Skin Friction and Heat Transfer Increase due to Free-Stream Turbulence

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Outline

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    - Free-Stream Turbulence Generation
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- Results
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    - Results
- Conclusions & Outlook

Motivation

Basic understanding of wall-bounded flows with heat transfer, especially flows with turbulent free stream:

- Crucial in industrial situations:
  - *e.g.* turbomachines, reactors, gas turbine, combustion chambers of motors *etc*.

  accurate prediction of both boundary layer development and convective heat transfer → cycle efficiency, cooling design, hardware durability

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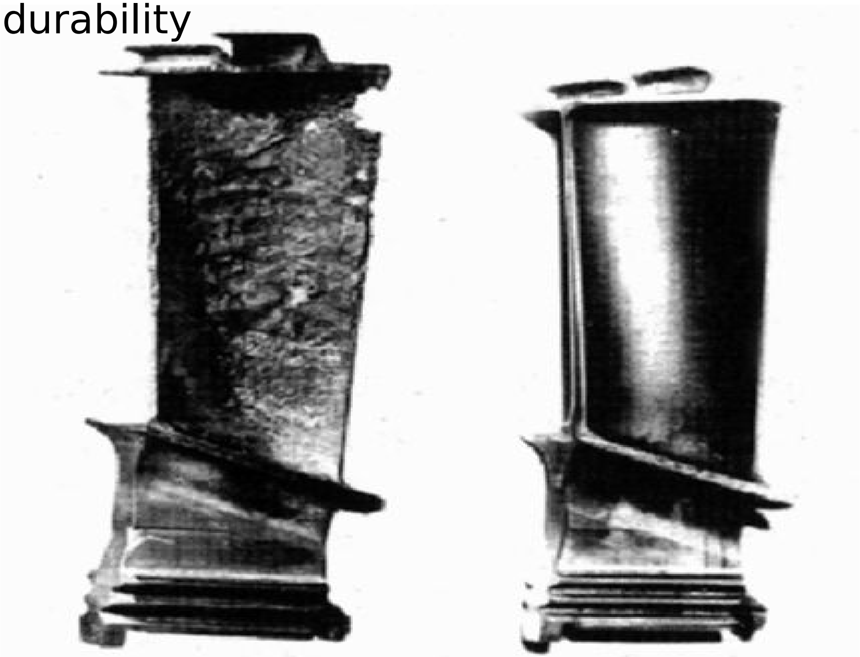

A destroyed turbine blade due to hot corrosion, *Eskner, (*2004*)*

Motivation

Basic understanding of wall-bounded flows with heat transfer, especially flows with turbulent free stream:

- Crucial in academic situations:
  - Understanding of the heat transfer subjected to FST is limited (*e.g.* Reynolds Analogy)
  - It is difficult when measuring close to the wall → numerical simulations are needed
  - Effects of the large-scale structures on the heat transfer on the wall are not well-understood
  - Clearly a need for well resolved numerical simulations of heat transfer in TBL with ambient FST

(Jacobs & Durbin, 2000, Péneau *et al*., 2000)

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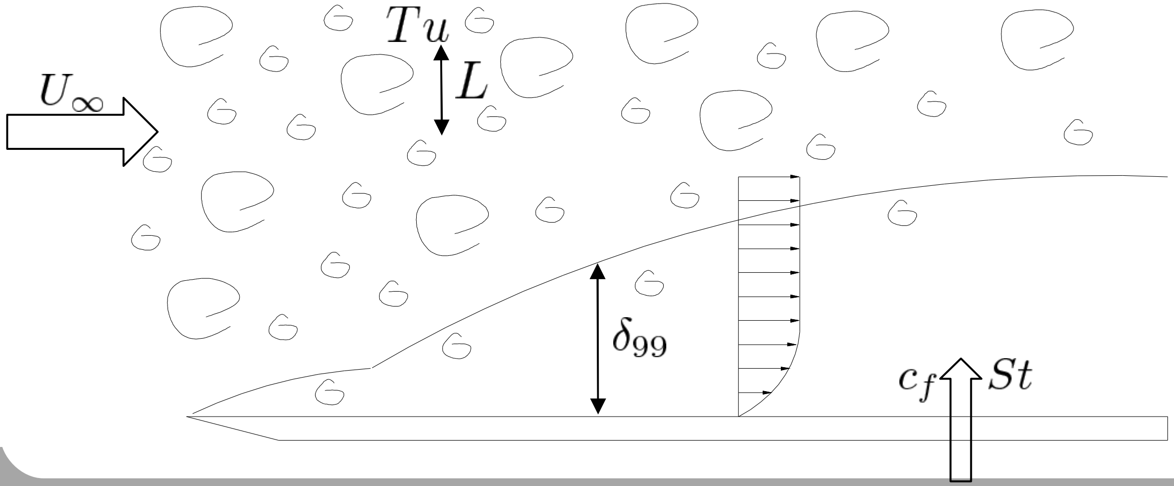

Previous Studies

		Re_θ	Tu %	c_f %	St %
Simonich & Bradshaw, 1978	Exp	6000	4.7	10	30
Blair, 1983	Exp	6000	3.7	15	20
Péneau *et al.*, 2000	LES	1000	21	10	20
Jacobs & Durbin, 2000	DNS	800	1	5	12

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•c_f and St increase with Tu, St increase at a higher rate than c_f → Reynolds Analogy Factor is increasing with Tu

