Enhancing Accuracy of Large Eddy Simulation for Particle-Laden Wall-Bounded Flows Through Stochastic Subgrid Scale Fluctuations Modeling

Farid Rousta[1], Goodarz Ahmadi[1], Bamdad Lessani[2]

[1] Department of Mechanical and Aerospace Engineering
Clarkson University, Potsdam, NY

[2] Department of Mechanical Engineering and Engineering Science
The University of North Carolina at Charlotte, NC

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  - ❑ Stochastic SGS fluctuations modeling
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Turbulent particle-laden flow

Aerosol in exhaled breath or sneeze

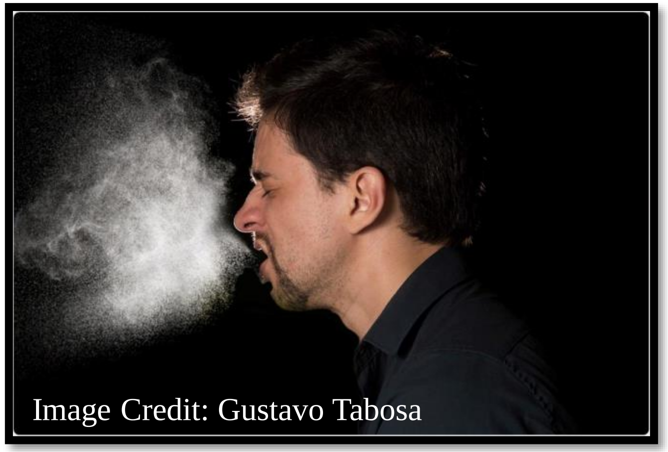


Image Credit: Gustavo Tabosa

Sediment transport in rivers


esa.int

blood flow (plasma (liquid), red blood cells(solid))


rdworldonline.com

Air pollution


forbes.com

Volcanic eruptions


iberdrola.com

Rain formation in clouds


netweather.tv

Sand and dust storms

Turbulent particle-laden flow

Study of turbulent particle-laden flows

Due to inherent complexity of turbulent flow, analyzing its interaction with dispersed phase, particle deposition and heat transfer is challenging.

Experimental

- Useful physical information
- Data can be used to validate the numerical solver
- Sometimes hard to perform
- Expensive and time consuming

Numerical

- Robust numerical algorithms are needed (ongoing topics of research)
- Effect of different parameters can be studied
- Future behaviors of the flow can be predicted
- The design optimization can be performed

Solver and computational domain

Numerical simulation

Eulerian-Lagrangian method
With point-particle assumption

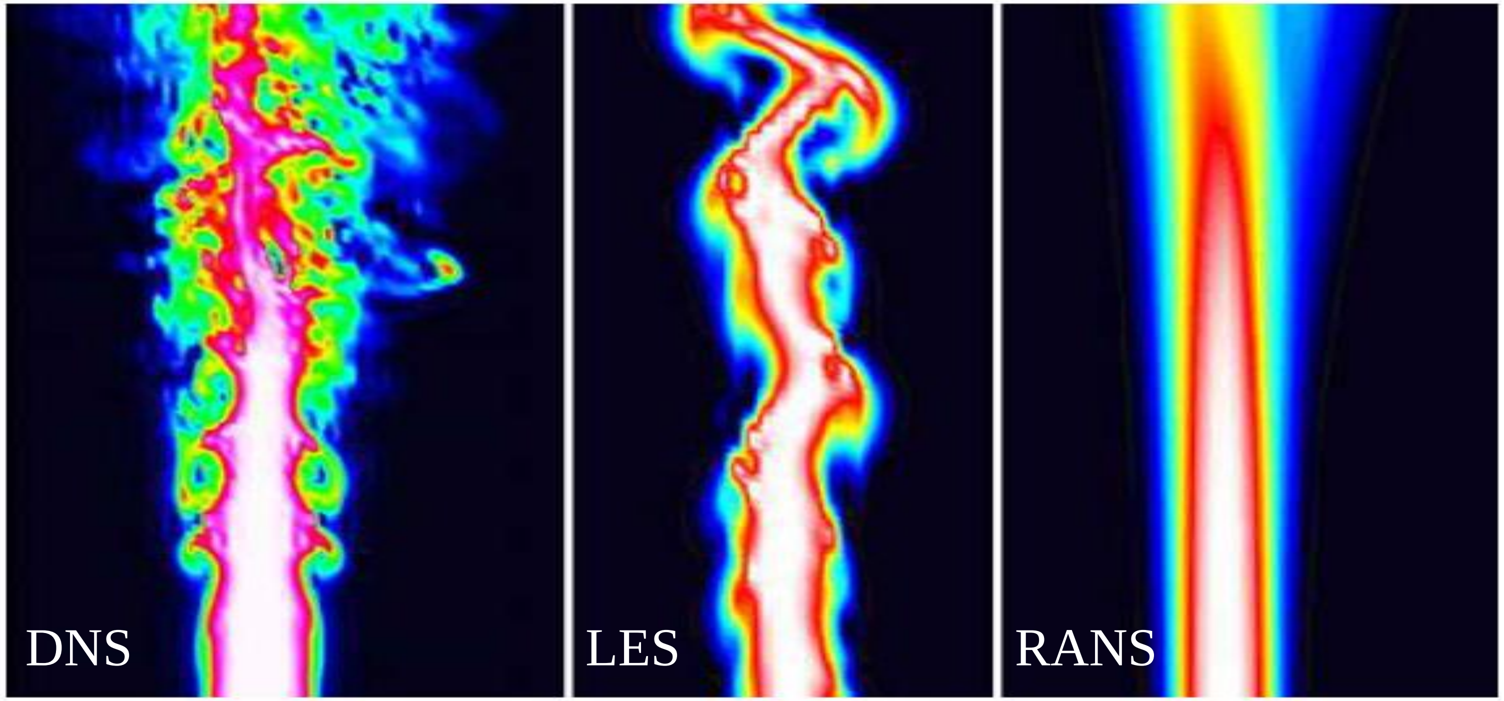
- High accuracy

To resolve the dispersed phase at lower mass fractions.

