Nonlinear Subgrid-Scale Models for Large-Eddy Simulation of Rotating Turbulent Flows

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Direct and Large-Eddy Simulation 11
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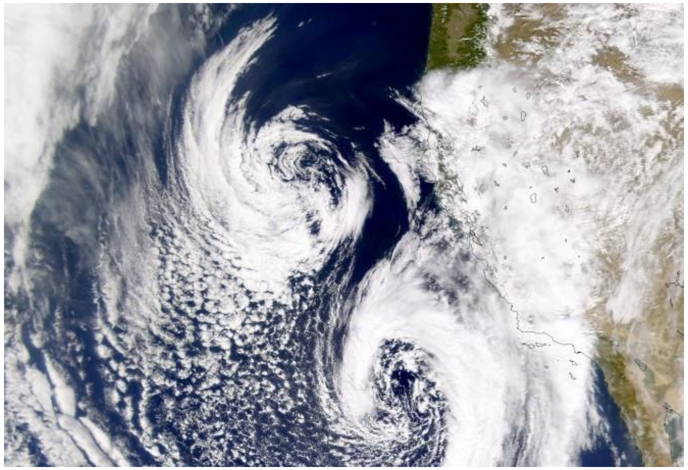
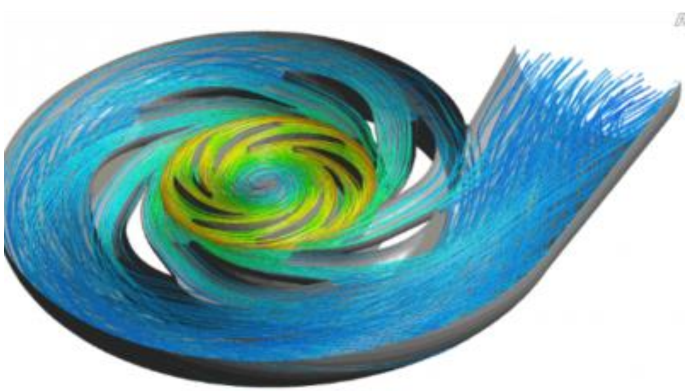
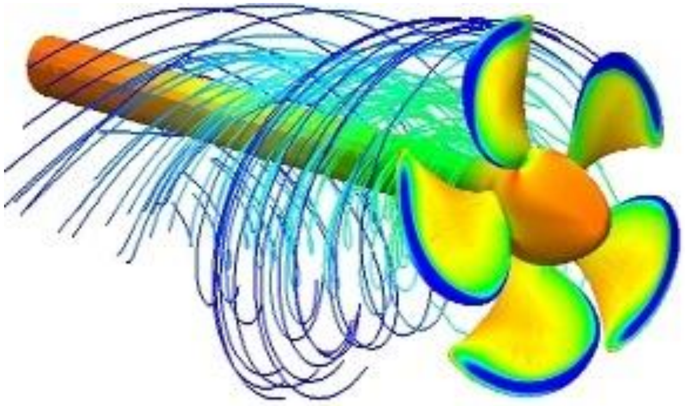
Introduction