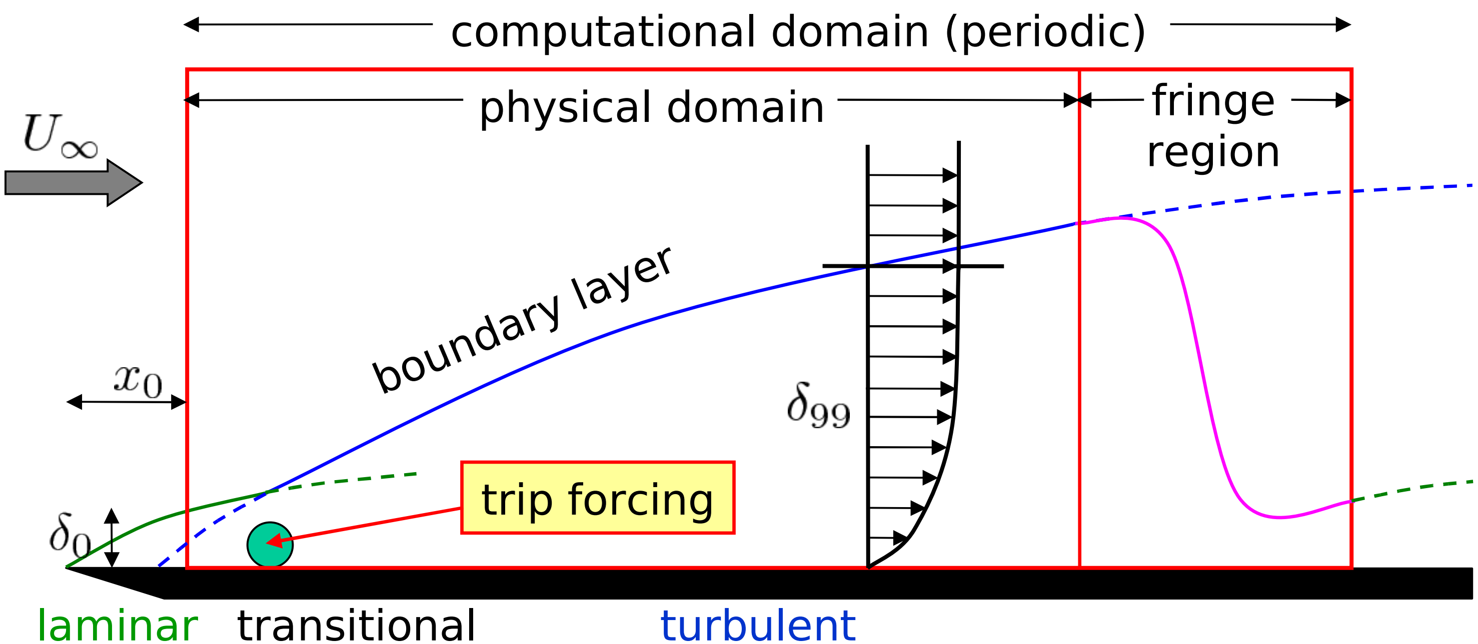
•The relative increase of c_f and St depend on Tu, L, Re

•Wake region is depressed even vanished for high Tu

•How much increase is different from one to another

•No real explanations provided

Spatial Boundary Layer



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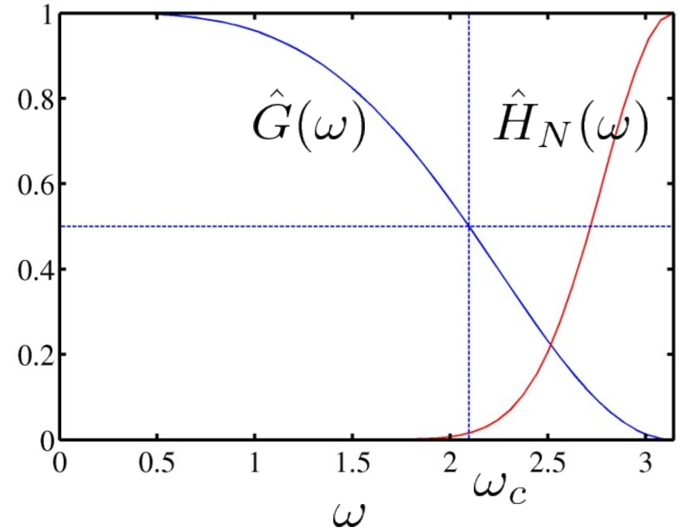
- Fully spectral method: Fourier/Chebyshev tau method
- Periodic b.c. in the wall-parallel directions, no-slip at lower wall, Neumann conditions at upper boundary. Air flow, Pr=0.71
- Fringe region (volume force) to enforce laminar Blasius inflow
- Trip forcing to induce “natural” laminar-turbulent transition
- Code **SIMSON** (Chevalier *et al.* 2007) on 1024 processors BG/L

Relaxation Term (RT) Model



Recently RT model for heat transfer is implemented

$$\frac{\partial \tau_{ij}}{\partial x_i} = \chi H_N * \widetilde{u}_i$$

$$\frac{\partial \sigma_i}{\partial x_i} = \chi_\theta H_N * \widetilde{\theta} \qquad \chi_\theta = \frac{\chi}{Pr_t}$$

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- High-pass filter: $\hat{H}_N = (1 - \hat{G})^{N+1}$

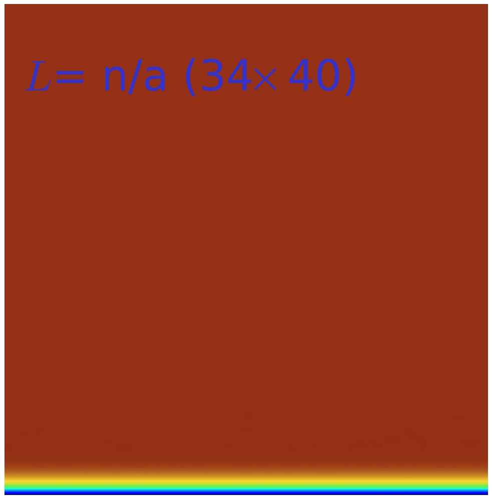
  with $N = 5$ and $\omega_c = 2\pi/3$

Model Coefficient $\chi = 0.2$ with $Pr_t = 0.6$

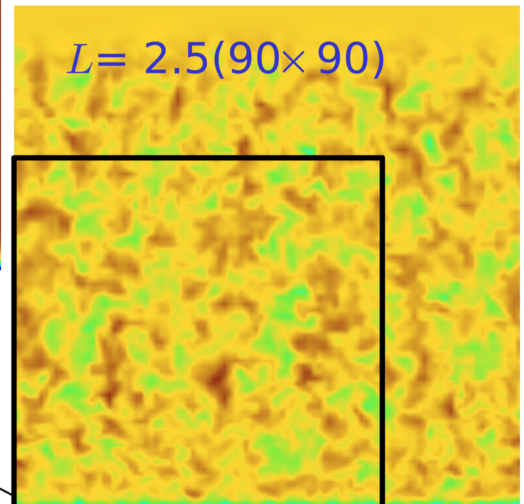
Relaxation Term Necessary drain of energy (SGS dissipation), acting on the small scales (large wavenumber) only

