 51% of the numerical contributions were LES.
- ✓ Significant dispersion of some flow quantities of interest, as e.g. the mean pressure distribution on the cylinder side.







- ✓ Deterministic sensitivity analyses to some parameters were not conclusive and in some case controversial. For instance, Bruno et al. (2012) showed a strong impact of spanwise resolution, but the results on the finest grid significantly deviate from the ensemble average of BARC contributions.

Motivation

Main sources of Uncertainty in BARC

Discretization errors | Modeling errors

~~Uncertainties in problem set-up~~ | ~~Measure uncertainties~~

CFD

Experiments

Aim of the present work: contribute to understand to which extent the discretization and modeling errors may explain the dispersion of the BARC numerical contributions (at least for LES)

Impact of uncertainties in inlet conditions by means of probabilistic methods and URANS simulations. (Witteveen et al. AIAA paper 2015-0663, Mariotti et al.,Computers and Fluids, 136 (2016)).

Mariotti et al., Eur. J. Mechanics/B Fluids, 62 (2017).

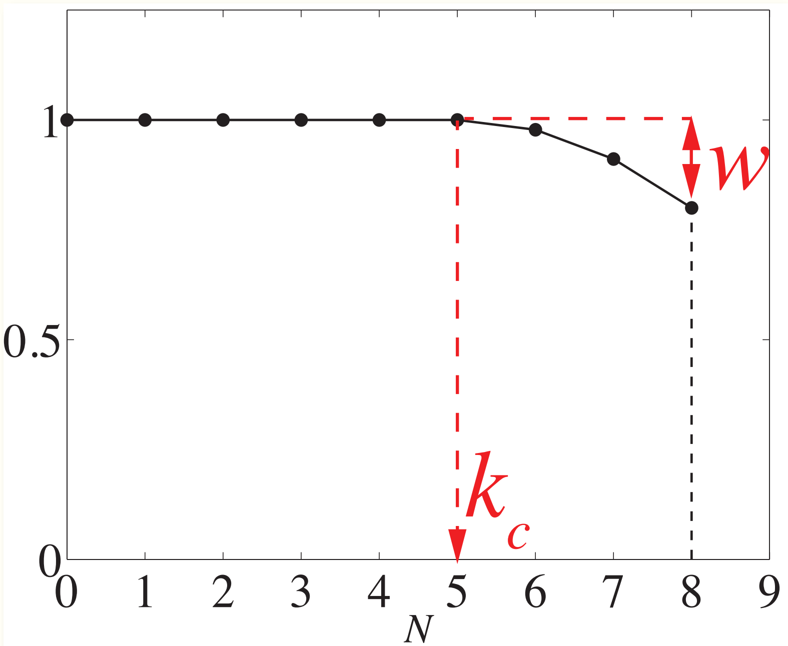
Methodology and modeling

✓ Numerical method: LES were carried out using NEK5000 (open-source spectral element code):

☞ N-th order Lagrangian polynomial interpolants in each grid element (N-2 for pressure). N=6 in the present simulations

☞ Third-order backward finite difference scheme for time advancing.

✓ LES modeling: based on explicit modal filtering. The adopted filter is a sharp cut-off for the modes up to $N-k_c$ (unfiltered) and it has a quadratic transfer function for the modes $N-k_c \leq p \leq N$, which can be tuned through a weighting parameter, w. This modal filter provides a dissipation in the highest resolved modes, which can be interpreted as a SGS dissipation (e.g. Mathew et al., 2003, Domaradzki, 2010).



UQ approach: non intrusive generalized polynomial chaos

UQ inputs → NUMERICAL MODEL → Output quantities

Choice of the uncertain parameters:

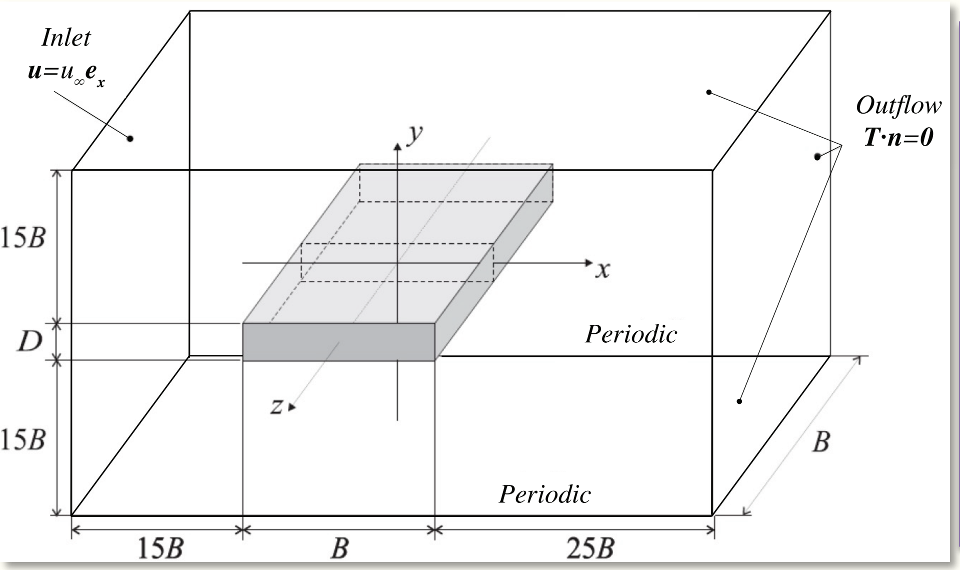
- ✧ filter weight, w, because it directly controls the amount of 'SGS dissipation'. The number of filtered modes is for the moment kept constant ($N-k_c=3$)
- ✧ grid resolution in the spanwise direction, Bruno et al. (2012) showed a strong impact of spanwise resolution, but the results on the finest grid significantly deviate from the ensemble average of BARC contributions.