Rotating turbulent flows



Ubiquitous in nature and engineering

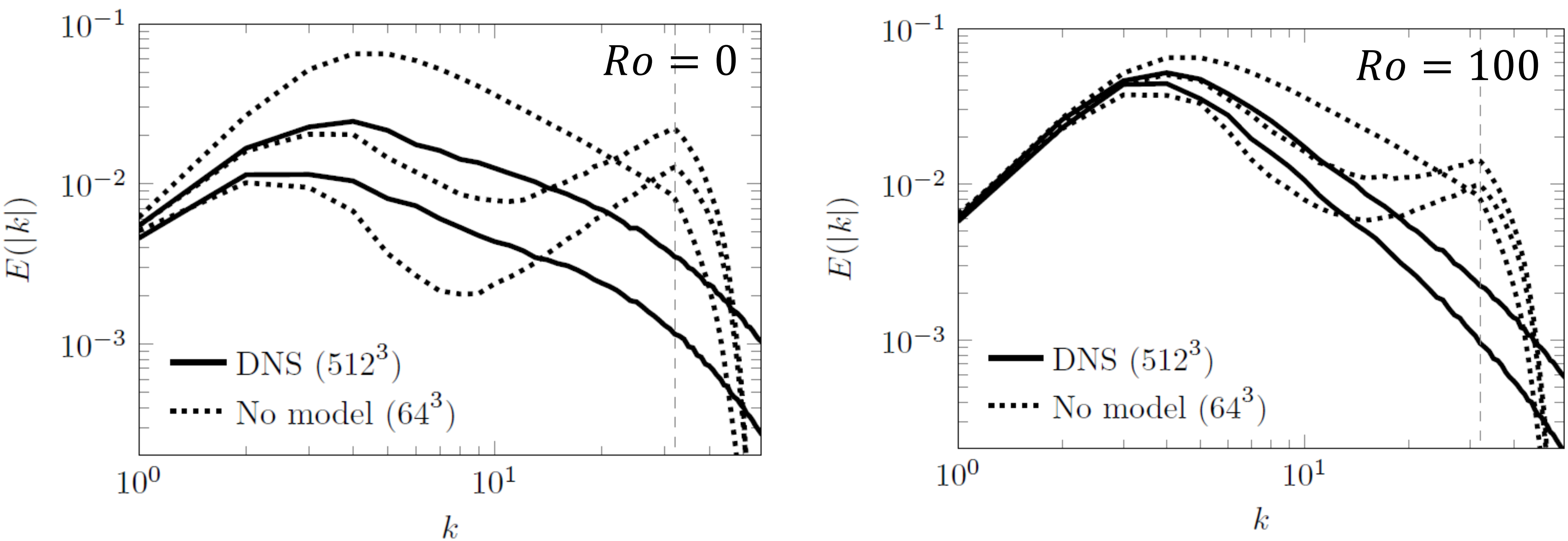




Introduction

Challenges

- Coriolis force
  - Conserves total kinetic energy, but does redistribute it
  - Anisotropy
  - Observations: *rotating homogeneous isotropic turbulence*



Silvis *et al.* (2016), *Proceedings of the CTR Summer Program*, 265

Large-eddy simulation of rotating turbulent flows

- Navier-Stokes equations in a rotating frame

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + 2\nu\frac{\partial}{\partial x_j}S_{ij} + 2\epsilon_{ijk}u_j\Omega_k$$

convection pressure diffusion Coriolis

- Large-eddy simulation without explicit filtering
  - Coarse grid
  - Extra forcing term

$$-\frac{\partial}{\partial x_j}\tau_{ij}^{\mathrm{mod}}$$

model

Nonlinear subgrid-scale models

- Focus: velocity-gradient-based models:

$$\tau^{\mathrm{mod}} = \underbrace{-2\nu_{\mathrm{e}}S}_{\text{eddy viscosity}} + \underbrace{\mu_{\mathrm{e}}(S\,\Omega - \Omega\,S)}_{\text{nonlinear}}$$

- Eddy viscosity term:
  - Describes dissipation
  - Models well established

Nondynamic vortex-stretching-based coefficients:

$$\nu_{\mathrm{e}} = C_\nu^2\delta^2\sqrt{2|S|}f(|S\vec{\omega}|^2)$$

$$\mu_{\mathrm{e}} = C_\mu^2\delta^2 g(|S\vec{\omega}|^2)$$

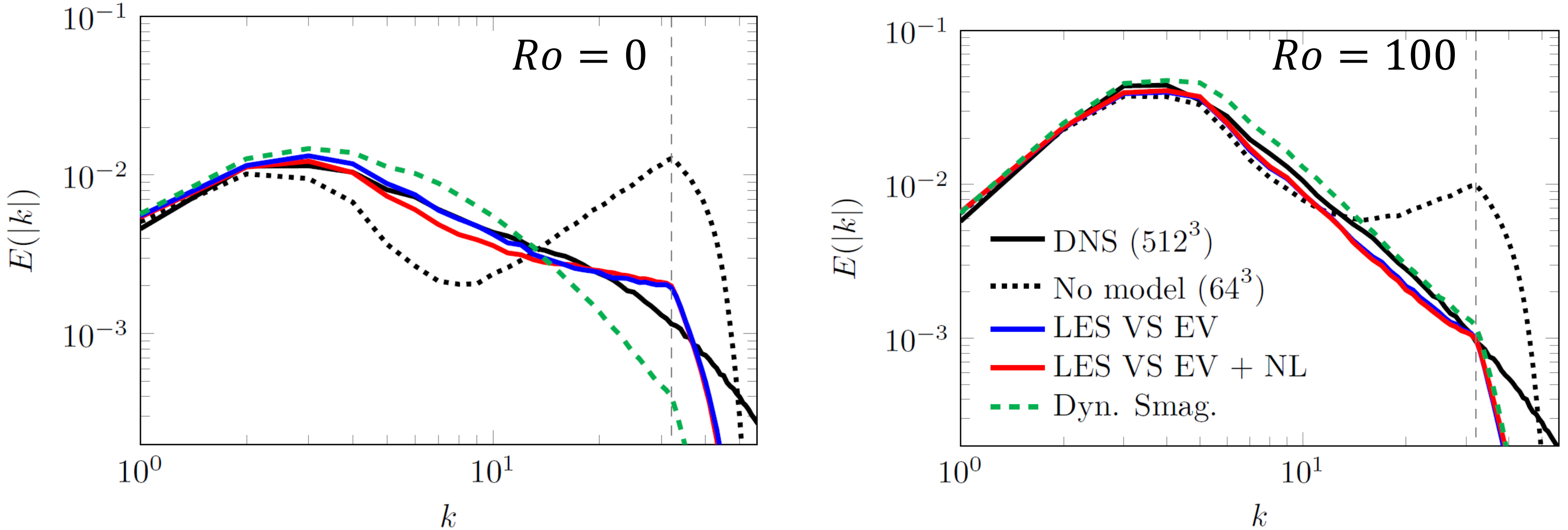
- Nonlinear term:
  - Stable part of gradient model
  - Nondissipative
  - Describes transport?