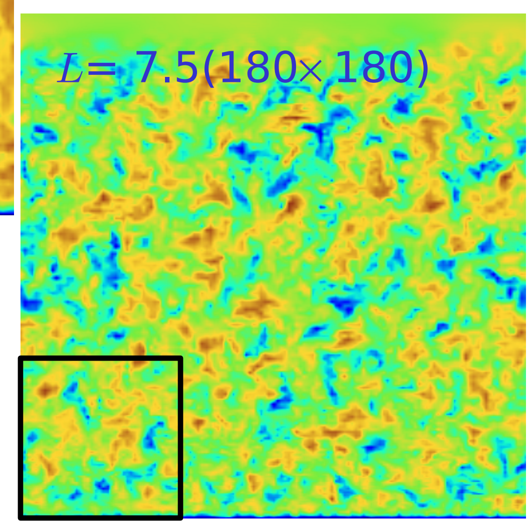
Reference: Schlatter *et al*, *Int. J. Heat Fluid Flow* (2004)

Free-Stream Turbulence



Streamwise velocity in the Y-Z plane at the inlet for different length scale





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L increases

Brandt, *et al.*, *JFM*(2004), L=5

Similar method is used by Jacbos & Durbin, *JFM (2001)*

The generated FST is homogeneous and isotropic

Main Parameters

	$x_l \times y_l \times z_l$ δ_0^*	$N_x \times N_y \times N_z$ (grid points)	$Re_{\delta_0^*}$
Box 1	$1500 \times 90 \times 90$	$384 \times 121 \times 96$	300
Box 2	$1500 \times 180 \times 180$	$384 \times 201 \times 128$	300
Box 3	$1500 \times 180 \times 240$	$384 \times 201 \times 192$	300
Box 4	$750 \times 40 \times 34$	$1024 \times 289 \times 128$	450

	Tu %	L δ_0^*	Box
Case 1	0	n/a	Box 1
Case 2	4.7, 20	2.5, 5, 7.5	Box 1
Case 3	4.7, 20, 40	5, 7.5, 15	Box 2
Case 4	4.7, 20, 40	7.5, 15	Box 3
Case 5	0	n/a	Box 4

The grid spacing is Δx^+=60, Δz^+=16

2 points below y^+=1 and 8 points below y^+=10

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Validation of the LES Results

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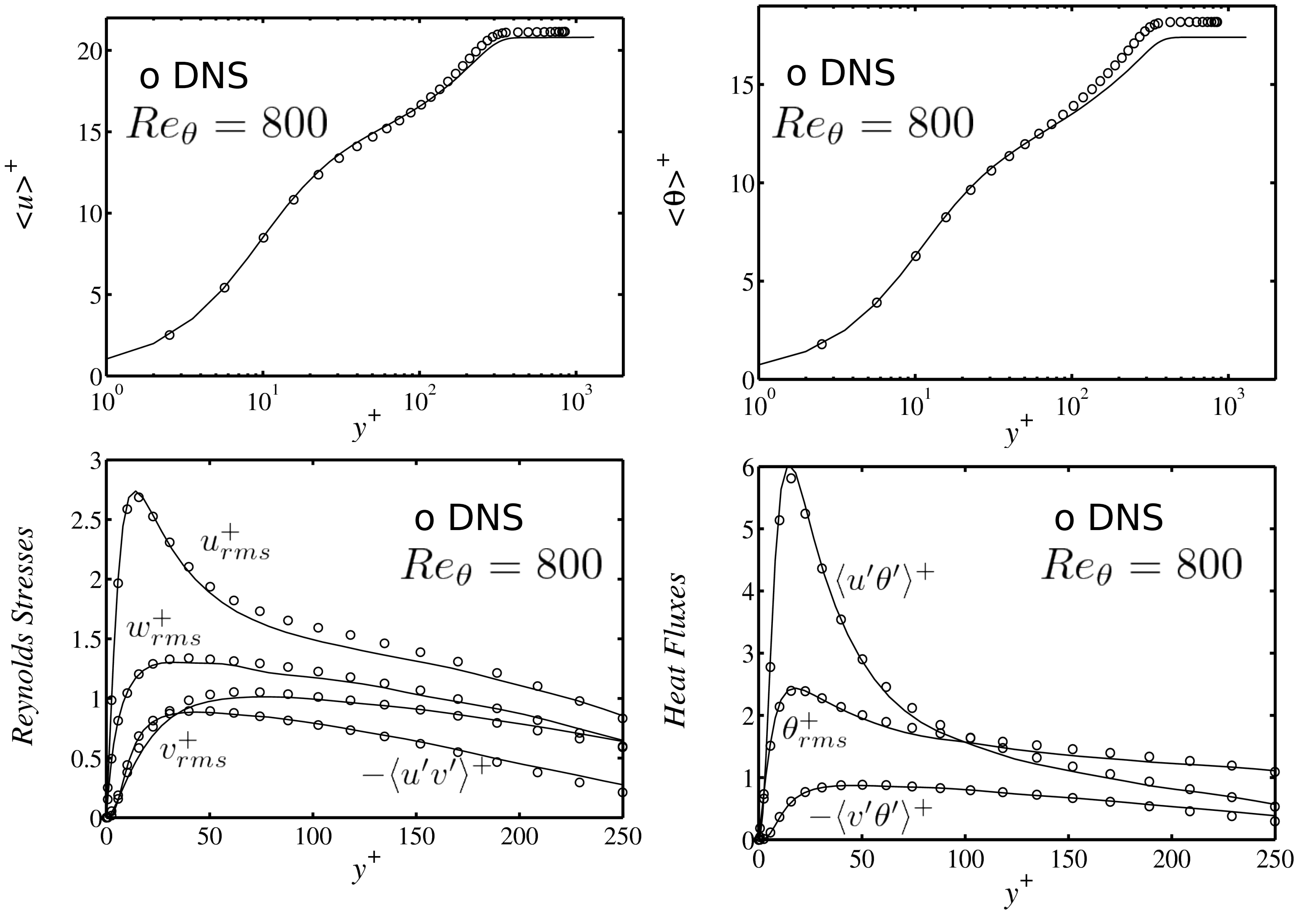
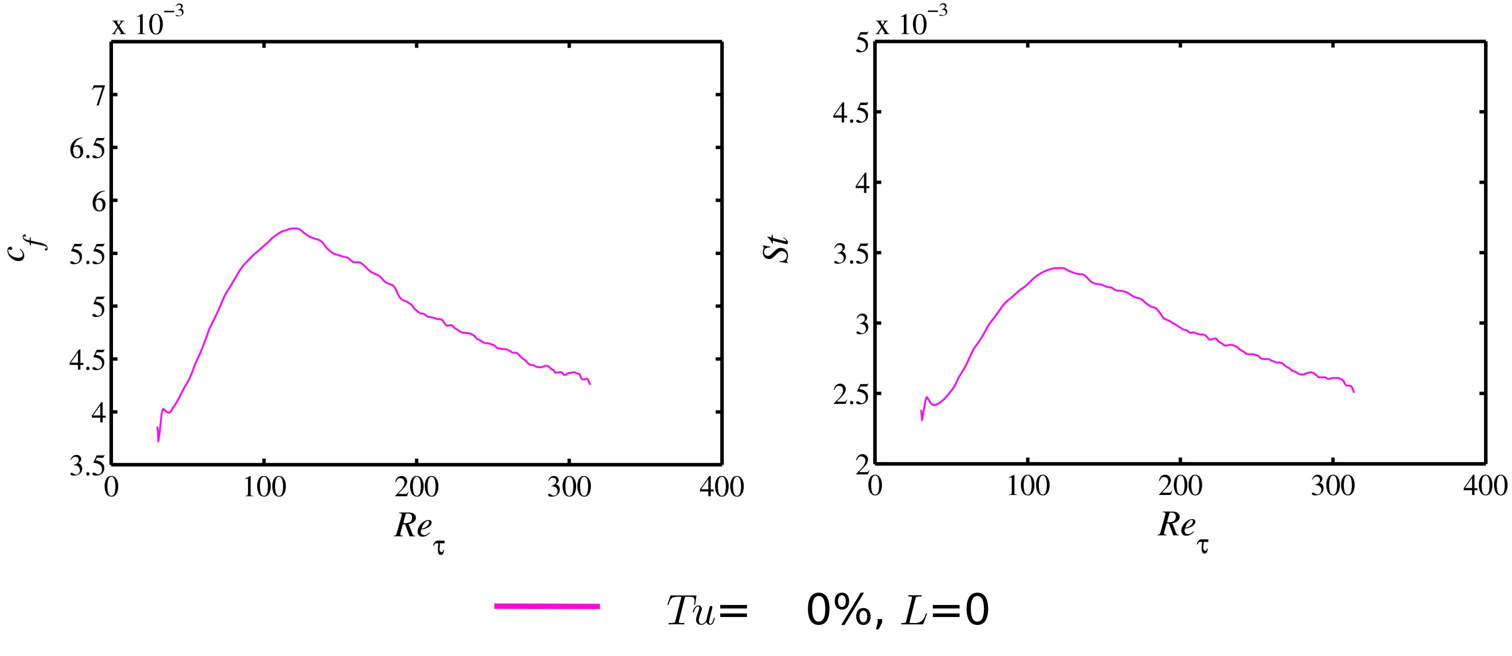


