DNS of a Turbulent Boundary Layer with Passive Scalar Transport

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Outline

- Introduction
  - Motivation
  - Basic Concepts
  - Purposes
- Direct Numerical Simulation (DNS)
- Results
- Conclusions & Outlook

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Motivation

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Basic understanding of wall-bounded turbulence:

- Crucial in engineering applications: external flows, e.g. turbine blades, vehicles, airfoils etc.
- Need for spatial simulations at moderate to high Re

Passive scalar mixing (e.g. heat transfer):

- Understanding of the passive scalar transport is limited (Reynolds analogy etc.)
- Quantities that cannot be measured in a wind tunnel or other experimental facilities (budgets, dissipation, h.o.t. etc.)
- Clearly a lack of fully-resolved numerical simulations (DNS) in boundary layer with passive scalar
- Applications in cooling, pollutant dispersion, combustion, heat exchanger

Basic Concepts

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- Boundary layer
  Ludwig Prandtl in 1905

- Passive scalar
  diffusive contaminant
  low concentration: small amounts of heat or pollutant

- Molecular Prandtl number $Pr = \frac{\nu}{\alpha}$
  ν is the kinematic viscosity
  α the scalar molecular diffusivity

large Pr ⟹ convection is effective
small Pr ⟹ conduction is effective

	air	water	oil	mercury
Pr	0.71	7	100-40000	0.025

values from White (2006)

Purposes

- Implement a huge variety of low and higher-order statistics, two-point correlations and time signals in the code (SIMSON)
- Perform a DNS to extend our knowledge of Re and Pr effects on the turbulence velocity and scalar statistics
- Based on the DNS results to develop new SGS models for scalars
- Generate a database for research community

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Outline

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- Introduction
- Direct Numerical Simulation (DNS)
  - Governing Equations
  - Numerical Scheme
  - Computational Domain
  - Boundary Conditions
  - Main Parameters
- Results
- Conclusions & Outlook

Governing Equations

- Incompressible Navier-Stokes equation
  → good approximation for low-speed flows (Ma < 0.3)

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

- Continuity equation

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

- Scalar transport equation

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = \frac{1}{RePr}\frac{\partial^2 \theta}{\partial x_i \partial x_i}$$

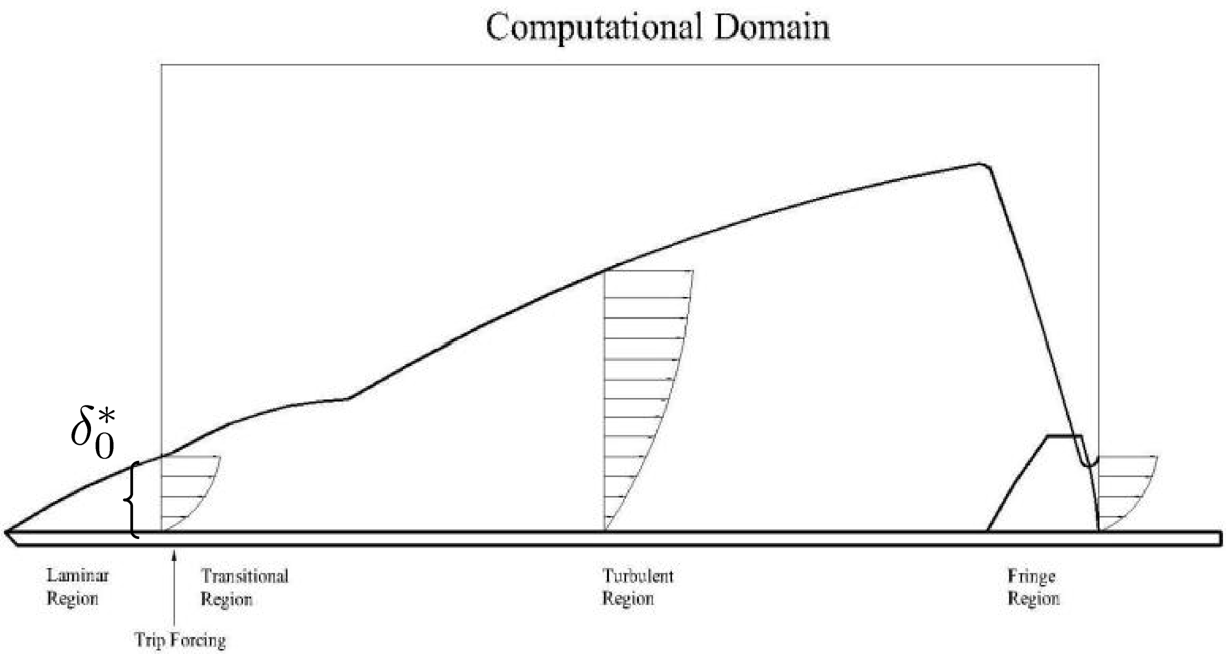
$$Re = \frac{U_\infty \delta_0^*}{\nu}, Pr = \frac{\nu}{\alpha}, Pe = RePr$$