Marstorp *et al.* (2009), *J. Fluid Mech.* **639**, 403

Silvis *et al.* (2017), *Phys. Fluids* **29**, 015105

Nonlinear subgrid-scale models

- Rotating homogeneous isotropic turbulence



  – Nonlinear model term can in-/decrease energy transport

Silvis *et al.* (2016), *APS DFD Meeting*

Introduction

Code

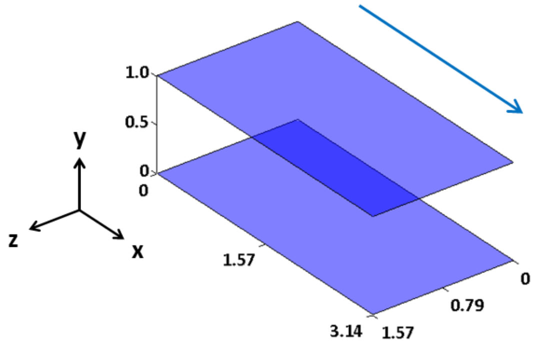
- Incompressible Navier-Stokes solver
- Finite-volume method on a staggered grid
- Pressure projection method
- One-leg explicit second-order time integration method

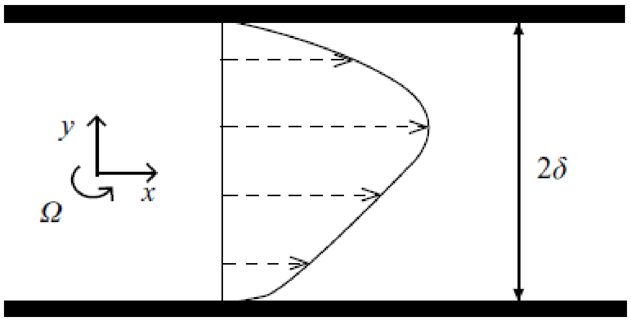
- Second-order symmetry-preserving spatial discretization
  - Kinetic energy conservation by …
    - convection
    - Coriolis force
    - nonlinear subgrid-scale model

Verstappen & Veldman (2003), *J. Comput. Phys.* **187**, 343
Beddhu *et al.* (1996), *J. Comput. Phys.* **128**, 427
Remmerswaal (2016), MSc thesis, University of Groningen

Test case

Spanwise-rotating plane-channel flow





- Domain size: $2\pi d \times 2d \times \pi d$
- Periodic in x and z directions
- Rotation about the spanwise axis