DNS Reference: Li *et al*, (2009), *Int. J. Heat Fluid Flow*

Free-Stream Turbulence

Influence of the FST on c_f and St



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Free-Stream Turbulence

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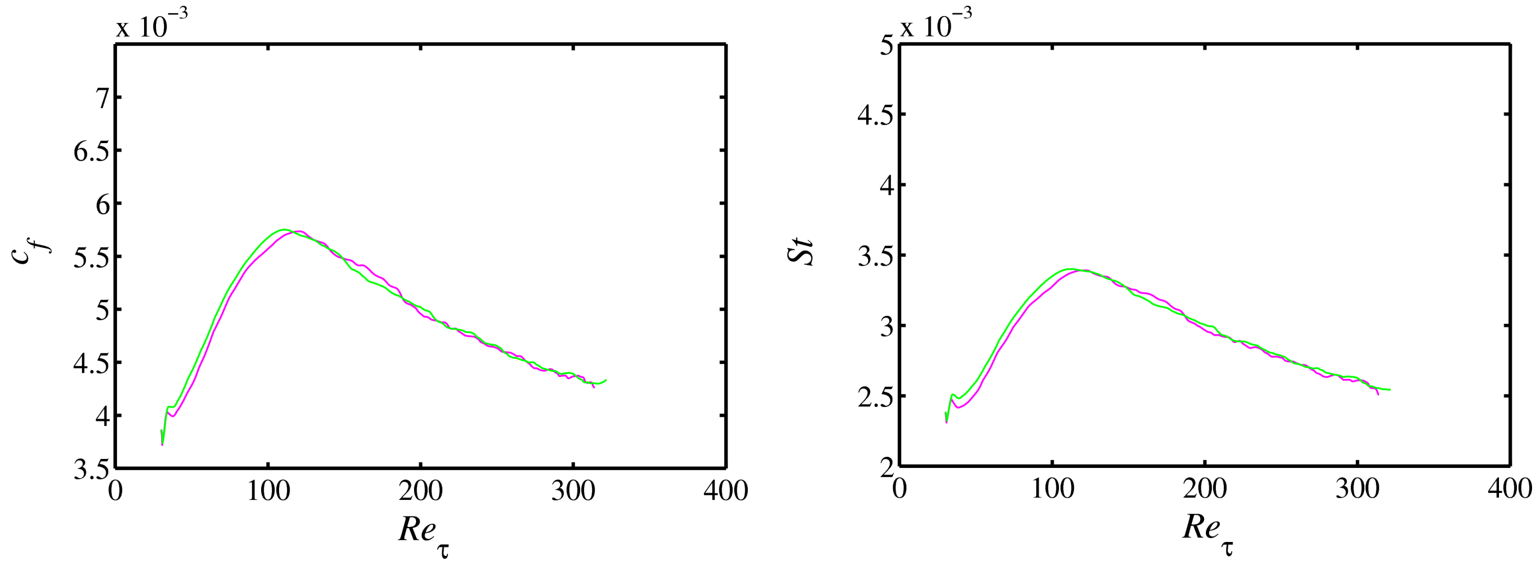
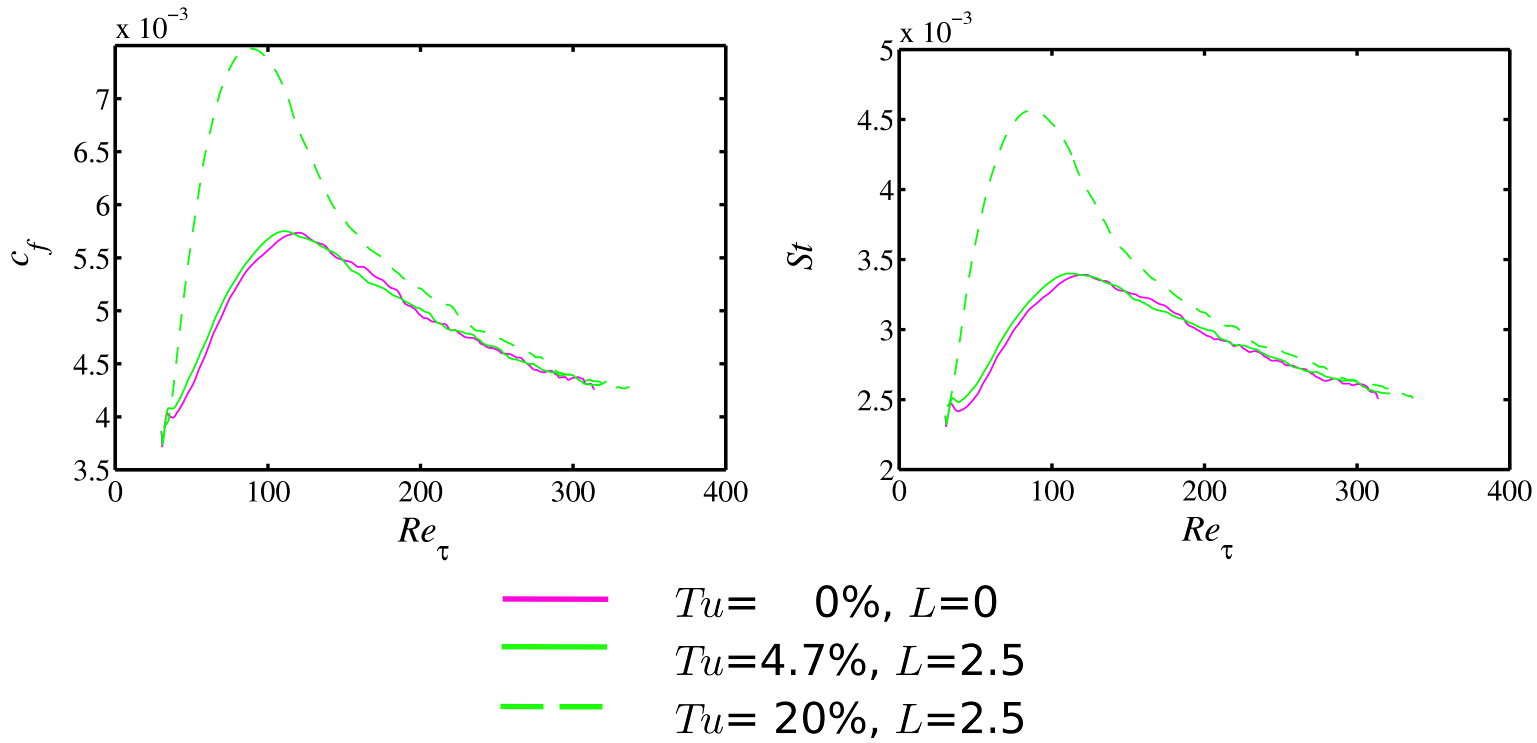