Uniform PDF distribution in the following ranges:

$$\Delta z \in [0.31D, 0.67D]$$
$$w \in [0.01, 0.13]$$

UQ approach: non intrusive generalized polynomial chaos

UQ inputs — **NUMERICAL MODEL** — Output quantities

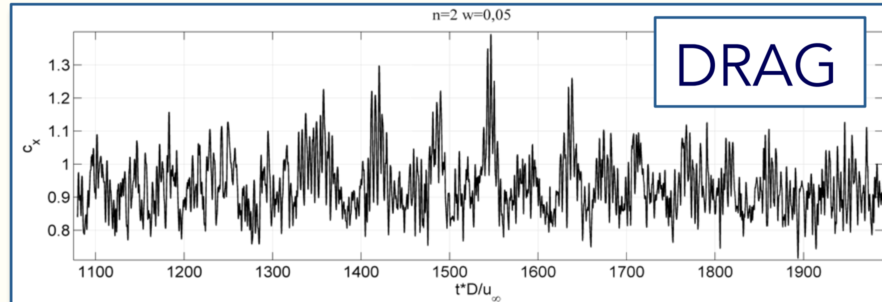


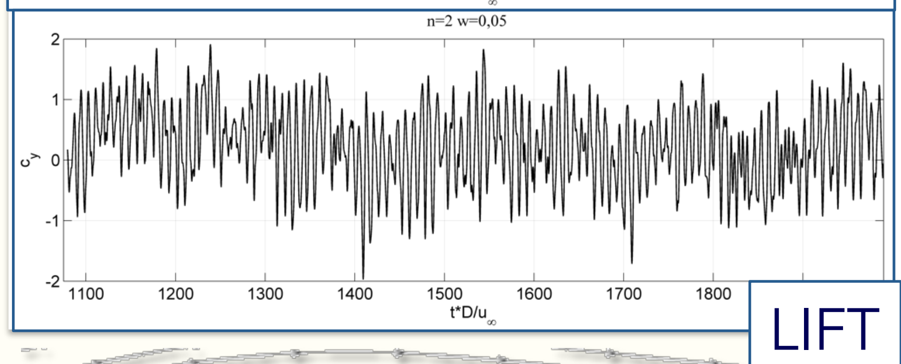
- ✓ Polynomial order: N=6
- ✓ (PN-PN-2 form.)
- ✓ N filtered modes: 3
- ✓ B/D=5
- ✓ Re_D=40000
- ✓ No freestream turbulence
- ✓ Δt=0.004 (CFL≈0.37)

- ✓ Uniform PDF distribution →Legendre polynomials
- ✓ gPC expansion truncated at order 3→16 deterministic LES simulations
- ✓ The UQ analysis is carried out for two different grid resolutions in the x-y plane: Hx=Hy=0.2D and 0.1D → effects of discretization

UQ approach: non intrusive generalized polynomial chaos

UQ inputs — NUMERICAL MODEL — **Output quantities**





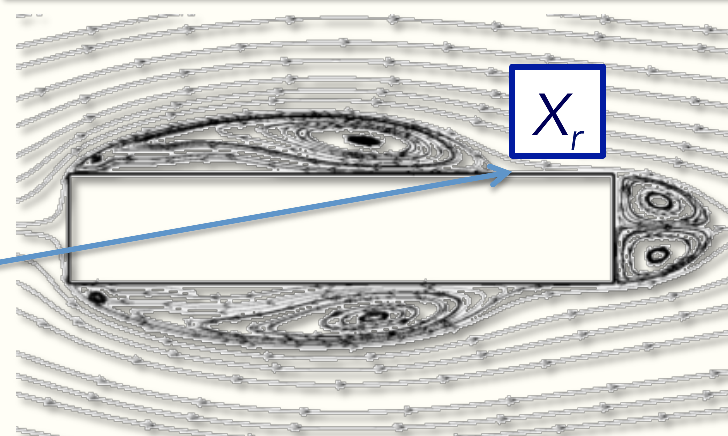
Statistics of the aerodynamics loads

- Mean drag coefficient t-avg(Cx)
- Standard deviation of the lift coefficient t-std(Cy)

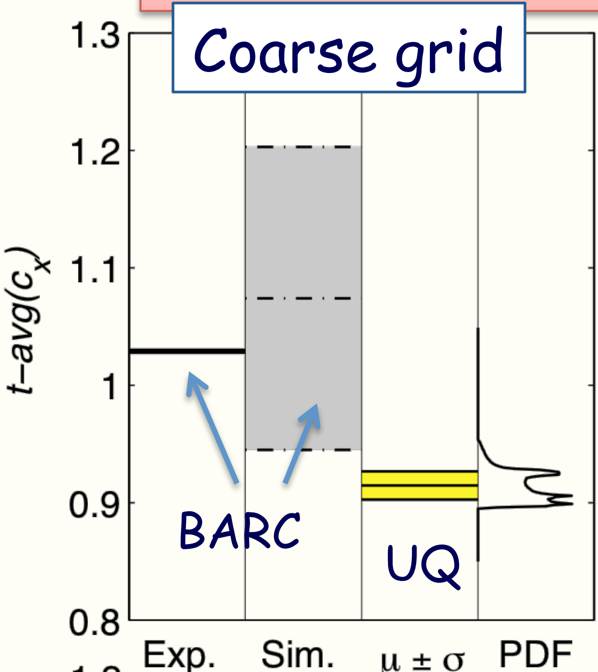
Pressure distribution on the lateral side (spanwise averaged)

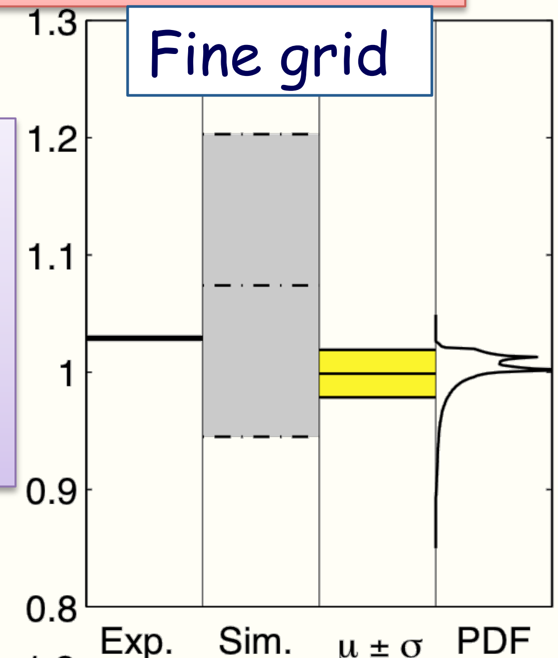
- Mean pressure coefficient t-avg(Cp)
- Standard deviation of the pressure coefficient t-std(Cp)