- Solved by DNS → all scales are resolved, terms are evaluated without modelling → expensive
- Memory ~ $Re^{9/4}$ and CPU time ~ Re^3

Numerical Scheme

- Code SIMSON, developed at KTH Mekanik, Reference: Chevalier et al. (2007)
- Spatial Discretization (Fully spectral)
  - Horizontal directions
    - Fourier expansions → Periodic B.C.
  - Wall-normal direction
    - Chebyshev expansions
- Time Advancement
  - linear terms
    - 2nd-order Crank-Nicolson method
  - Non-linear terms
    - 3rd-order 4-step Runge-Kutta method

Computational Domain



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- Domain does not include leading edge
- Laminar inflow, tripped by random forcing
- Fringe region at the end
- No-slip at the wall, Neumann on top

Boundary Conditions

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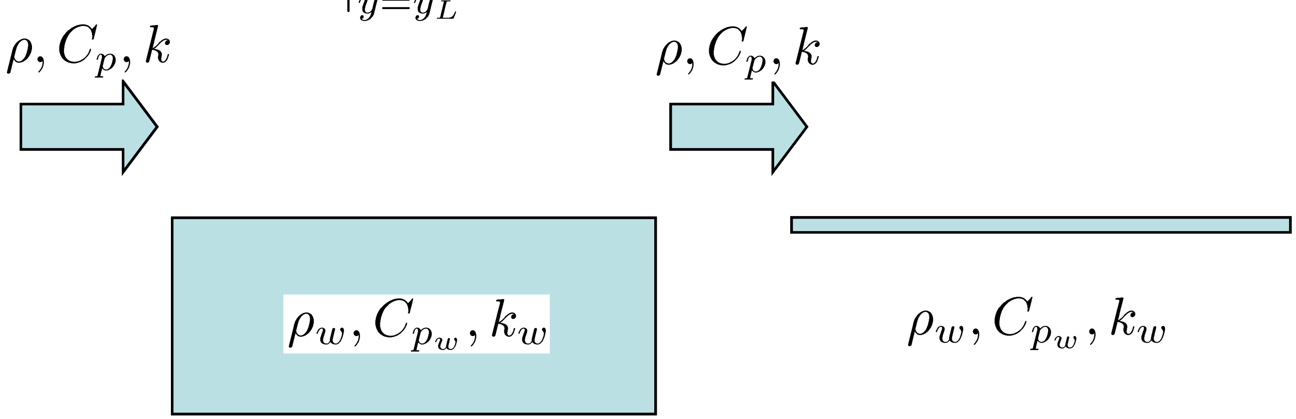
- Scalar Field
  - Lower boundary condition

$$\theta\Big|_{y=0} = 0 \text{ , for the isothermal boundary condition}$$

$$\frac{\partial\theta}{\partial y}\Big|_{y=0} = 1 \text{ , for the isoflux boundary condition}$$

  - Upper boundary condition

$$\theta\Big|_{y=y_L} = 1$$



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Main Parameters

Re_x	68450-315950
Re_{δ^*}	450-1234
Re_θ	175-830
$Re_{\delta_{99}}$	46-316
geometry (δ_0^*)	$750 \times 40 \times 34$
fringe start x_{start}	660
fringe end x_{end}	750
fringe strength λ_{max}	1.0
Δ_{rise}	50
Δ_{fall}	15
resolution	$1024 \times 289 \times 128$
grid spacing in x (Δx^+)	17
grid spacing in y (Δy^+)	0.025-4.6
grid spacing in z (Δz^+)	6.3

$+$ viscous units

CPU time → 5 months

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  - Hydrodynamic Results
  - Scalar Transport Results
  - Comparison between the Two Fields
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Hydrodynamic Results