- Characterized by

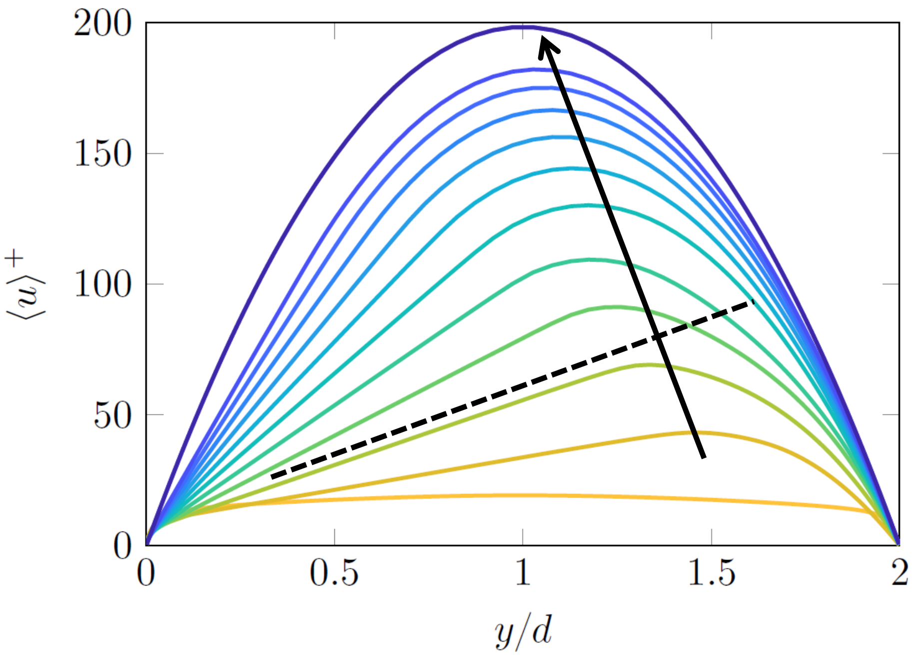
$$Re_\tau = \frac{u_\tau d}{\nu} \approx 395 \qquad Ro^+ = \frac{2\Omega d}{u_\tau} = 0 - 1000$$

Grundestam *et al.* (2008), *J. Fluid Mech.* **598**, 177
Brethouwer (2016), *arXiv* 1612.00254