- Simplicity of modeling

The interaction between the phases.

Carrier phase, Eulerian



- Resolving all of the turbulence scales
- No modeling
- Computationally expensive

- Resolving large scales
- Sub-grid Scale stresses are model
- Trade-off between accuracy and computational cost

- Mean quantities of fluid flows
- Reynolds stress terms are model
- Lowest computational cost

Maries, Adrian, et al. "Interactive exploration of stress tensors used in computational turbulent combustion." New Developments in the Visualization and Processing of Tensor Fields. Springer, Berlin, Heidelberg, 2012. 137-156.

Motivation and Objective

Motivation

- Enhancing LES accuracy in particle-laden wall-bounded flows through subgrid-scale fluctuations modeling for particles.

Objective

- Develop an appropriate Langevin equation for simulating sub-grid scale velocity fluctuations seen by particles so that particle fluctuation and concentration are correctly predicted.

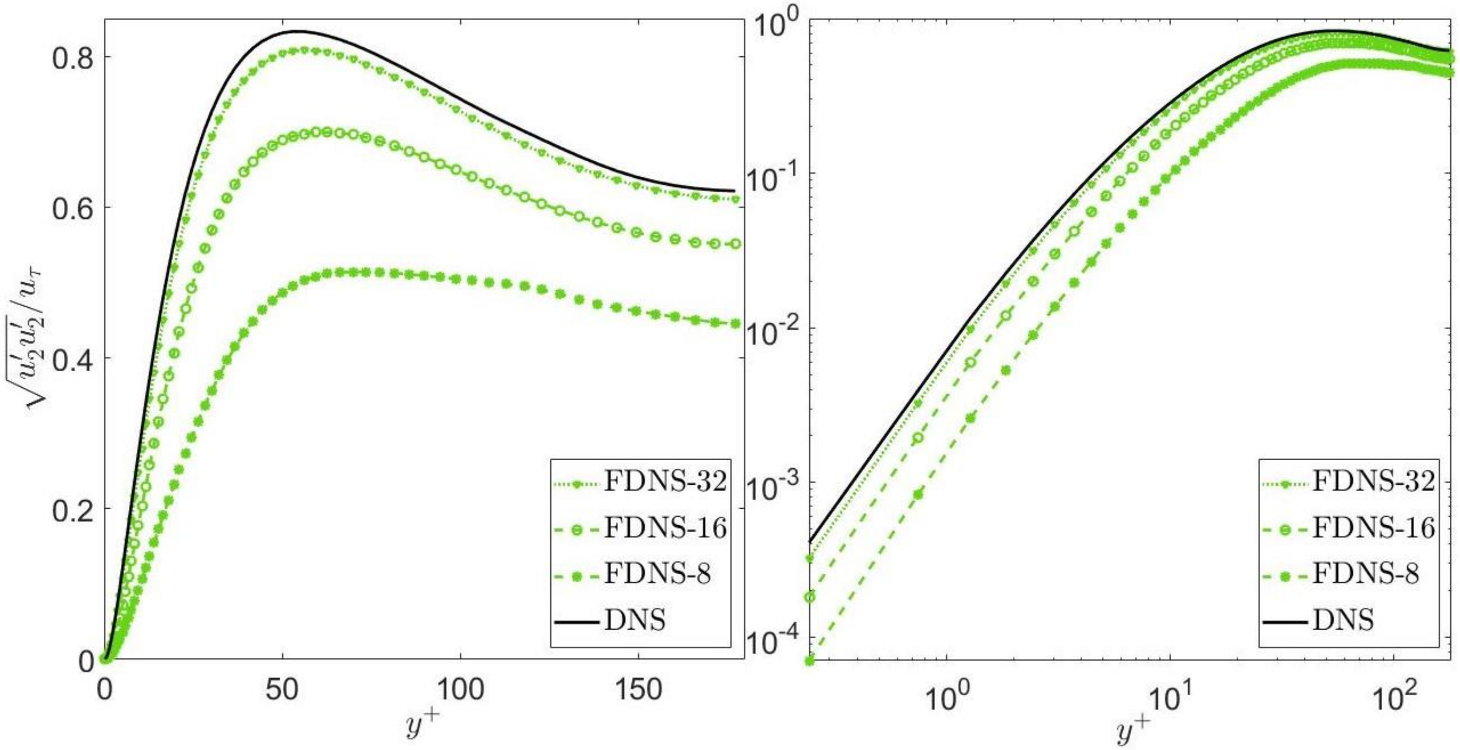
Solver and Computational domain

- Eulerian-Lagrangian approach
- Point-particle assumption, one-way coupling
- Channel flow with periodic boundary conditions in the streamwise and spanwise directions.
- Re_{τ}= 180 - tracking 200,000 particles
- Particle-wall collisions: Fully absorbing (trap-wall)
- For DNS 128^3 grid points
- The parallel solver runs in a distributed memory environment (MPI)

- Time integration with second-order Adams–Bashforth method.
- Fourth-order central scheme in the periodic streamwise and spanwise directions.
- Second-order central scheme in the wall-normal direction, and viscous terms.
- Second-order Lagrange interpolation for the fluid velocity at the particle location.
- Spectral method with a modified wave number is used for the pressure Poisson equation in the homogeneous direction and a tridiagonal solver for the normal direction.
- Parallel mode available by dividing the computational domain into rectangular blocks in the normal direction.