Tu= 0%, L=0
Tu=4.7%, L=2.5

Due to a low L → similar to the case with no FST

Free-Stream Turbulence

Influence of the FST on c_f and St



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Free-Stream Turbulence

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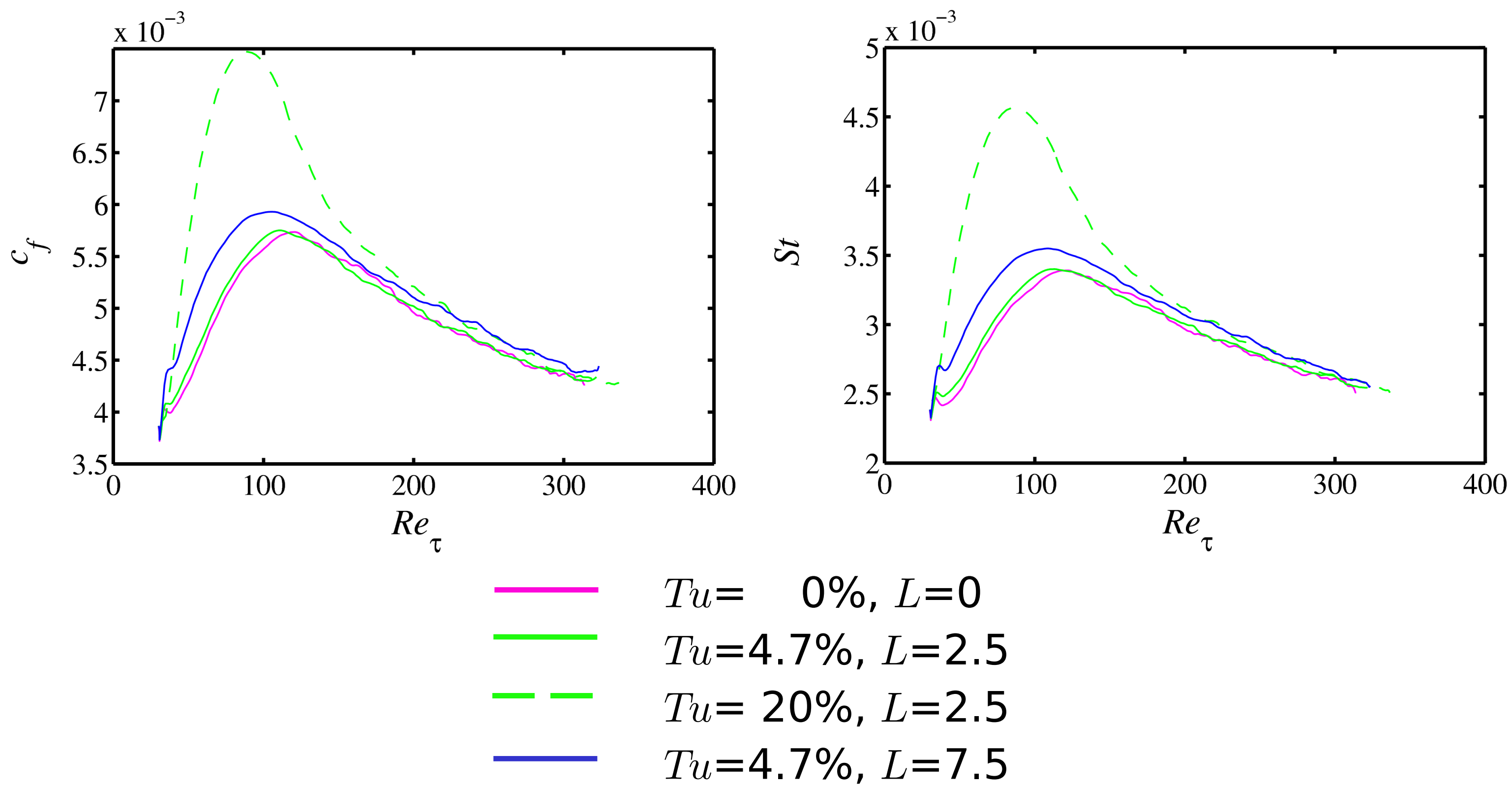
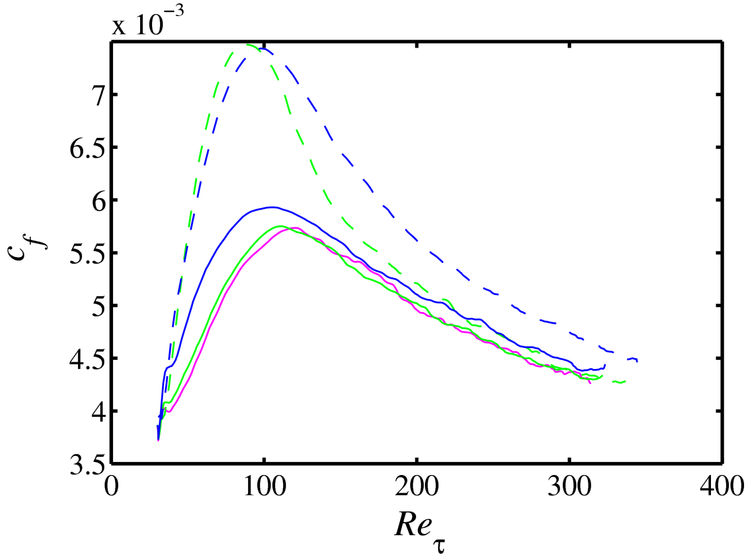
Influence of the FST on c_f and St