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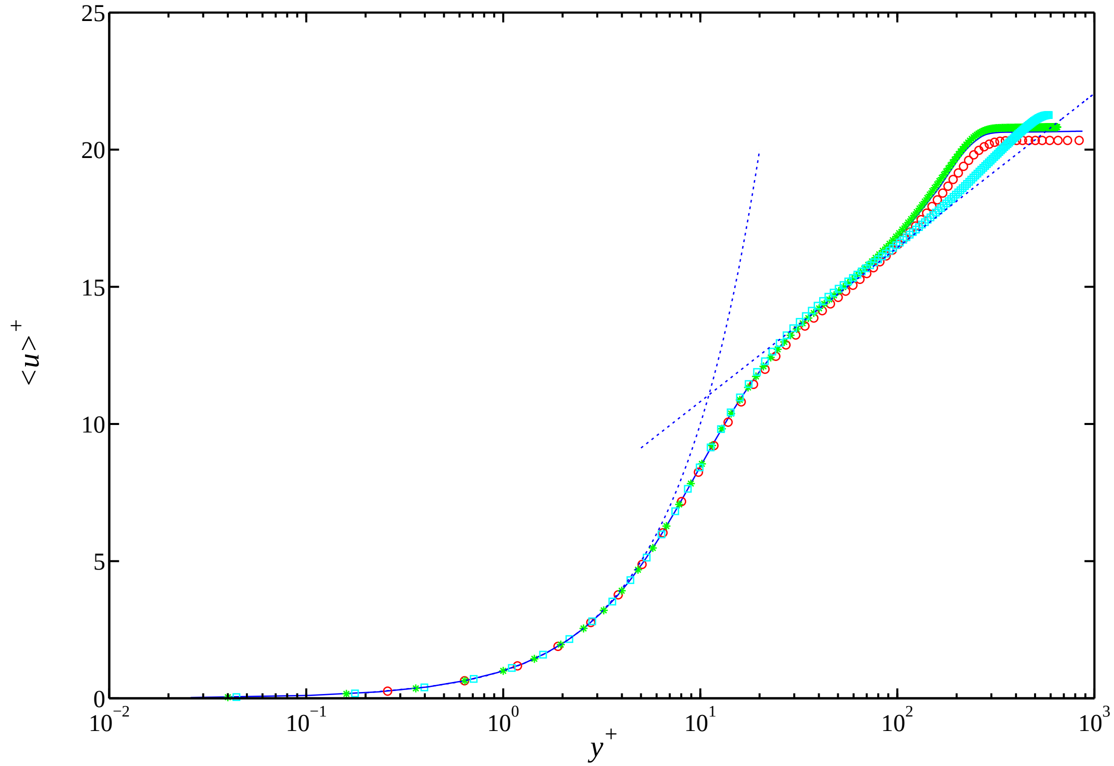
Mean Velocity Profile at $Re_\theta = 670$



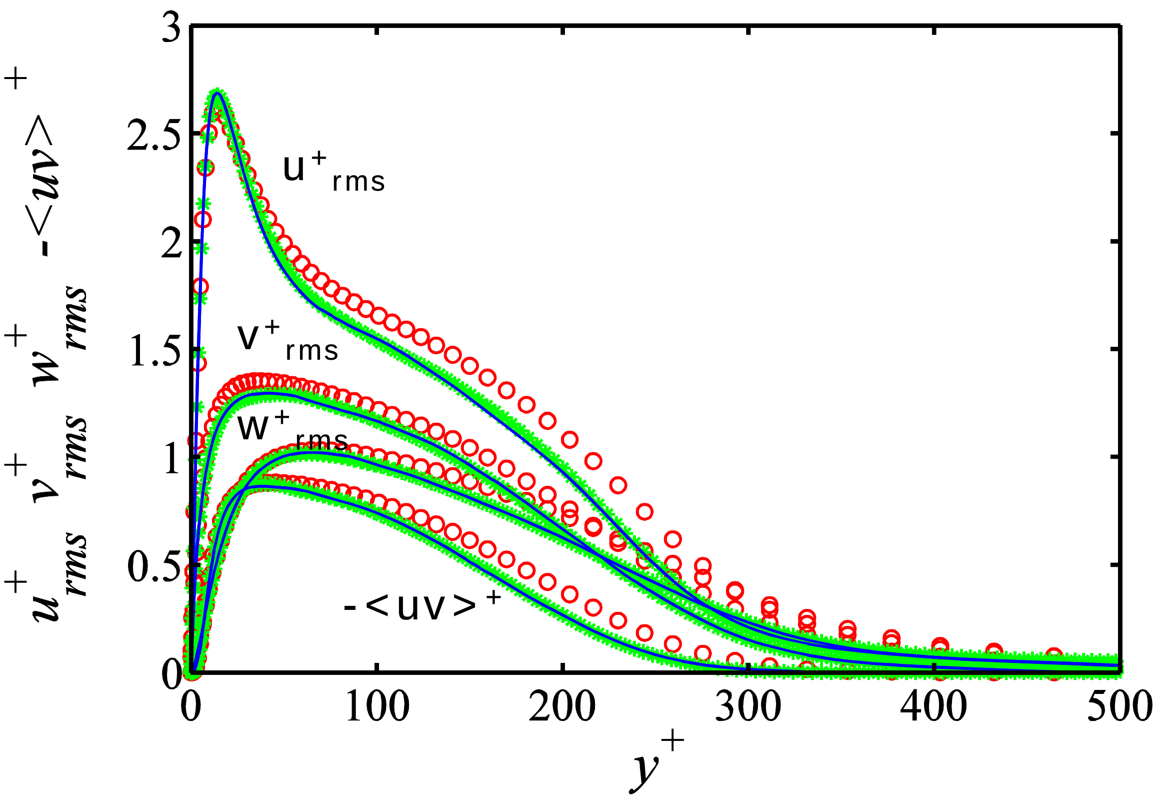
○ $Re_\theta = 670$ Spalart (1988), * $Re_\theta = 666$ Komminaho and Skote (2002),