Reattachment point of the mean recirculation region (spanwise and time averaged)



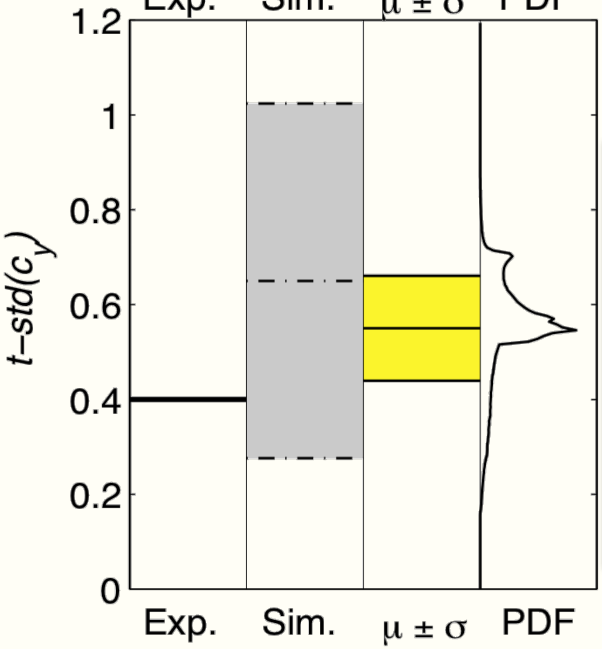
Statistics of the aerodynamic loads

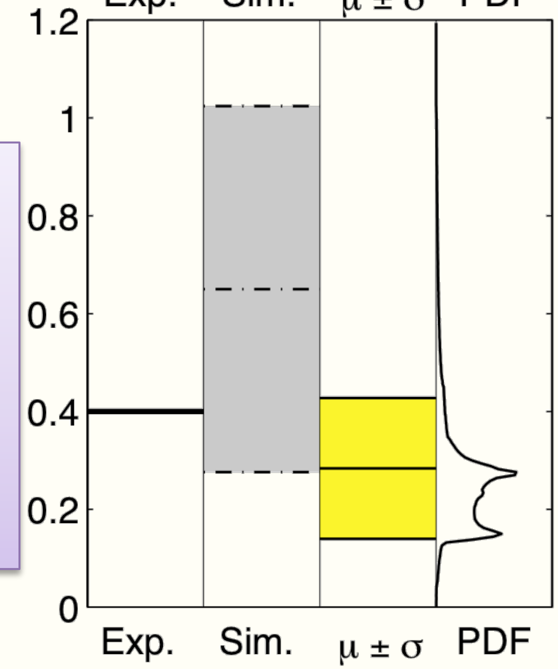




Mean drag

- Very low variability of mean drag
- Grid refinement changes the stochastic mean values, but only slightly the variability

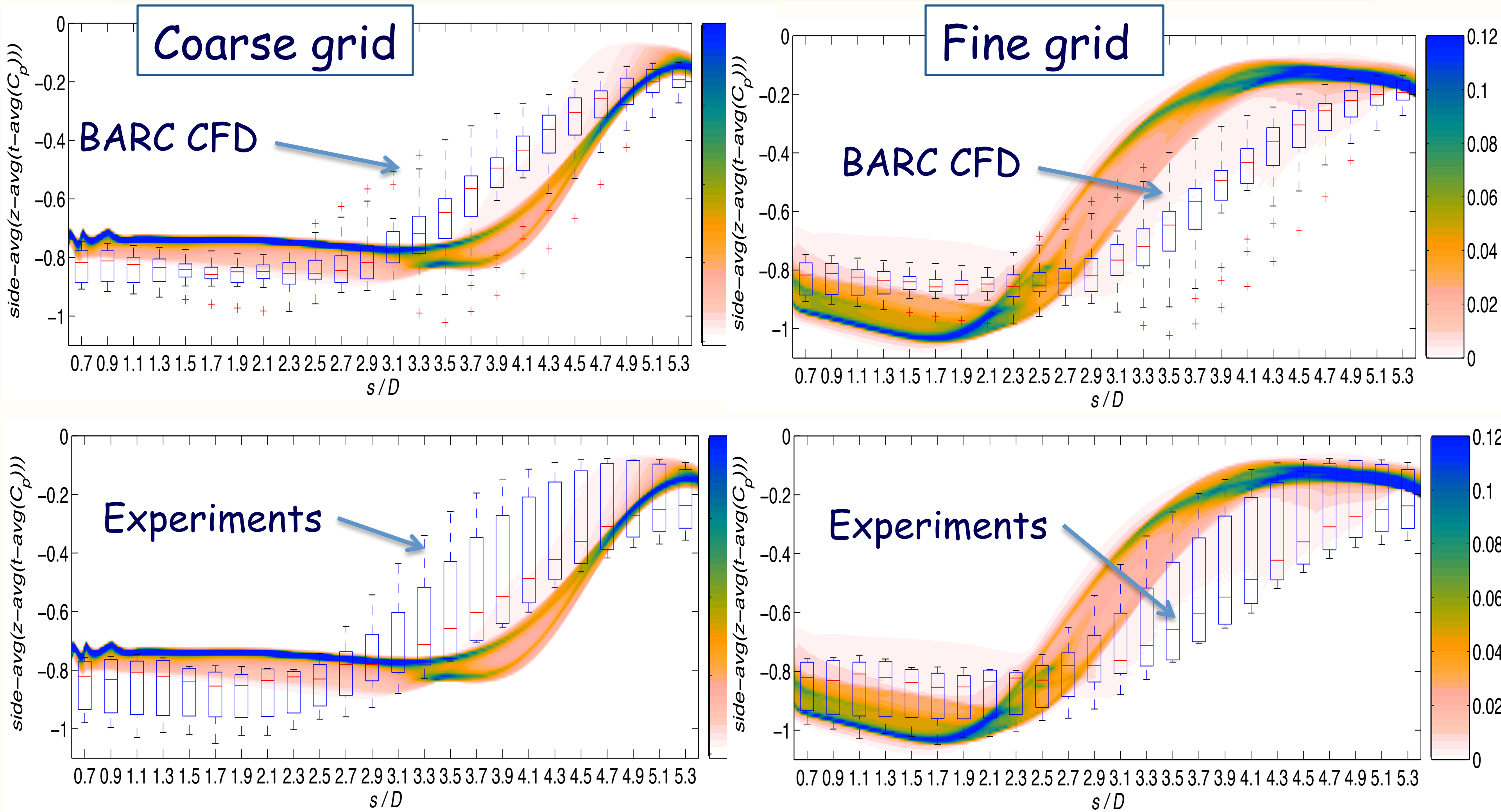




Lift standard deviation

- Larger variability as also observed in the BARC contributions
- Large tails of the PDF → some combinations of the parameters can lead to very different predictions