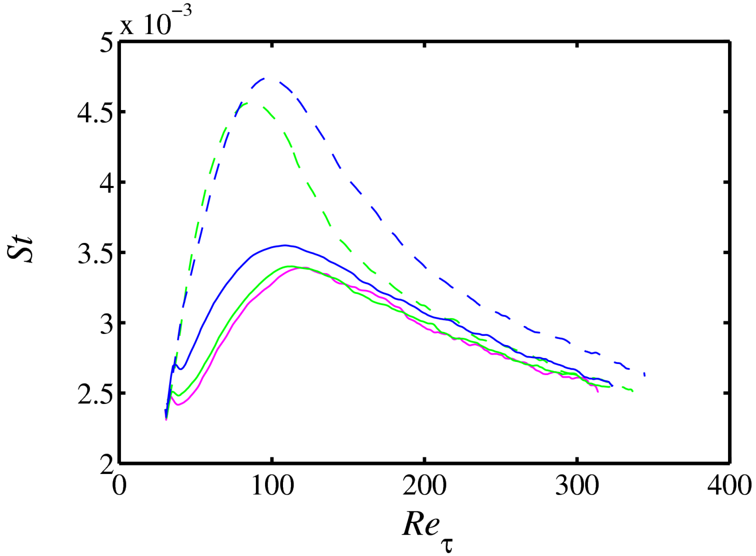


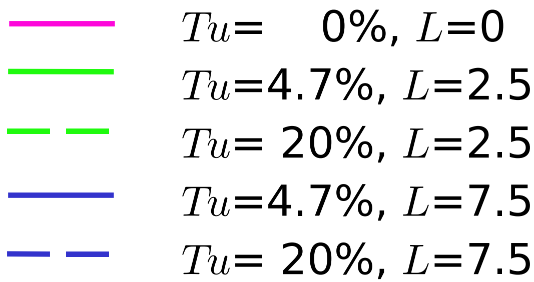
Even L is bigger, due to the low Tu, effects are not obvious