Filtered DNS (FDNS)

Normal velocity fluctuations

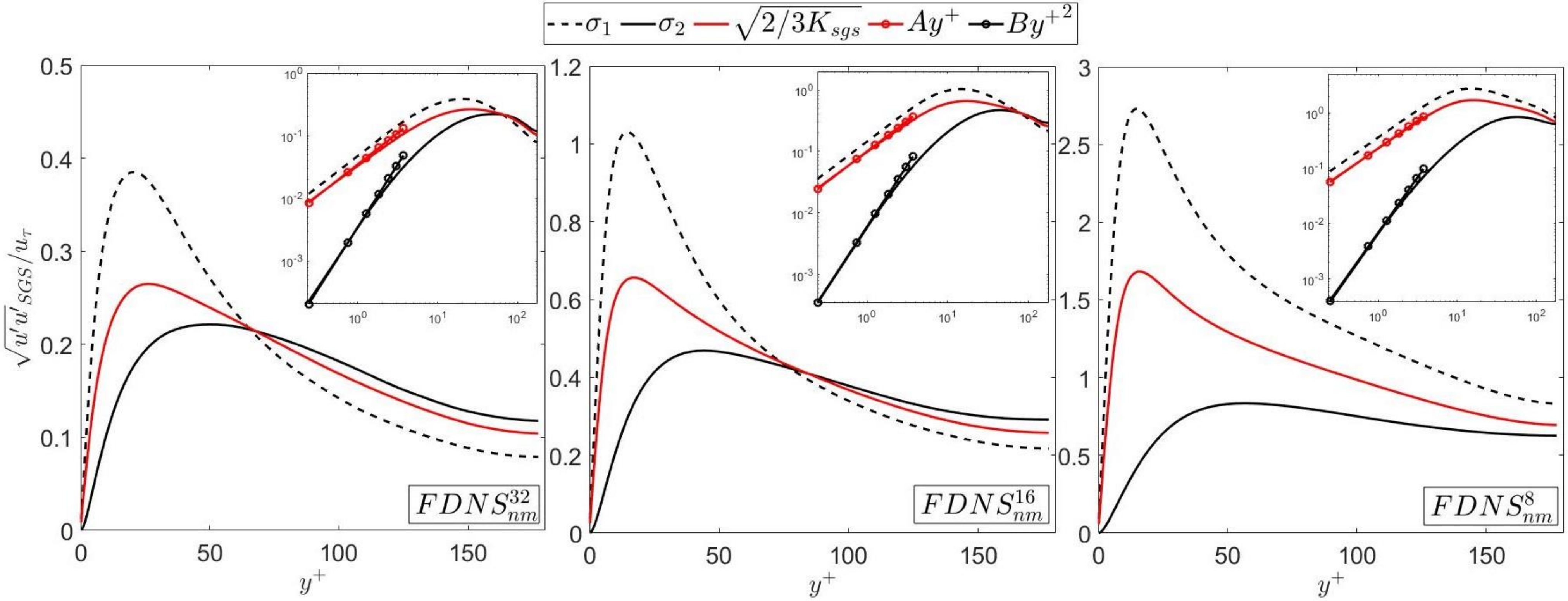


- $u_i^{\mathrm{FDNS}}(x,y,z,t) = \mathrm{FT}^{-1}\begin{cases}\hat{G}(\kappa_1).\,\hat{G}(\kappa_3).\,\hat{u}_i(\kappa_1,y,\kappa_3,t) & \text{if } \left|\kappa_j\right| \le \kappa_c \text{ with } j=1{,}3 \\ 0 & \text{otherwise}\end{cases}$
- Sharp-cut off filter in Fourier space: $\hat{G}\left(\kappa_j\right) = 1$