Spanwise-rotating plane-channel flow

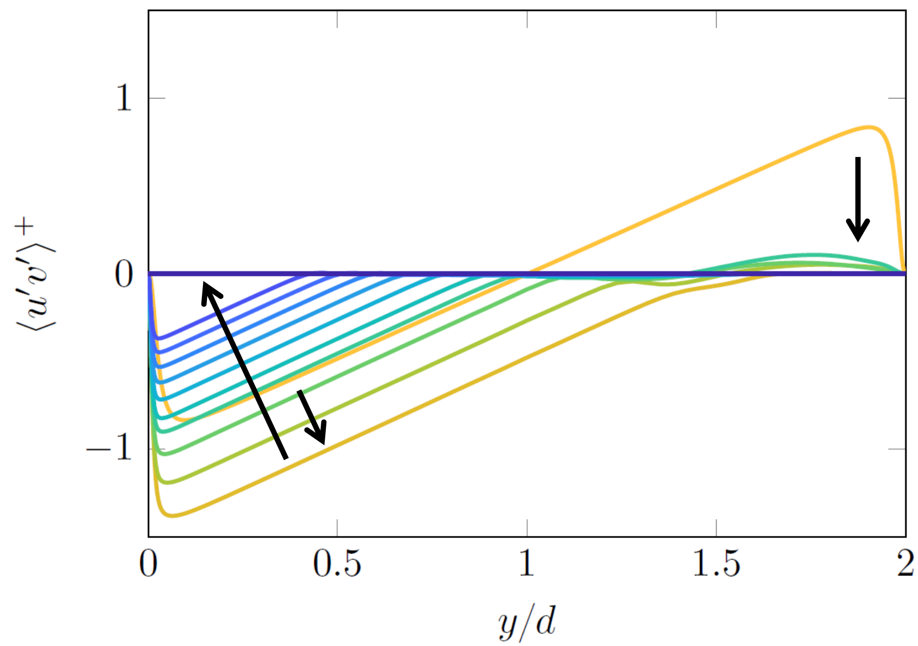
Typical observations: Ro^+ dependence

- Mean velocity profile



  - Linear slope $\sim Ro^+$
  - Flow laminarizes with Ro^+

- Reynolds shear stress



  - Turbulent and laminar side

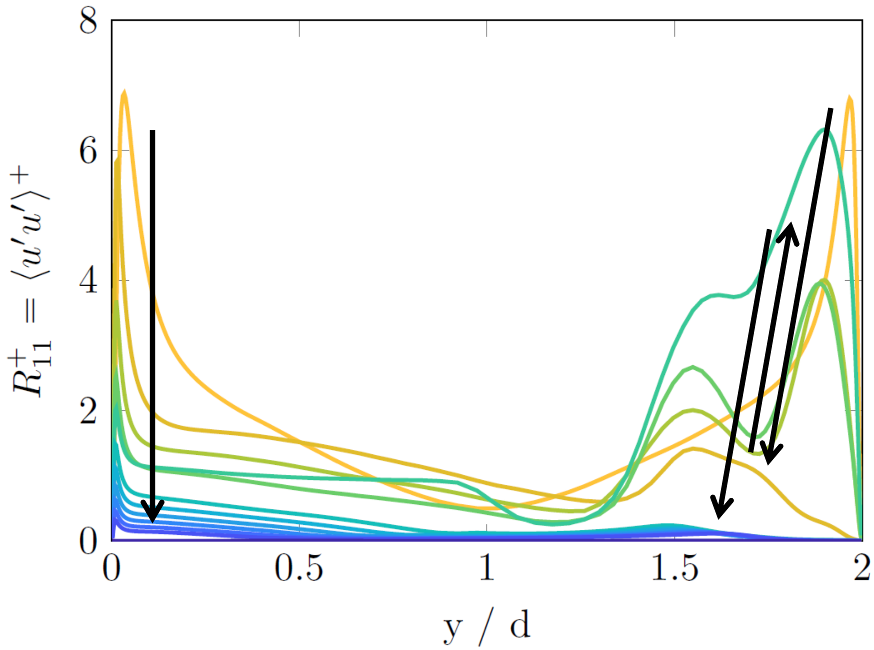
$Re_\tau \approx 395$, $Ro^+ = 0 - 1000$