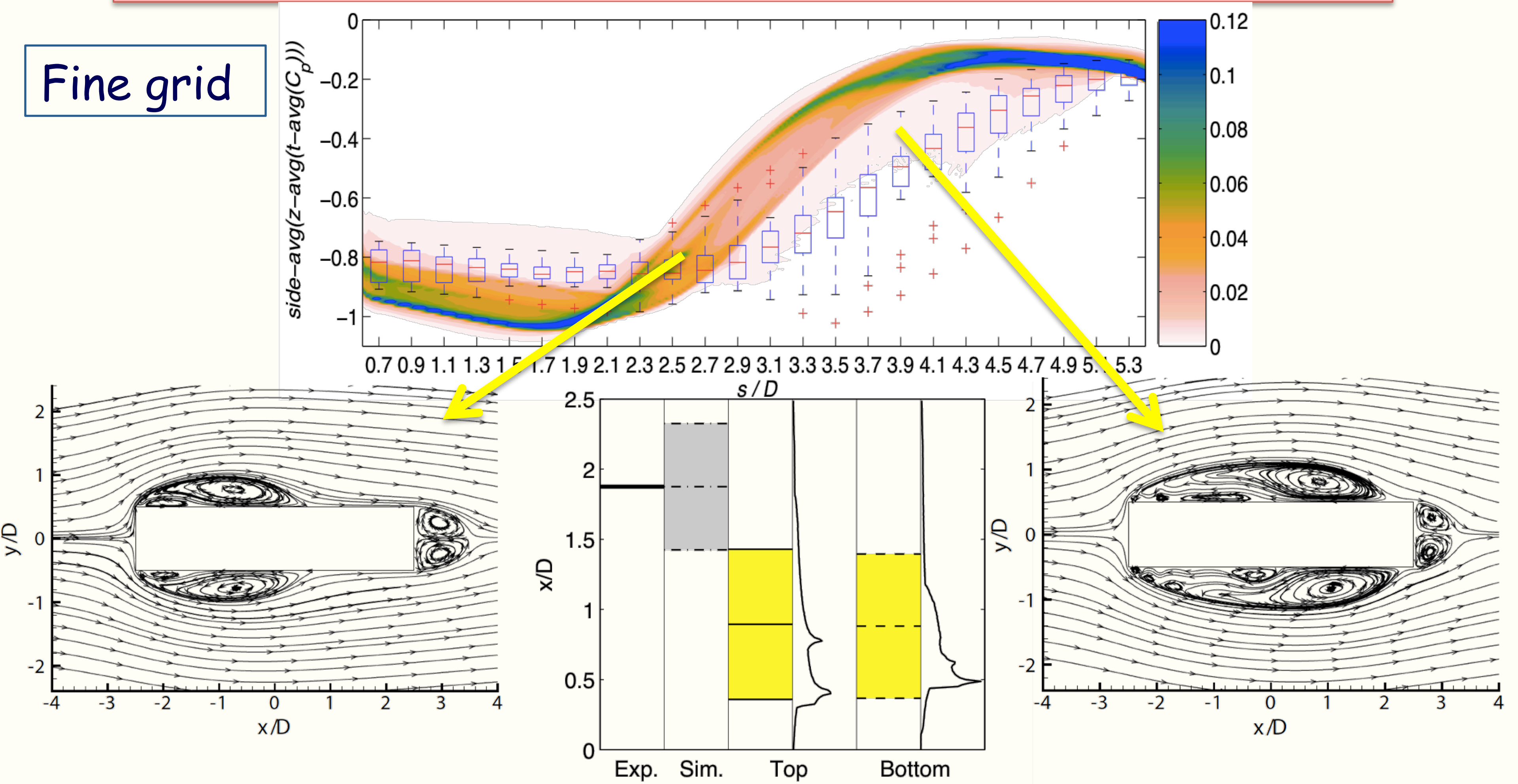
Mean pressure coefficient



- ✓ The variability of the mean pressure distribution on the coarse grid is significantly lower than the overall dispersion of the BARC contributions.
- ✓ On the fine grid the variability increases and the 'shape' of the mean pressure distribution changes