Missed fluctuations in FDNS

SGS velocity fluctuations

DNS Grid- 128×128×128

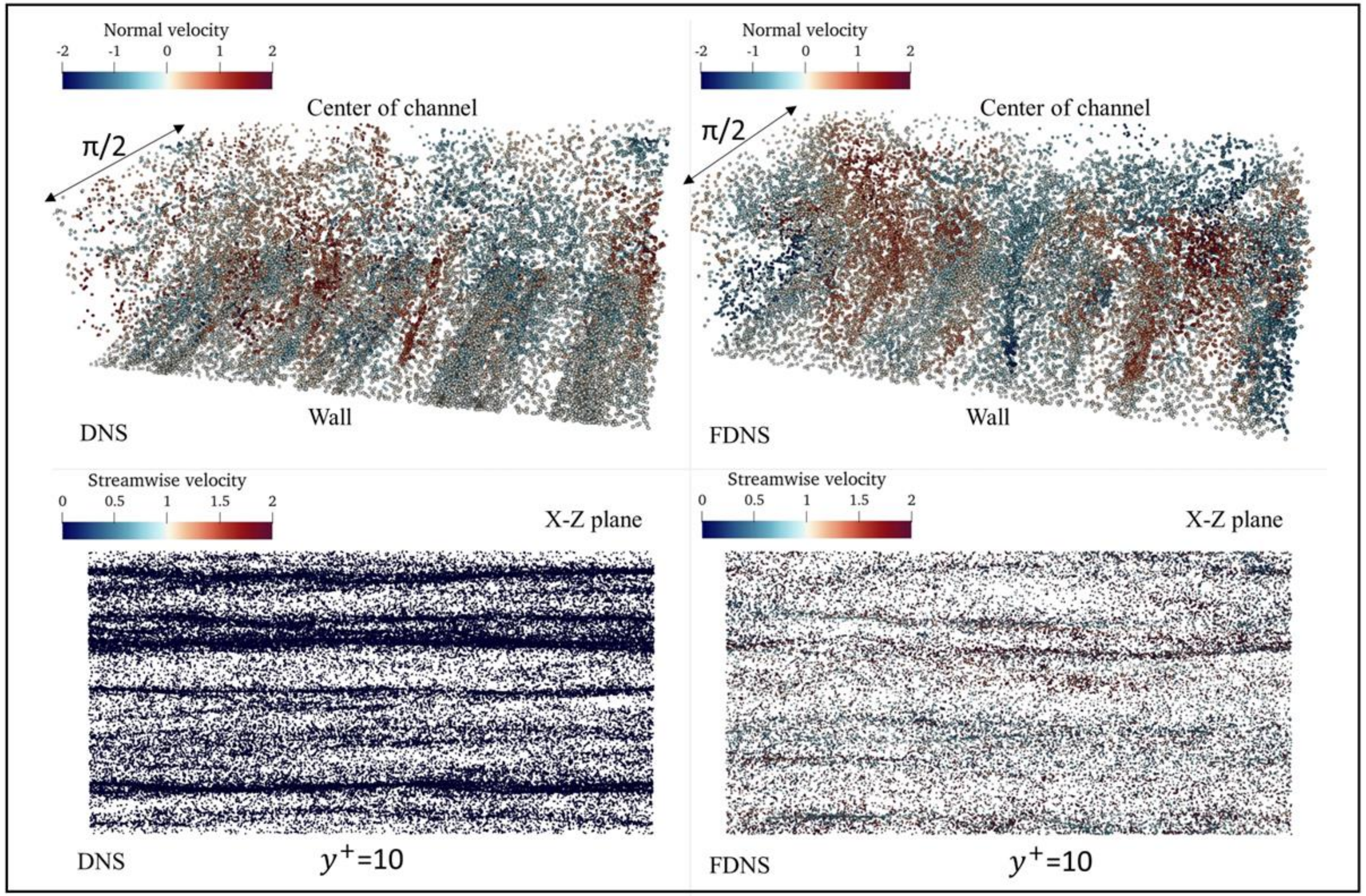


SGS velocity fluctuations are non-homogeneous and anisotropic.