$n_x \times n_y \times n_z = 128 \times 128 \times 128$

Spanwise-rotating plane-channel flow

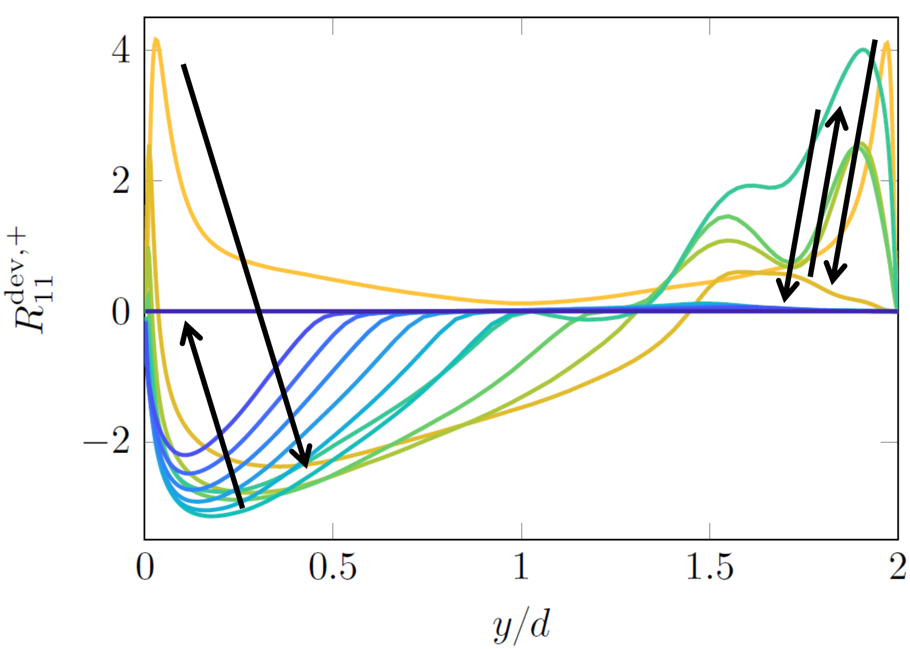
Typical observations: Ro^+ dependence

- Streamwise stress



  - Turbulent and laminar side
  - Flow laminarizes with Ro^+

- Deviatoric streamwise stress



  - Traceless subgrid-scale models: deviatoric stresses

$Re_\tau \approx 395$, $Ro^+ = 0 - 1000$

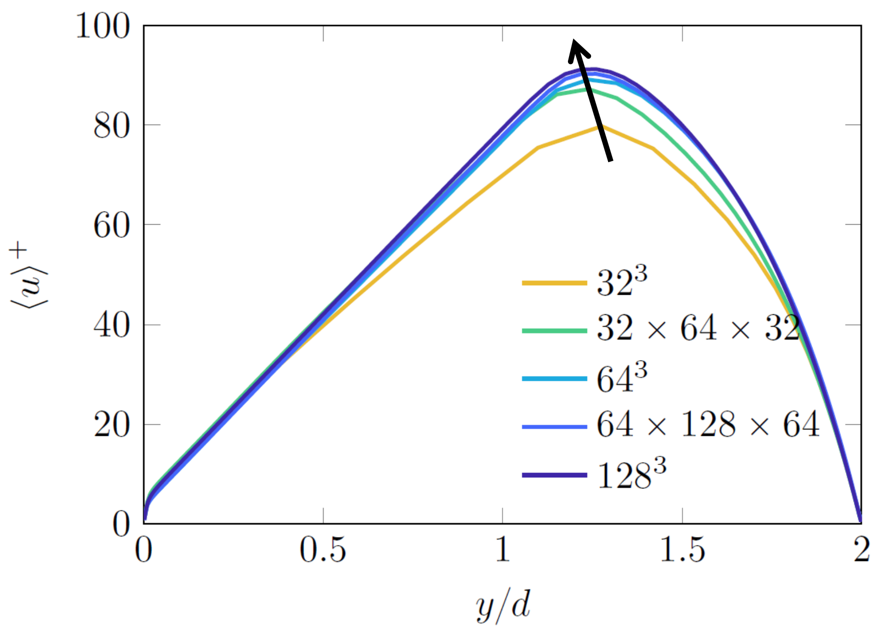
$n_x \times n_y \times n_z = 128 \times 128 \times 128$