Mean pressure coefficient

Fine grid

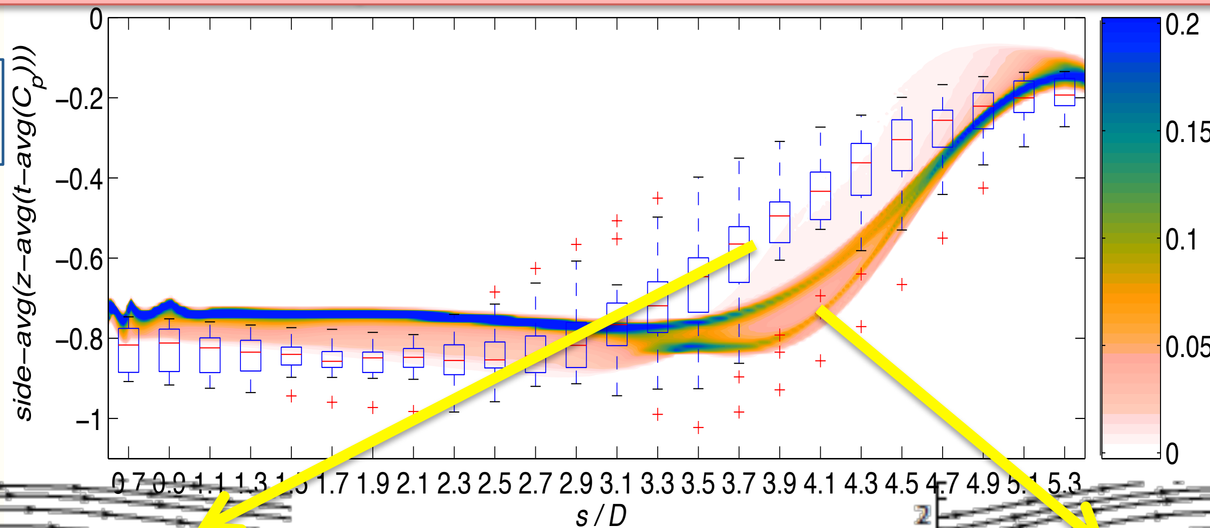


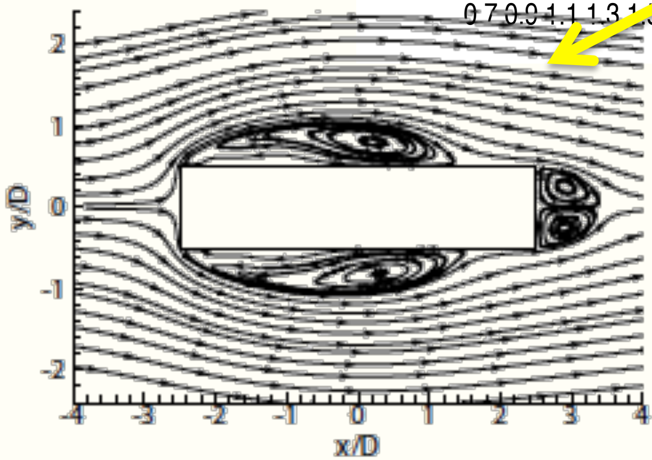
Reattachment point location

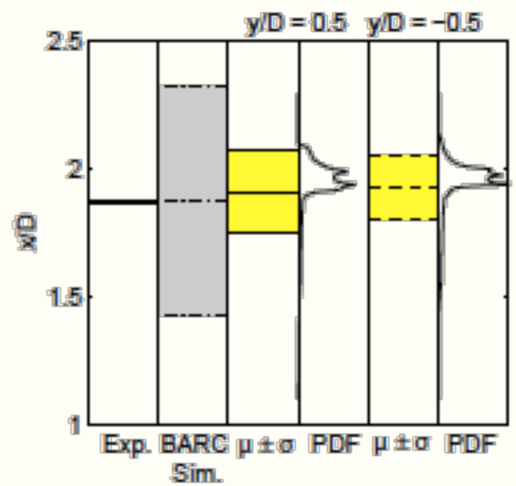
- ✓ Significantly different mean flow topology can be obtained on the fine grid by varying spanwise grid refinement and SGS modeling (short and long mean recirculation zones).
- ✓ The short mean recirculation zones are the 'most probable' configuration on the fine grid (in agreement with Bruno et al. (2002)).