Near wall flow structures

DNS

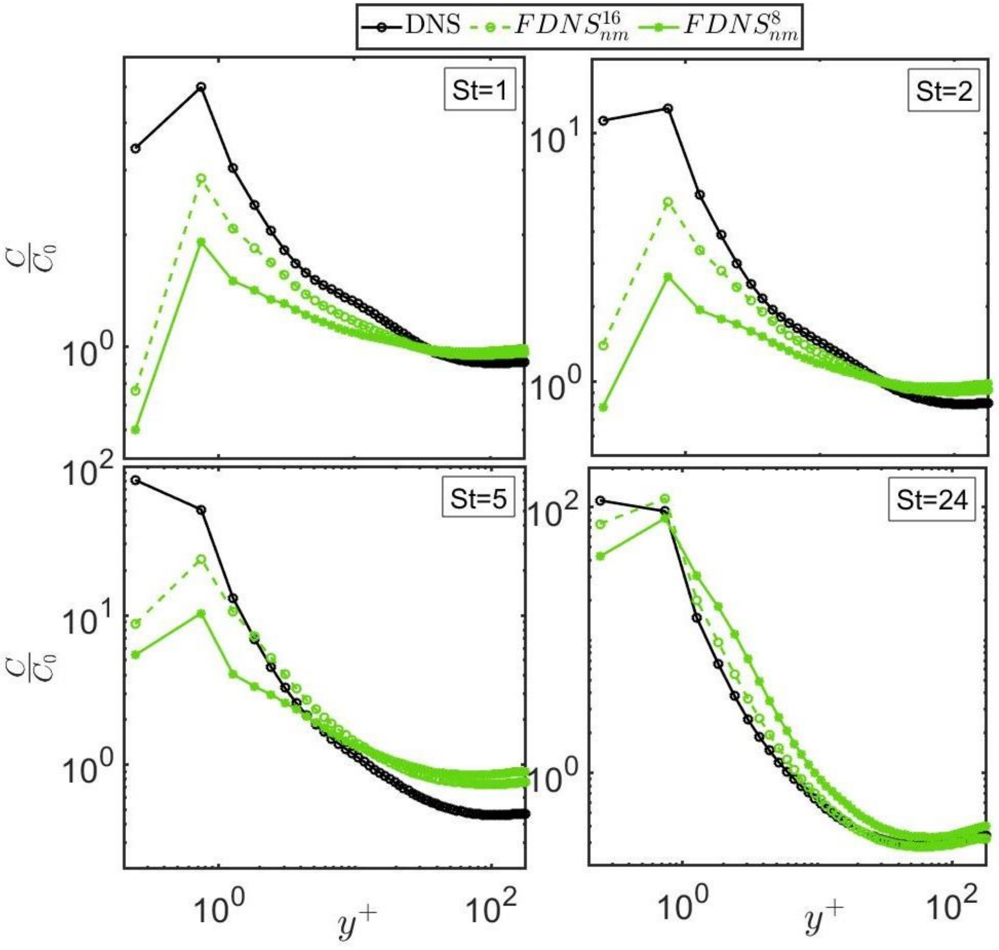
FDNS-16



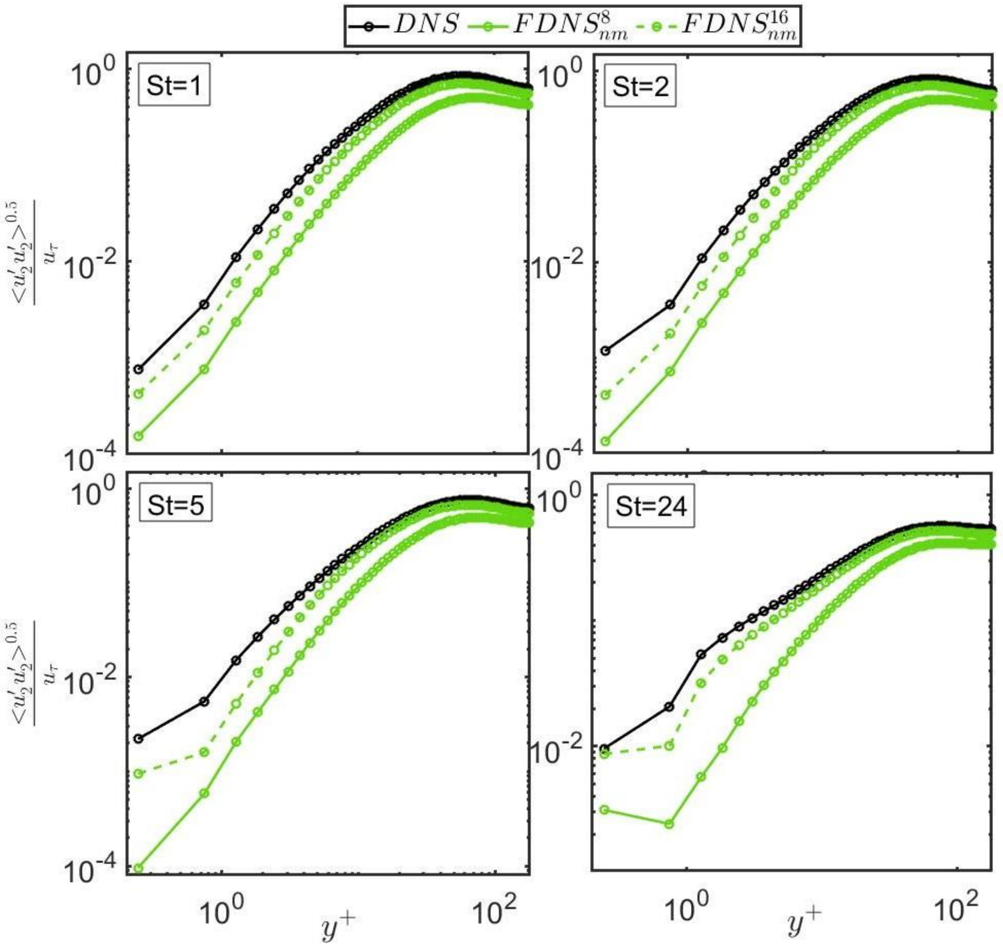
Snapshot of particle dispersion at tu_τ /h = 100

Effect of filtering on particles

Particle concentration

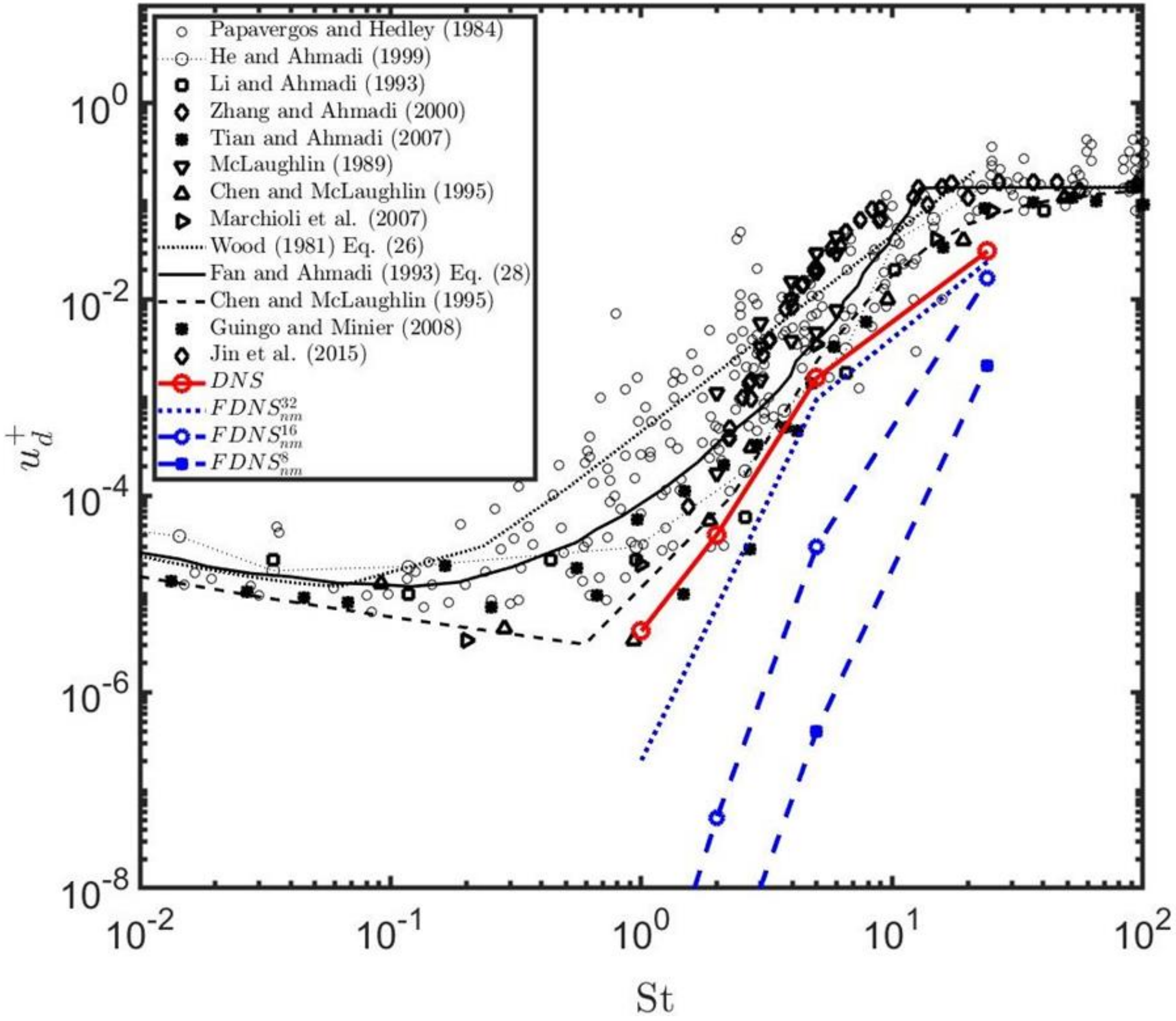


Particle velocity fluctuations



Effect of filtering on particles

Particle deposition velocity



Stochastic modeling

SGS velocity fluctuation see by particles

$$d\left(\frac{u_2'}{\sigma_2}\right) = \left(\frac{\partial \sigma_2}{\partial x_2} - \frac{u_2'}{\sigma_2 \tau}\right) dt + \sqrt{\frac{2}{\tau}}\, dW$$