□ $Re_\tau = 590$ Moser et al. (1999), ··· Log-law

- good agreement in log region and with log-law
- wake region only for BL cases

Hydrodynamic Results

Turbulent Intensities at $Re_\theta = 670$



○ $Re_\theta = 670$ Spalart (1988), * $Re_\theta = 666$ Komminaho and Skote (2002)

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Hydrodynamic Results

Budget for kinetic energy $k = \frac{1}{2}\langle u_i' u_i' \rangle$ at Re_θ=670

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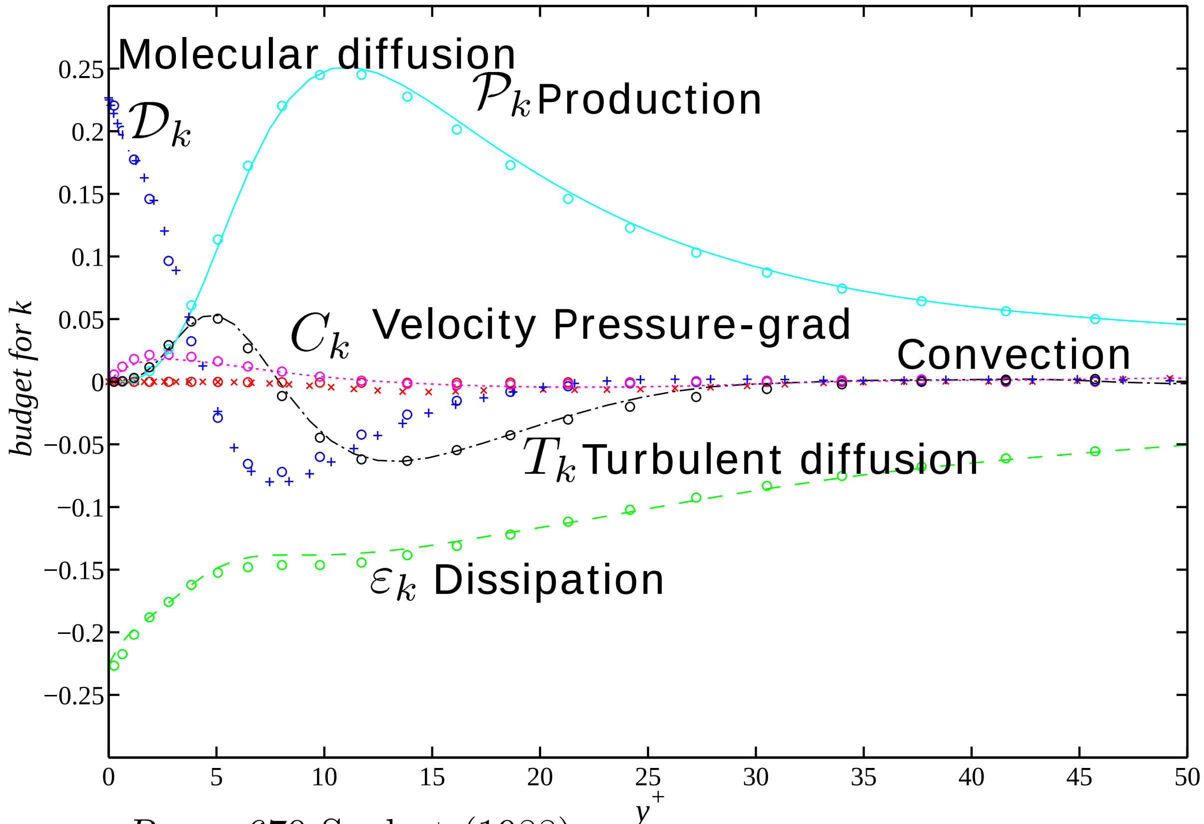

○ $Re_\theta = 670$ Spalart (1988)