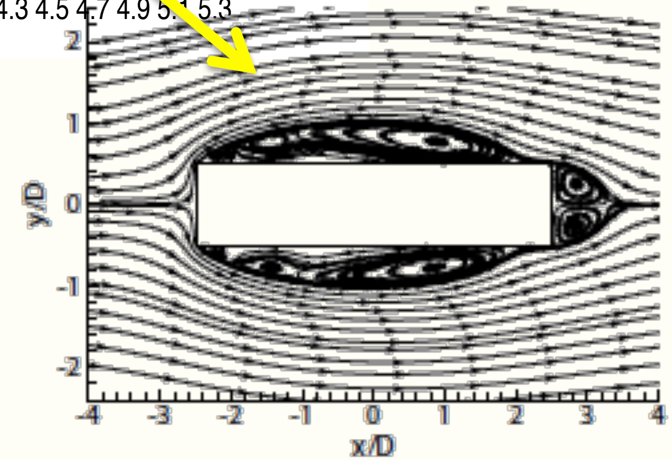
Mean pressure coefficient

Coarse grid





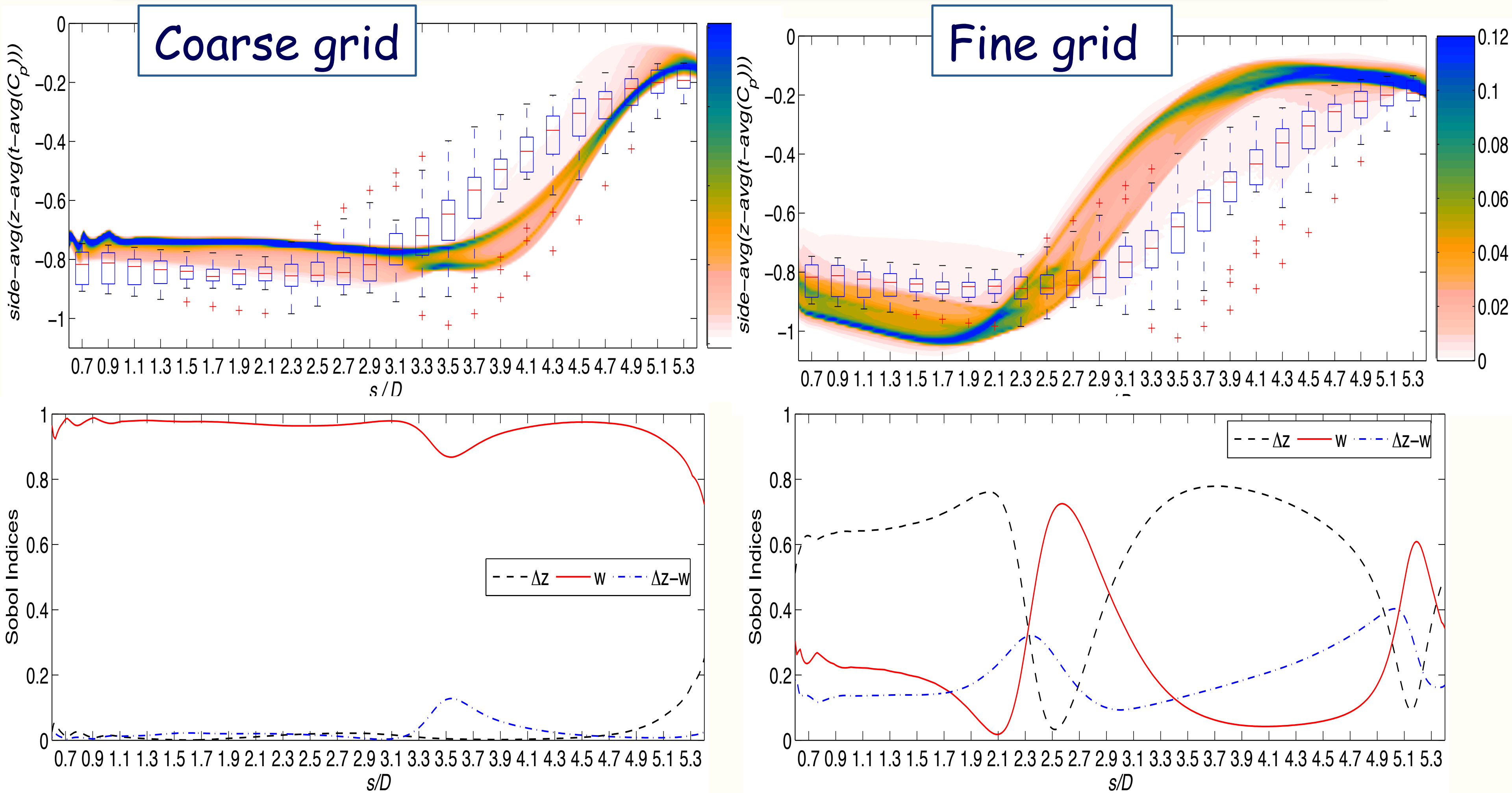




Reattachment point location

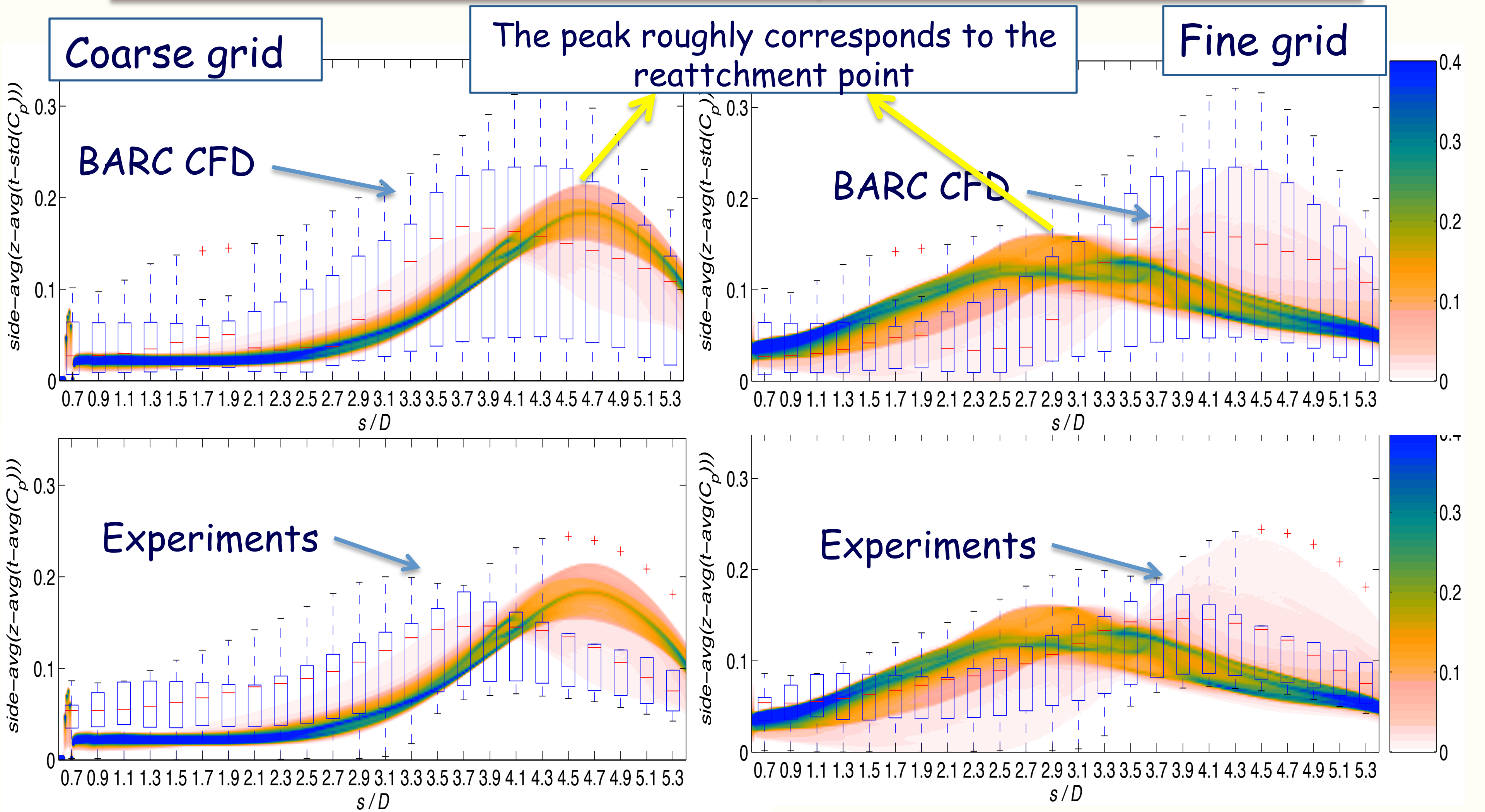
- ✓ The long mean recirculation zones are the 'most probable' configuration on the fine grid
- ✓ A slightly shorter recirculation is obtained only for the filter yielding the lowest SGS dissipation.

Mean pressure coefficient



- ✓ On the coarse grid, the mean pressure distribution is mainly sensitive to SGS modeling.
- ✓ For the fine grid, the sensitivity to the parameters is more complex; but the spanwise grid resolution seems to have the largest impact.