$$u_2'^{n+1} = \frac{\sigma_2^{n+1}}{\sigma_2^{n}} u_2'^{n} \exp\left(-\frac{\Delta t}{\tau_2}\right) + \sigma_2^{n+1}\left(1 - \exp\left(-2\frac{\Delta t}{\tau_2}\right)\right)^{\frac{1}{2}} \xi_2 + \frac{\tau_2}{1+St} \frac{\sigma_2^{n+1} \partial \sigma_2^{n+1}}{\partial y}\left(1 - \exp\left(-\frac{\Delta t}{\tau_2}\right)\right)$$

Drift term

Stokes number $= \frac{\tau_p}{\tau_f} = = \frac{\frac{\rho_p d_p^2}{18\mu}}{\frac{v}{u_\tau^2}}$

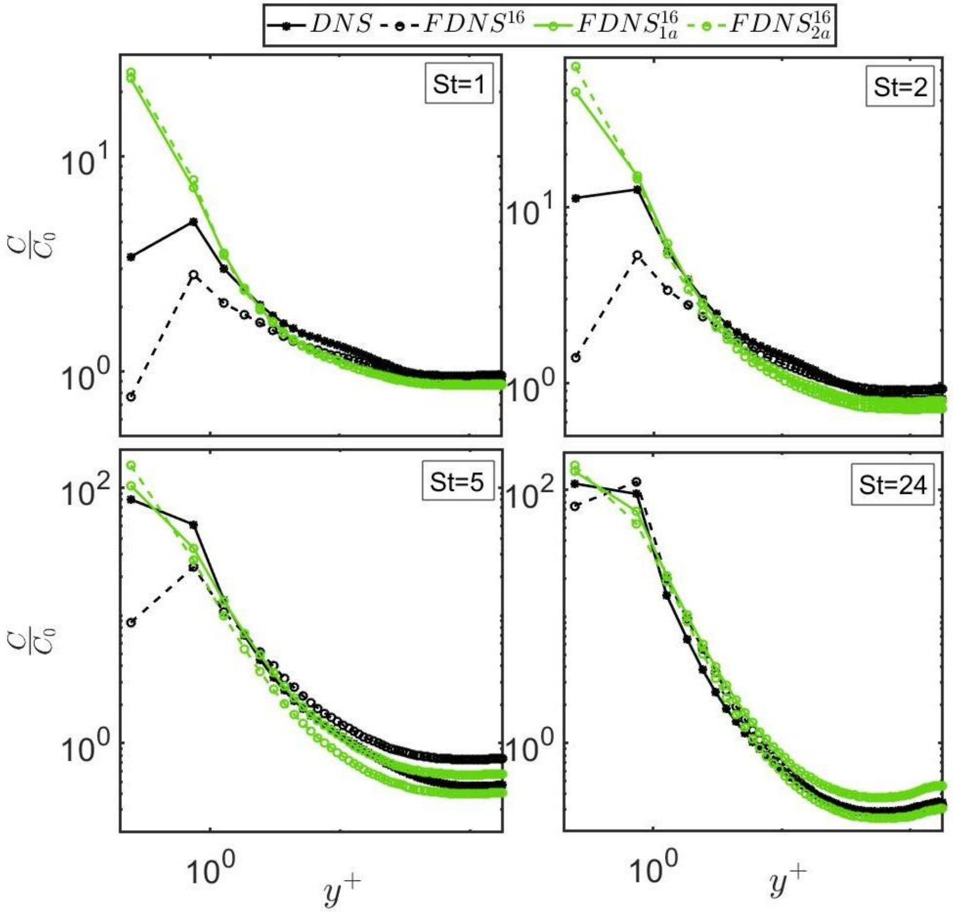
- τ is Lagrangian time scale
- σ is RMS of SGS velocity fluctuation

Isotropic Model

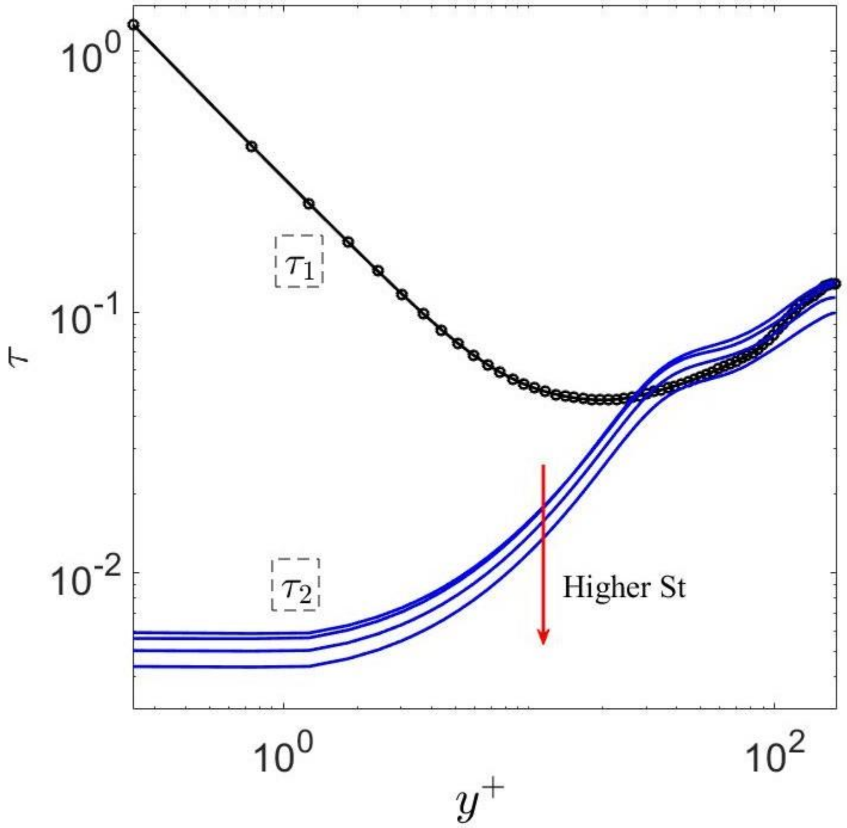
- $\tau \approx \Delta/(K_{SGS})^{1/2}$
- $\sigma = \left(\frac{2}{3} K_{SGS}\right)^{1/2}$