Winckelmans *et al.* (2002), *Phys. Fluids* **14**, 1809

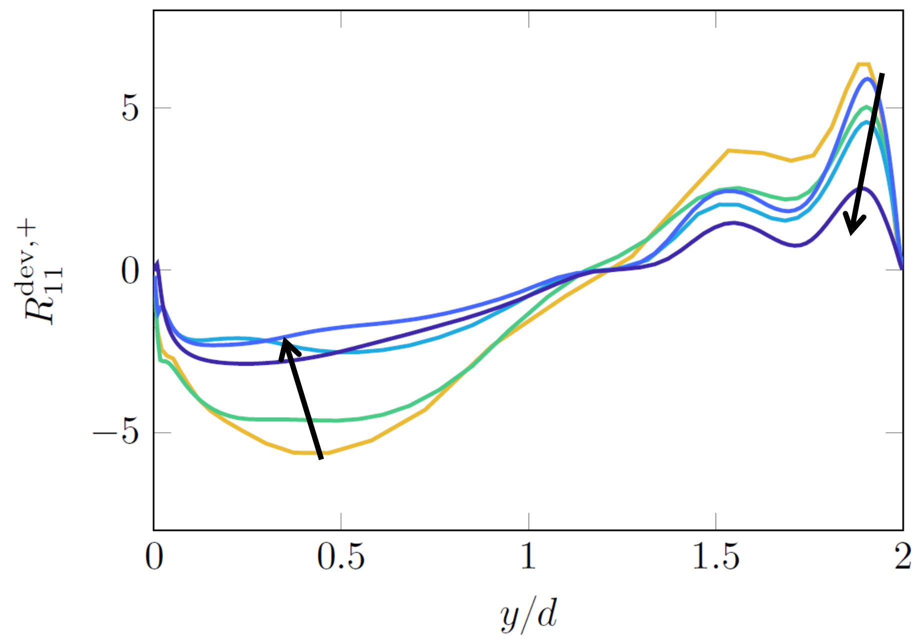
Spanwise-rotating plane-channel flow

Typical observations: resolution dependence

- Mean velocity profile



- Deviatoric streamwise stress



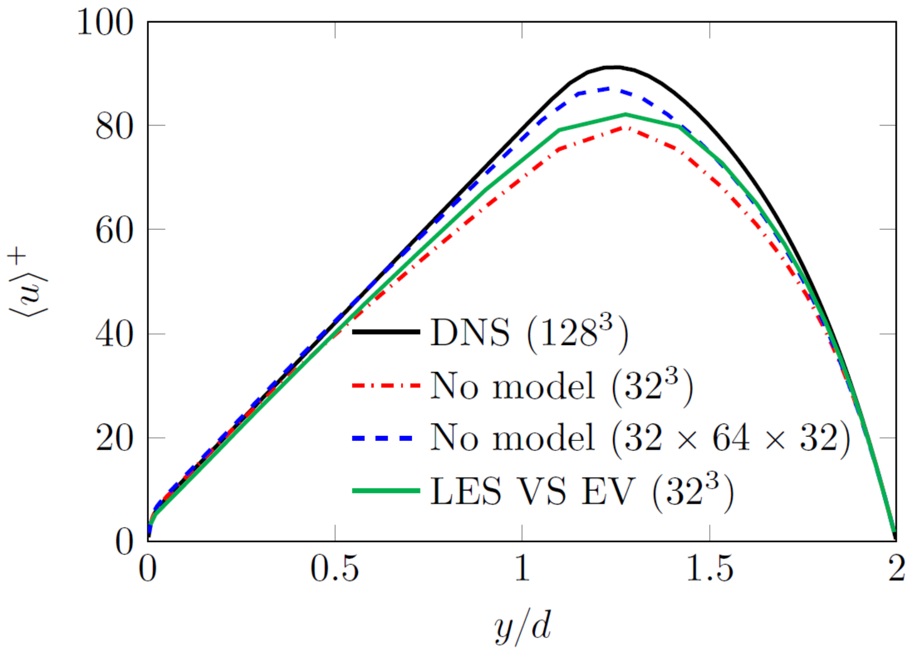
  – Ample opportunity for LES, even at $Re_\tau \approx 395$

$Re_\tau \approx 395$, $Ro^+ = 75$

Numerical results

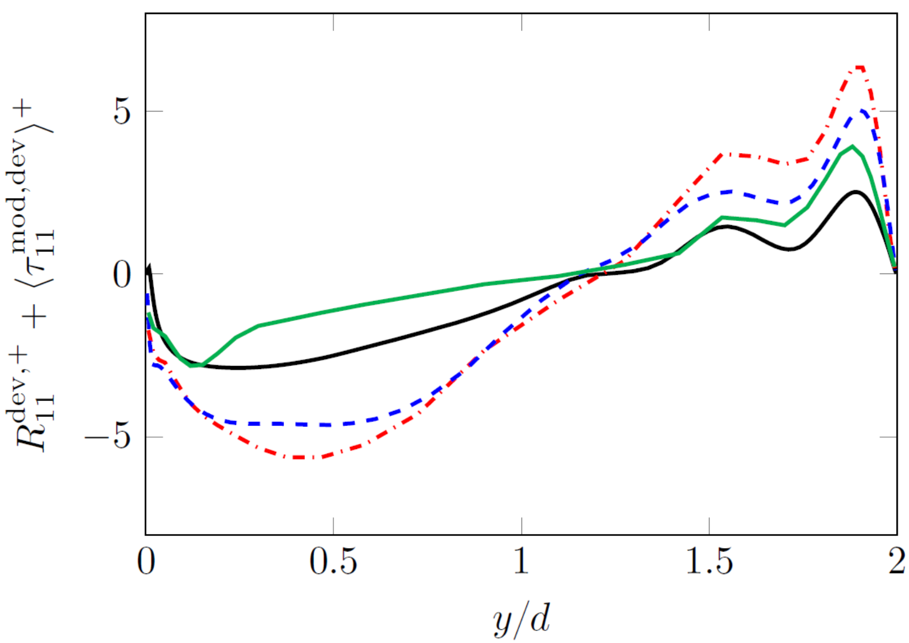
Large-eddy simulation with eddy viscosity model