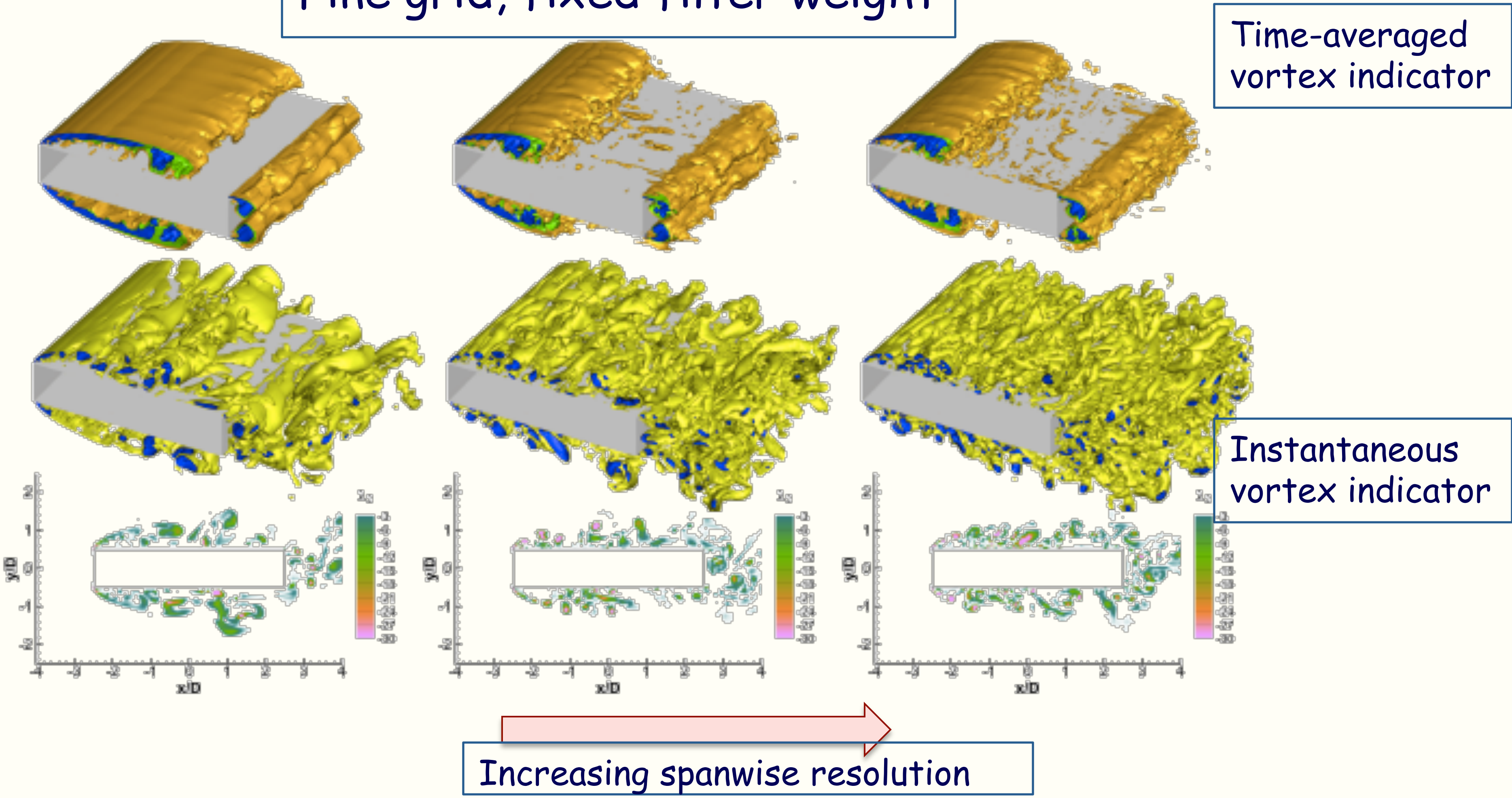
Standard deviation of the pressure coefficient



- ✓ The variability of this quantity on the coarse grid is once again much lower than the overall dispersion of the BARC contributions.
- ✓ On the fine grid, enhanced variability and different shape due to the changes in the mean flow topology.