Free-Stream Turbulence

Influence of the FST on c_f and St



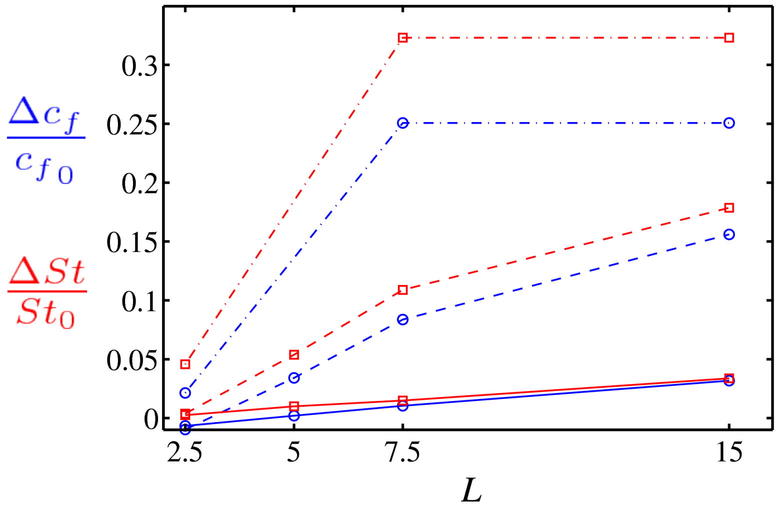




Both Tu and L are important to maintain the effects of FST

Free-Stream Turbulence

Relative increase of at c_f and St at $Re_\tau = 300$



—— inlet $Tu = 4.7\%$, - - - inlet $Tu = 20\%$, −·− inlet $Tu = 40\%$

For smaller L, St increase more than c_f, but not for larger L

For L=7.5, local Tu=7% → a relative increase of c_f 32% and St 25%

Free-Stream Turbulence

Influence of the FST on the mean profiles at $Re_\theta = 850$

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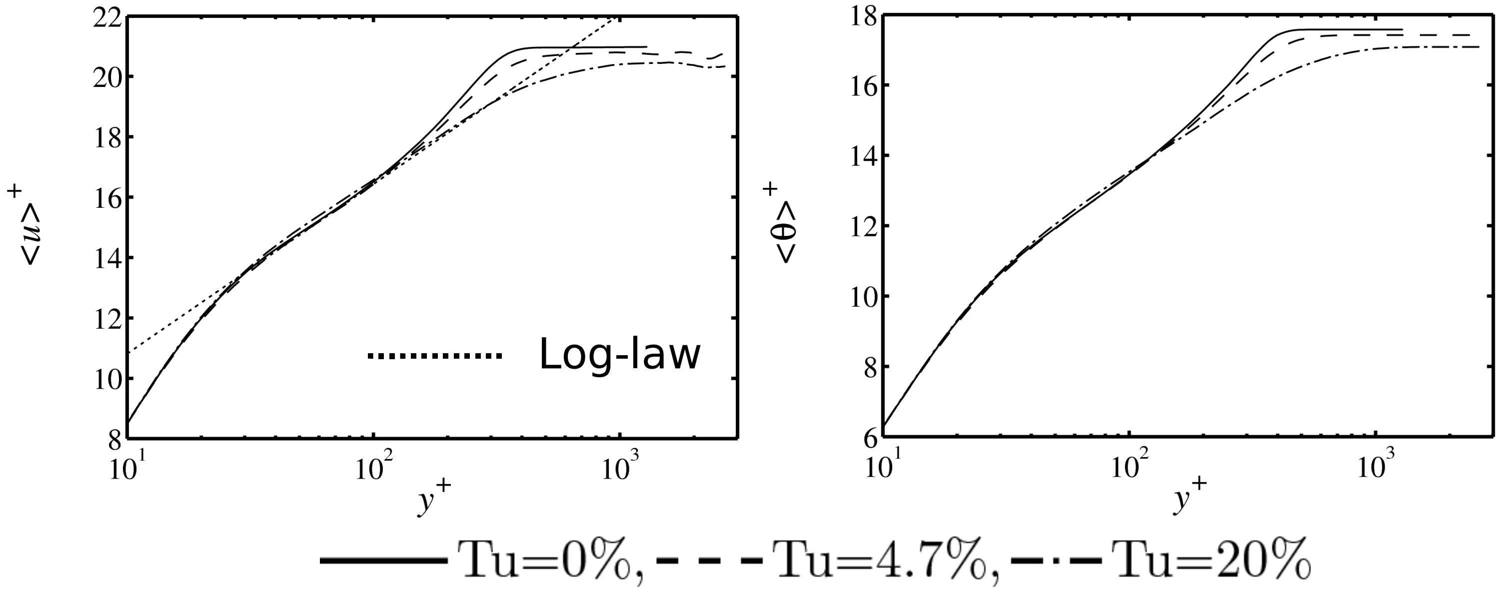
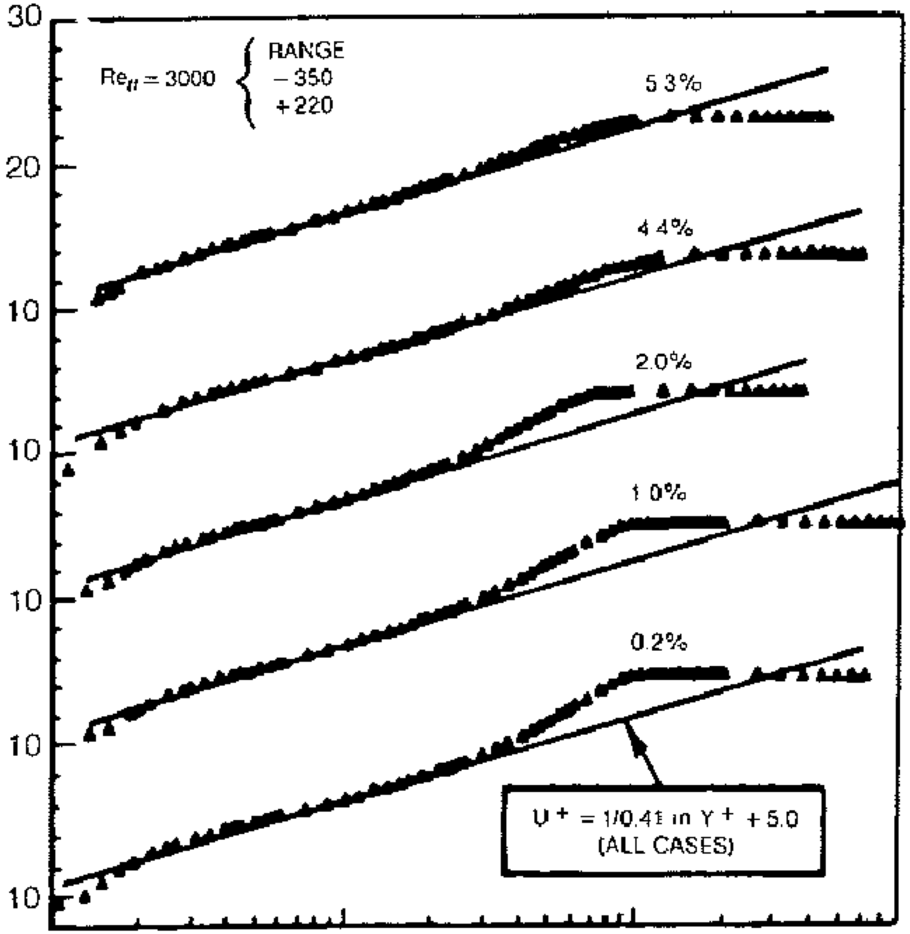


Depression of the boundary-layer wake region starts appearing with increasing Tu

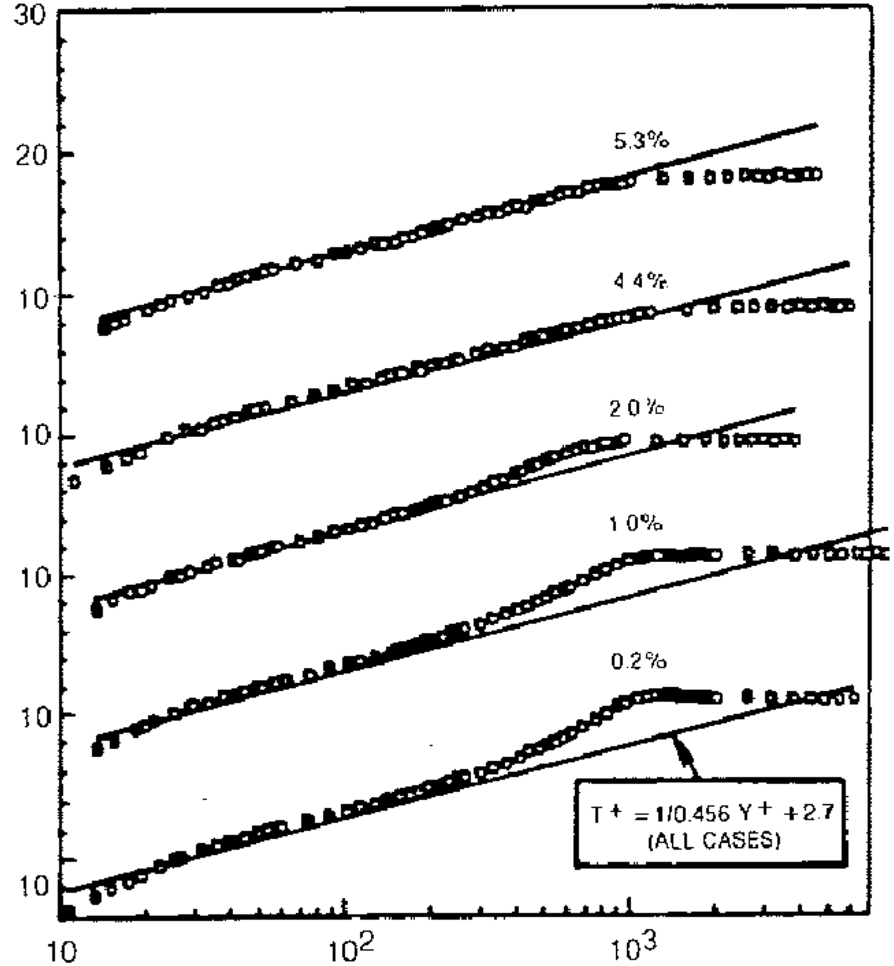
Viscous (conductive) sub-layer and logarithmic region are insensitive to the FST