- Mean velocity profile



  - Trend: eddy viscosity model improves results

- Deviatoric streamwise stress



  - Even improving upon $32 \times 64 \times 32$ result

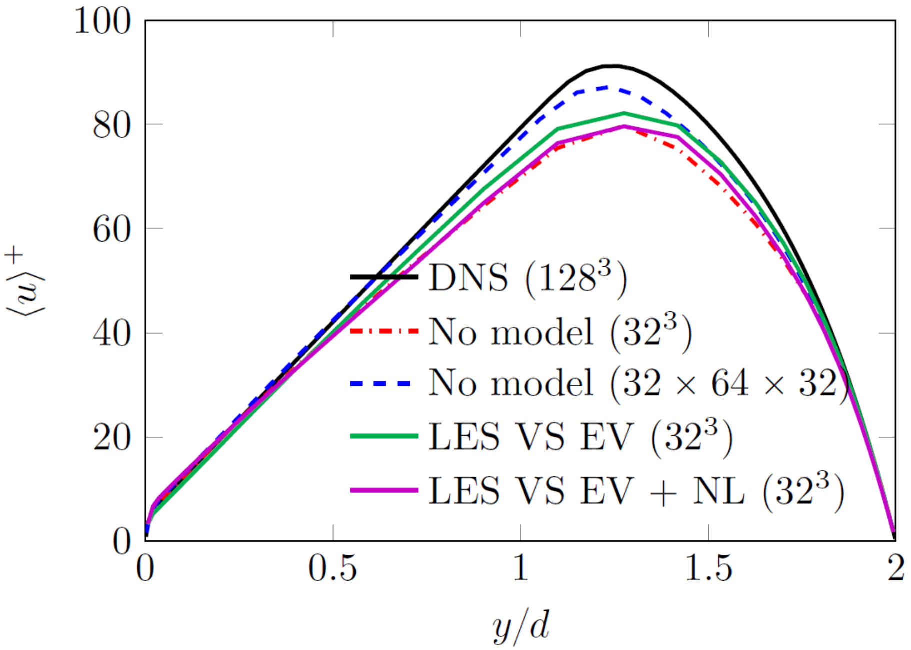
Silvis *et al.* (2017), *Phys. Fluids* **29**, 015105
Winckelmans *et al.* (2002), *Phys. Fluids* **14**, 1809

$Re_\tau \approx 395,\ Ro^+ = 75$

Numerical results

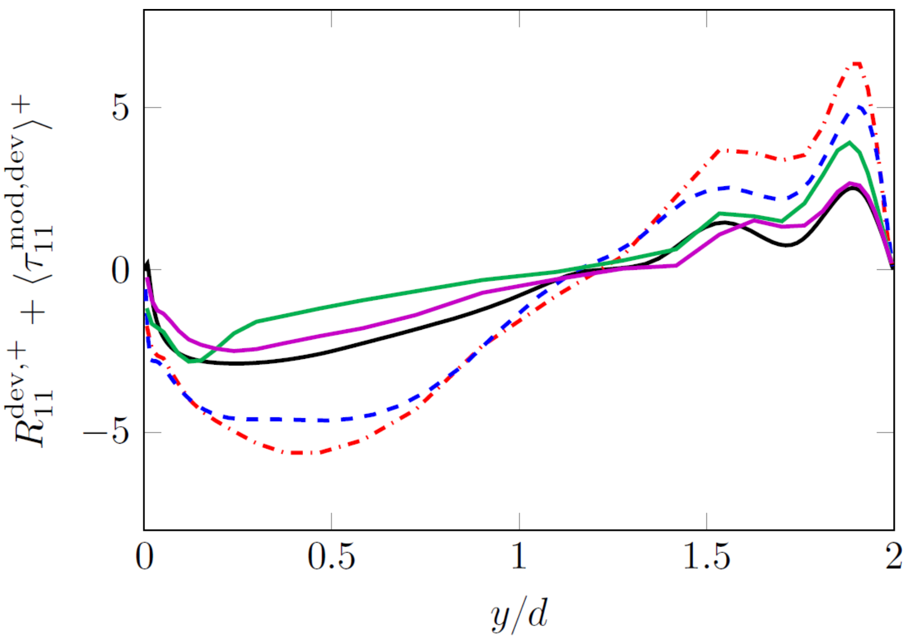
Large-eddy simulation with nonlinear model

- Mean velocity profile



  - Slight improvement on 32^3 result

- Deviatoric streamwise stress



  - Nonlinear model improves stresses w.r.t. eddy viscosity model case

$Re_\tau \approx 395, Ro^+ = 75$

Summary & Outlook

Summary

- Focus:
  - large-eddy simulation of rotating turbulent flows
- Observations:
  - vortex-stretching-based nonlinear model captures energy transport in rotating homogeneous isotropic turbulence
- Test case:
  - spanwise-rotating plane-channel flow
  - rich and interesting test case for large-eddy simulation, even at $Re_\tau \approx 395$
- Subgrid-scale modeling:
  - vortex-stretching-based eddy viscosity model leads to improved predictions of spanwise-rotating plane-channel flow
  - vortex-stretching-based nonlinear model further improves prediction of the Reynolds stresses

Summary & Outlook

Outlook

- Further study of nonlinear subgrid-scale model:
  - behavior on different grids
  - influence of model constants

- Combine subgrid-scale model with different length scales:
  - Trias *et al.* – A new subgrid characteristic length for LES
    Session SW5 – LES modeling II (room A2, 14.00h)

Thank you for your attention!

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