Physical explanation

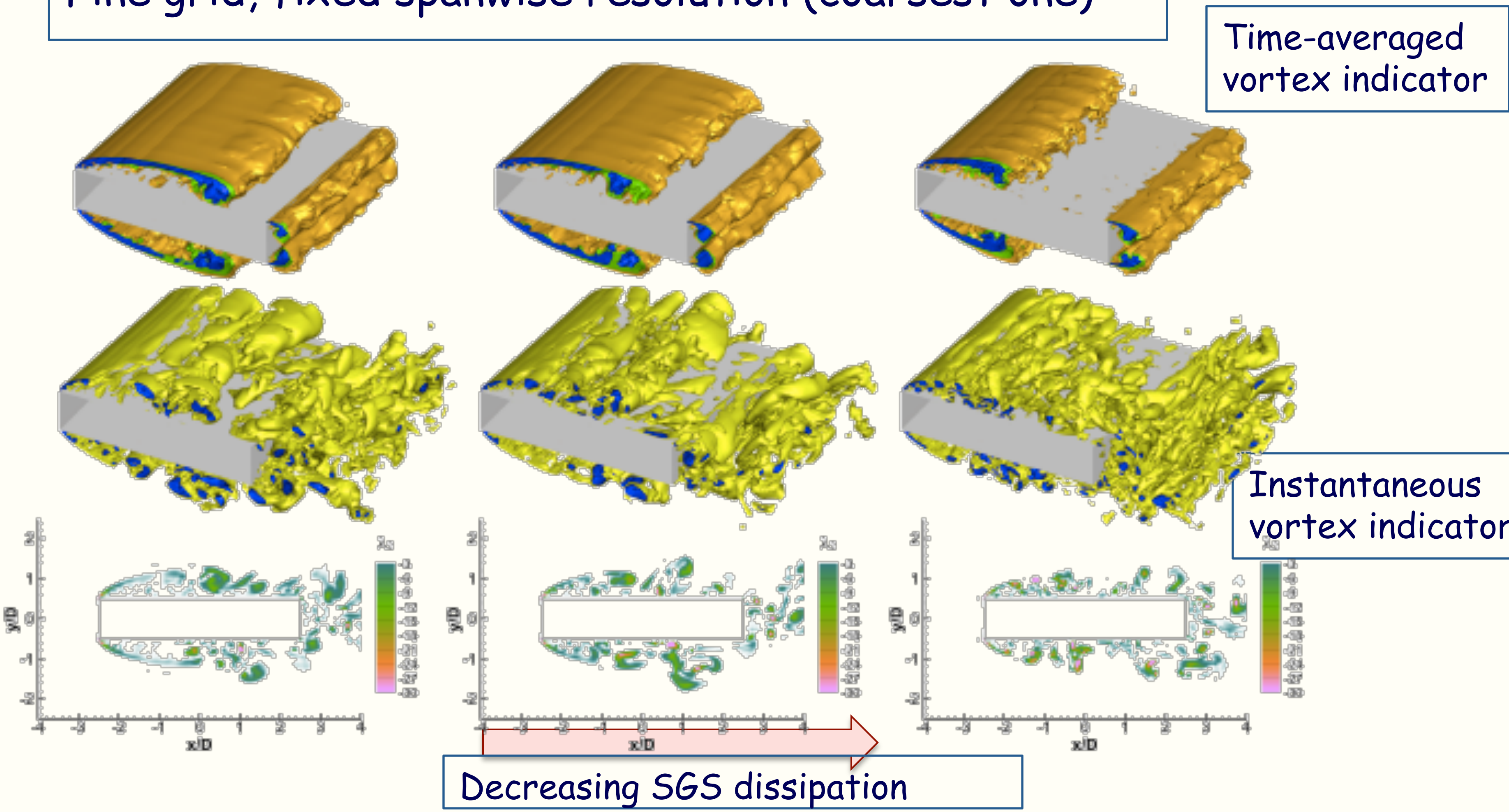
Fine grid, fixed filter weight



Increasing the spanwise resolution allows to capture very small 3D vortical structures which are related to an upstream instability of the shear layers detaching from the front corners, which in turn leads to a short mean recirculation zone.

Physical explanation

Fine grid, fixed spanwise resolution (coarsest one)



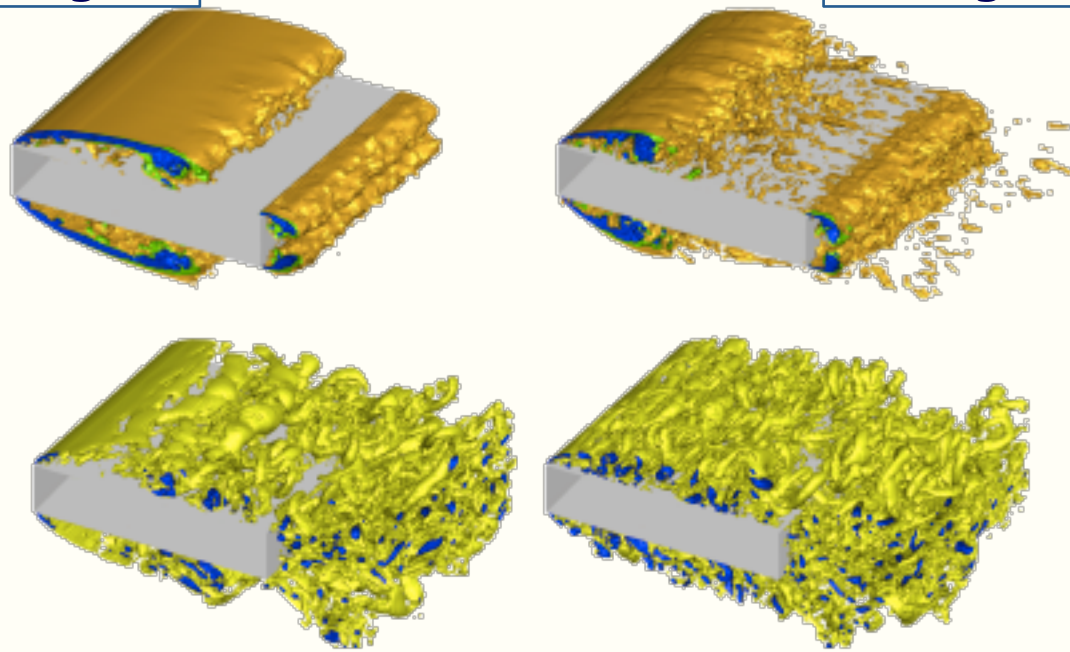
Decreasing the SGS dissipation allows to fairly capture small 3D vortical structures also for coarse spanwise grid resolution → short mean recirculation zone.

Physical explanation

Finest spanwise resolution and filter weight yielding the lowest SGS dissipation

Coarse grid

Fine grid



Time-averaged vortex indicator

Instantaneous vortex indicator

For the coarse horizontal grid also with the finest spanwise resolution and the lowest SGS dissipation small 3D vortical structures are not well resolved → longer mean recirculation zone.

Summary

- ✓ The stochastic sensitivity analysis reveals a high sensitivity for the quantities related to the flow features on the lateral surface of the cylinder, in agreement with BARC overview.
- ✓ The overall variance of the results of our LES on the coarse grid is generally much lower than the BARC global dispersion. The results are mainly affected by SGS dissipation.
- ✓ The strong effect of spanwise grid resolution, observed by Bruno et al. (2012), has been found in our analysis but only if combined with a fine grid resolution also on the other directions→ short mean recirculation zones on the cylinder side
- ✓ Analysis of deterministic simulations show that this is connected with the capability of resolving small 3D vortical structures which are related to an upstream instability of the shear layers detaching from the front corners, which in turn leads to a short mean recirculation zone.
- ✓ 'Best' results (fine resolution and small SGS dissipation) tend to deviate from the ensemble of the numerical contributions to BARC. This can be understood since URANS or hybrid approaches have difficulties in resolving small structures. The present study also shows that LES need a very fine grid resolution and limited dissipation.

Summary

'Best' results also deviate from experimental data

Why?

- ✓ Possible effect of perfectly sharp upstream corners in the numerical simulations while they have a certain degree of roundness in experiments?
- ✓ Possible effect of spanwise length?

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Possible future stochastic sensitivity analyses also to these additional parameters

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More efficient sampling techniques in the parameter space to avoid a too large increase of the required deterministic simulations

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