No Drift term

Concentration



Time scale

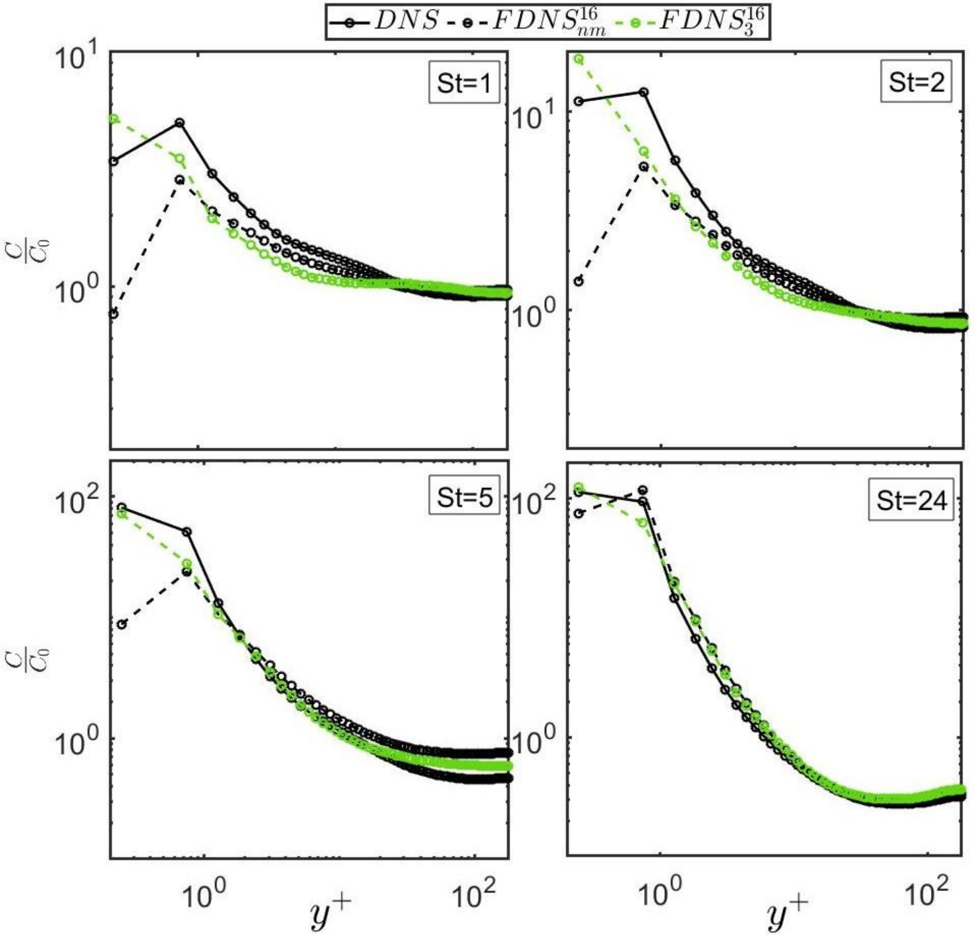


Excluding the drift term in the stochastic equation results in high concentration near the wall region, irrespective of the time scale employed in the equation (τ_1 or τ_2).

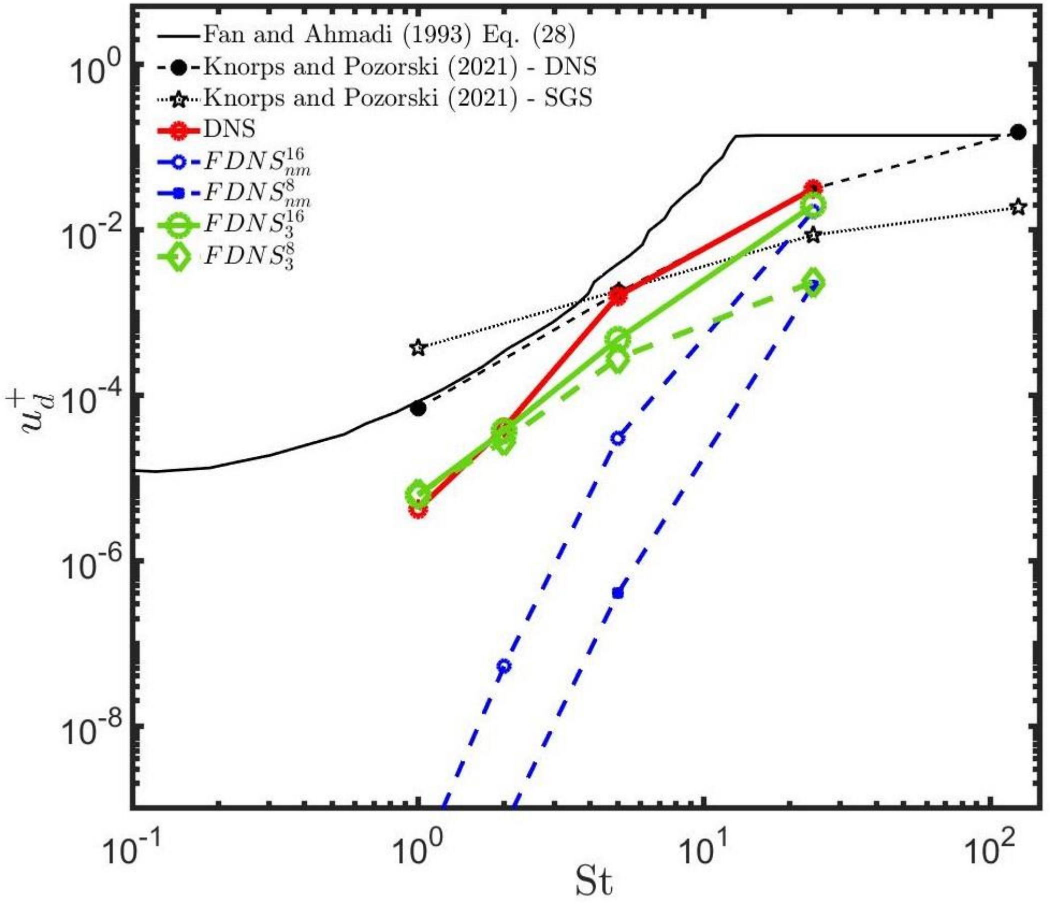
Model with drift term and modified time scale