Scalar Transport Results

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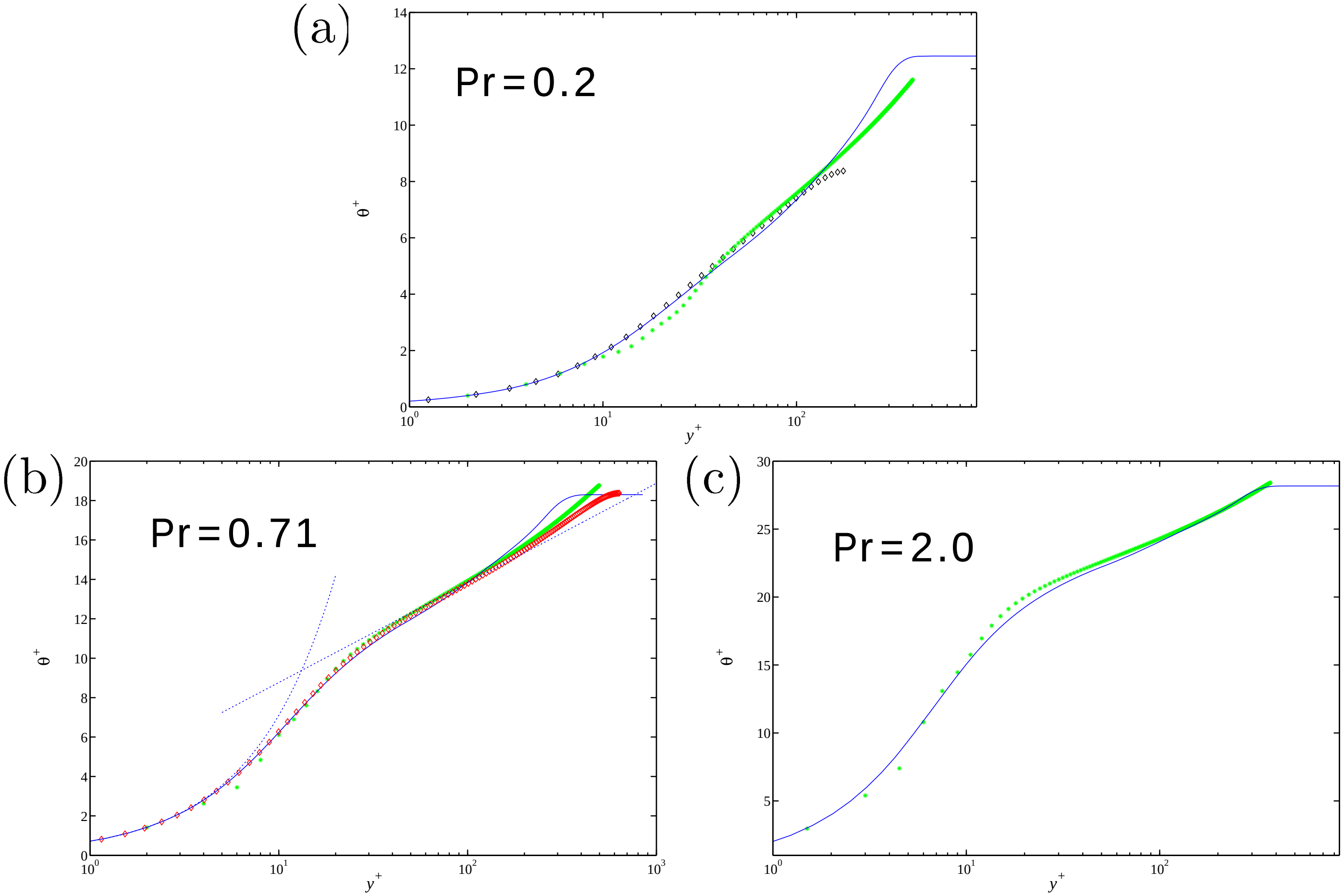
A list of scalars in the present DNS

scalar	boundary condition	Pr
θ_1	isothermal	0.2
θ_2	isothermal	0.71
θ_3	isoflux	0.71
θ_4	isothermal	2.0
θ_5	isoflux	2.0

Scalar Transport Results

Mean Scalar Profiles at $Re_\theta = 830$



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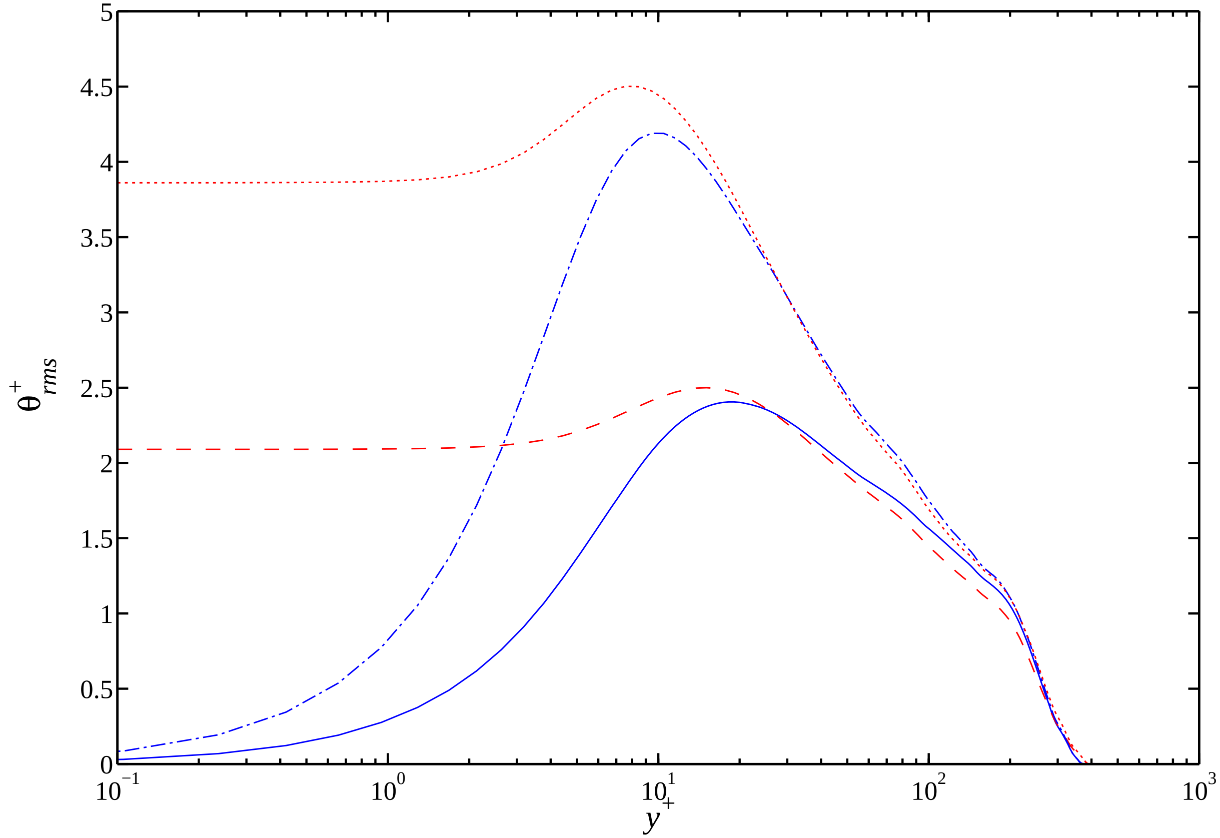
(a)θ_1,(b)θ_2,(c)θ_4, $\star$ Kader (1981), $\diamond$ $Re_\tau = 640$ Abe et al. (2004)
$\diamond$ $Re_\tau = 180$ Kawamura et al. (1998) , b.c. no difference

Scalar Transport Results

Comparisons between different boundary conditions at $Re_\theta = 830$



$— \theta_2, -- \theta_3, - \cdot - \theta_4, \cdots \theta_5$

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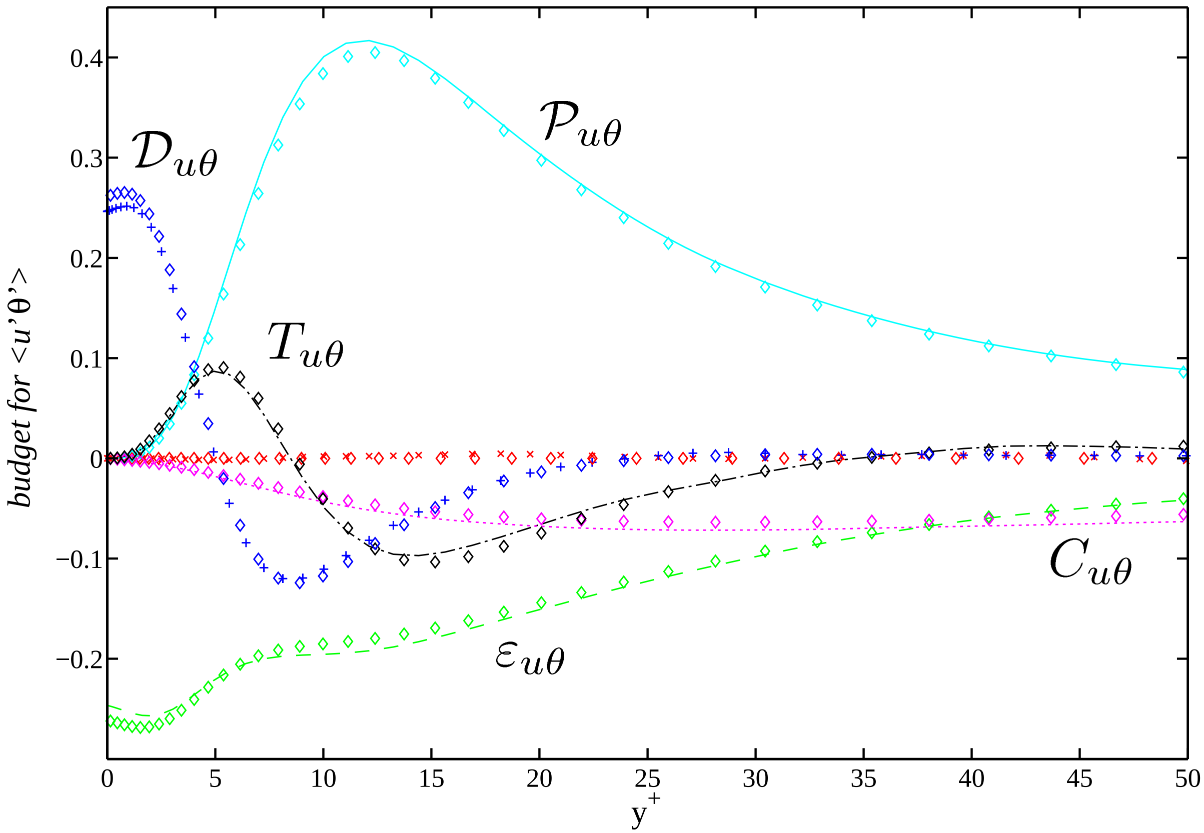
- non-zero at the wall and constant very near the wall
- far away, no difference