$$\tau(\Delta, \sigma_2, \mathrm{St}, y^+) = (1 - c_a \log(\mathrm{St}))\tanh(c_\tau y^{+2})\,\frac{\Delta}{\sigma_2}$$

$c_a = 0.0825$
$c_\tau = 0.001$



Particle concentration

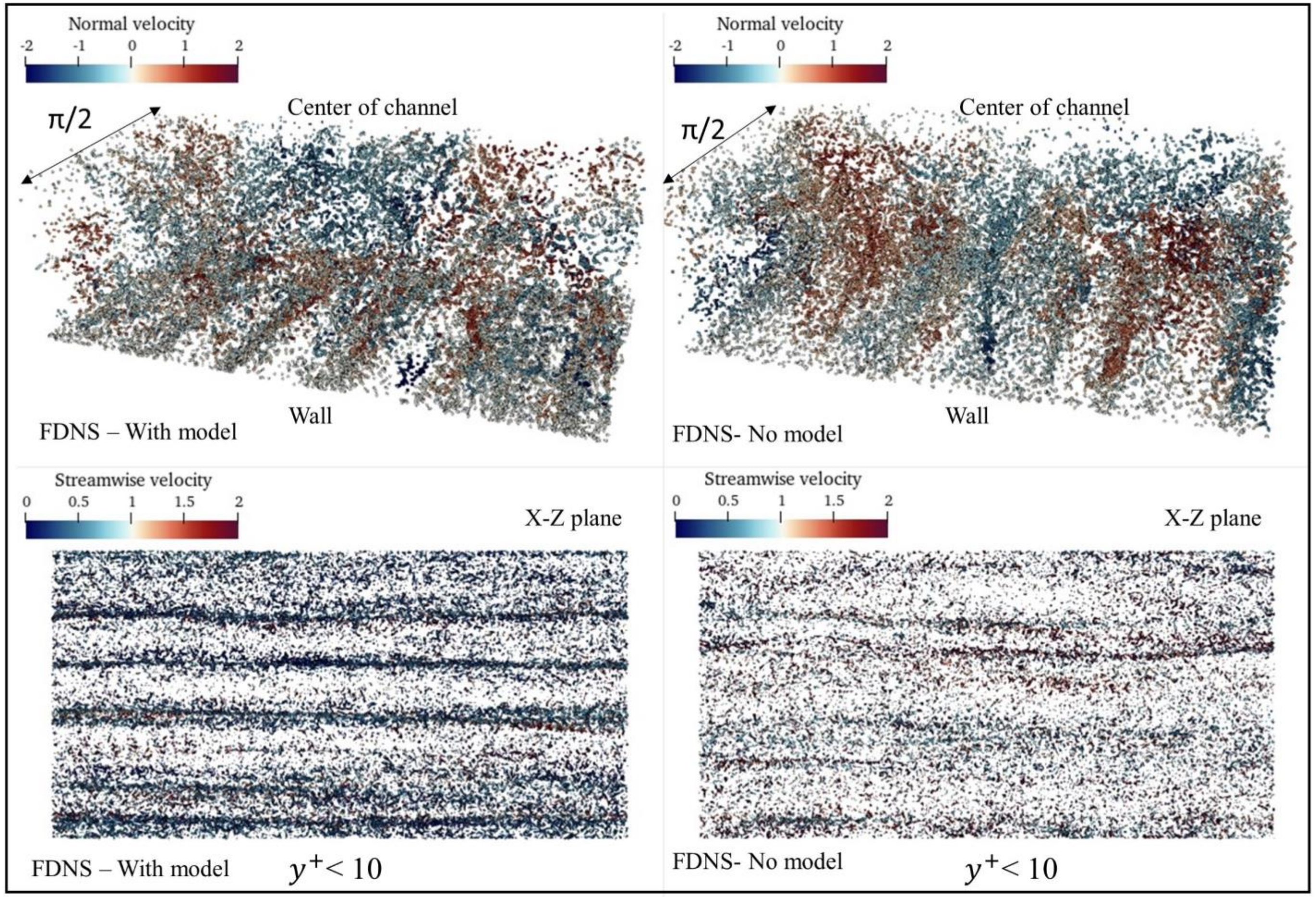


Particle deposition velocity

Near wall flow structures with model

With model

No model



Snapshot of particle dispersion $t u_\tau / h = 100$

Conclusions and future study

- Filtering significantly decreases the particle deposition velocities at lower Stokes numbers (St = 1, 2, 5) and affects the particle dispersion in channel.
- The developed stochastic model is capable of predicting the correct deposition velocities and concentration profiles of lower inertia particles when the proper time-scale was used.
- Future Work: Evaluating the model performance for real LES scenarios.

Conclusions and future study

Thank you for your attentions!

Questions?