Scalar Transport Results

Budget for streamwise scalar flux $\langle u'\theta'\rangle$ of θ_2 at Re_θ=830



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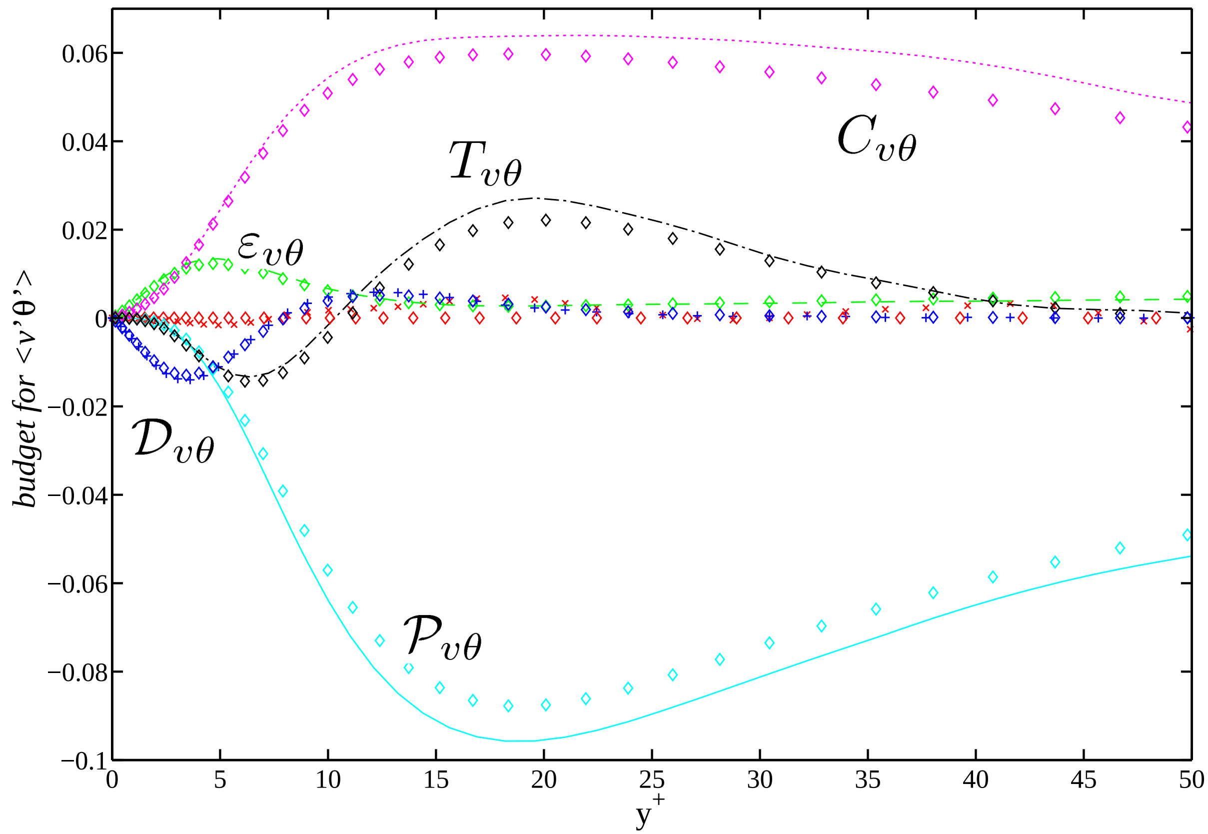
◇ $Re_\tau = 395$ Abe et al. (2004)

Scalar Transport Results

Budget for wall-normal scalar flux $\langle v'\theta' \rangle$ of θ_2 at Re_θ=830



◇ $Re_\tau = 395$ Abe et al. (2004)

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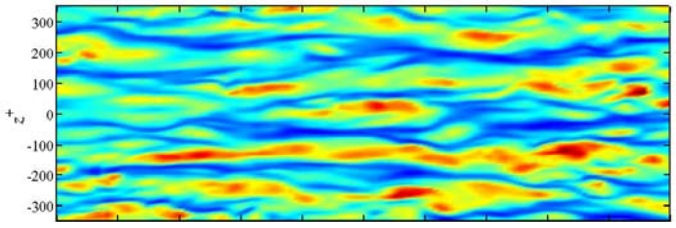
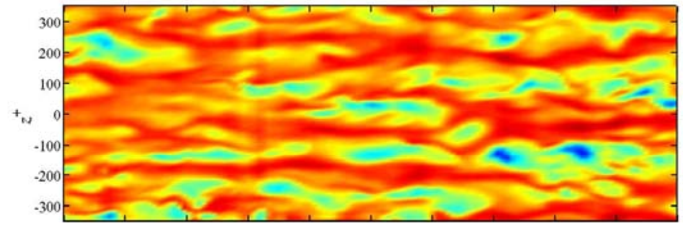
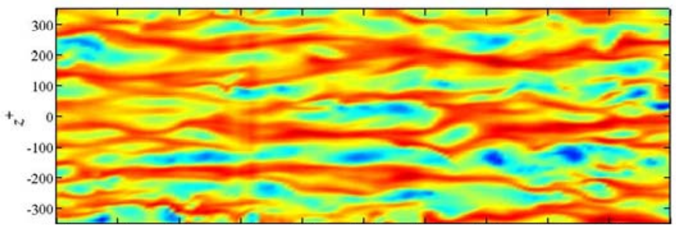
Instantaneous Fields



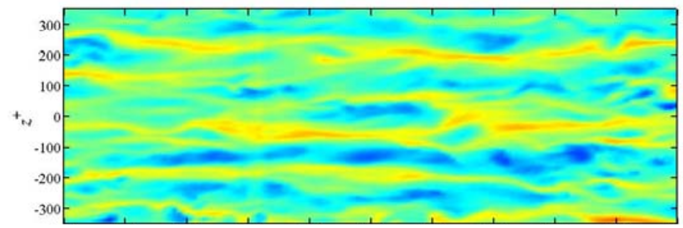
(a) u' at $y^+ \approx 7$



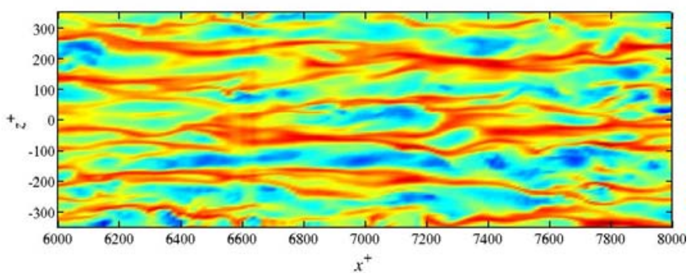
(b) θ'_1 at $y^+ \approx 7$



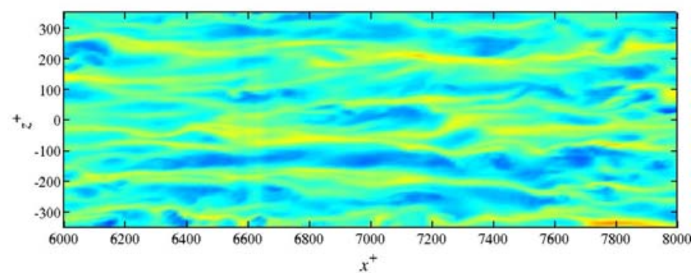
(c) θ'_2 at $y^+ \approx 7$



(d) θ'_3 at $y^+ \approx 7$



(e) θ'_4 at $y^+ \approx 7$



(f) θ'_5 at $y^+ \approx 7$

same time, x^+=6000-8000, $Re_\theta = 570 - 680$, $\Delta z^+ \approx 750$

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Conclusions

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- A DNS of turbulent boundary layer flow has been performed with five different scalars. Re is higher than the previously available DNS
- In general, comparisons with other DNS data are very good
- In the near-wall region boundary layer and channel simulations are very similar, however distinct differences are visible in the outer region
- The effect of the boundary condition is confined to the near-wall region

Outlook

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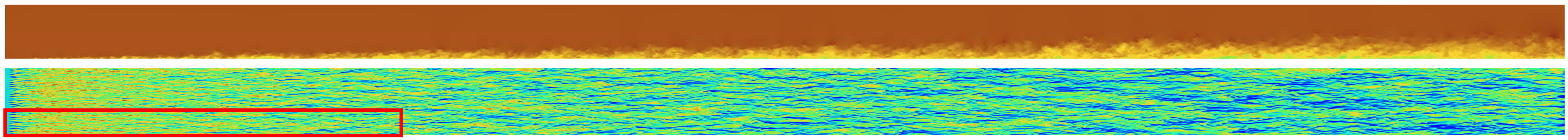
- Larger box to reach higher Re
- Higher or lower Pr: different grids for the two fields
- Active scalar, Boussinesq approximation
- Free-stream turbulence (FST), bypass transition, Reynolds analogy in the presence of FST
- Validation of LES: SGS modeling of the scalar field



1.5×10^9 grid points reaching $Re_\theta = 2500$

→ Compare with experiments

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Thank you!