Free-Stream Turbulence

Mean velocity profile

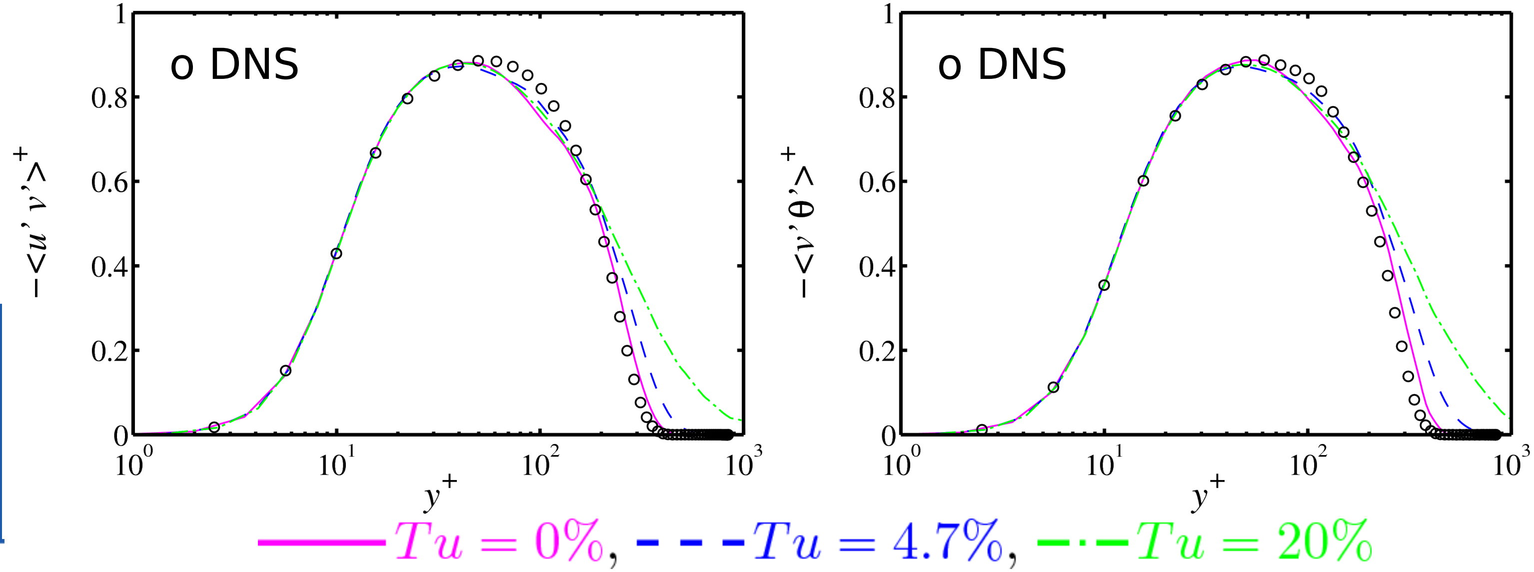


Mean temperature profile



Blair, 1983

Free-Stream Turbulence



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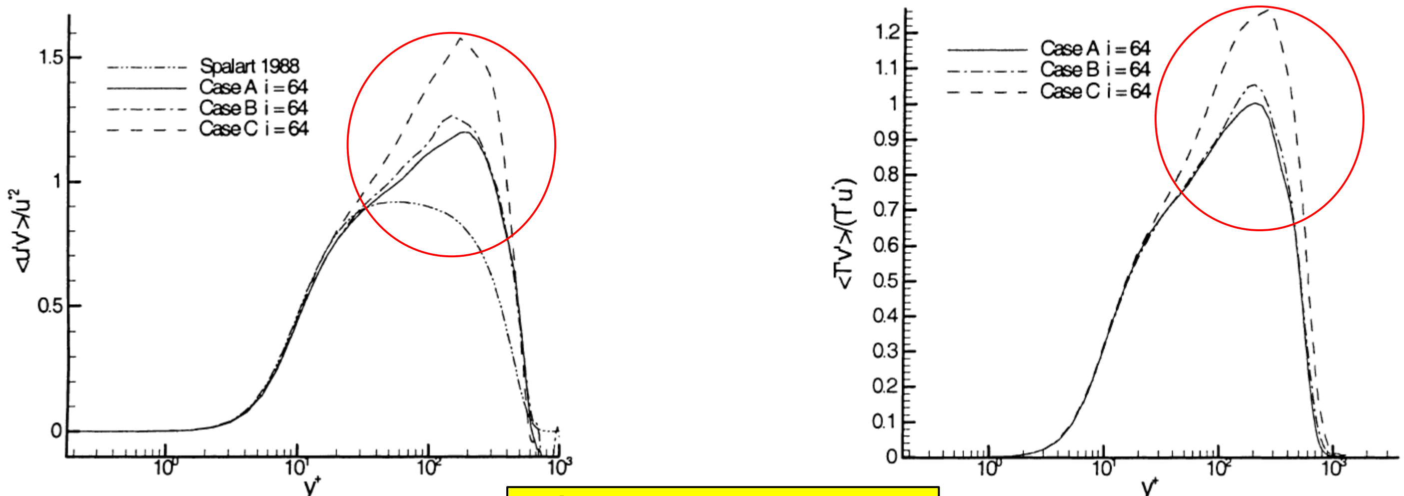
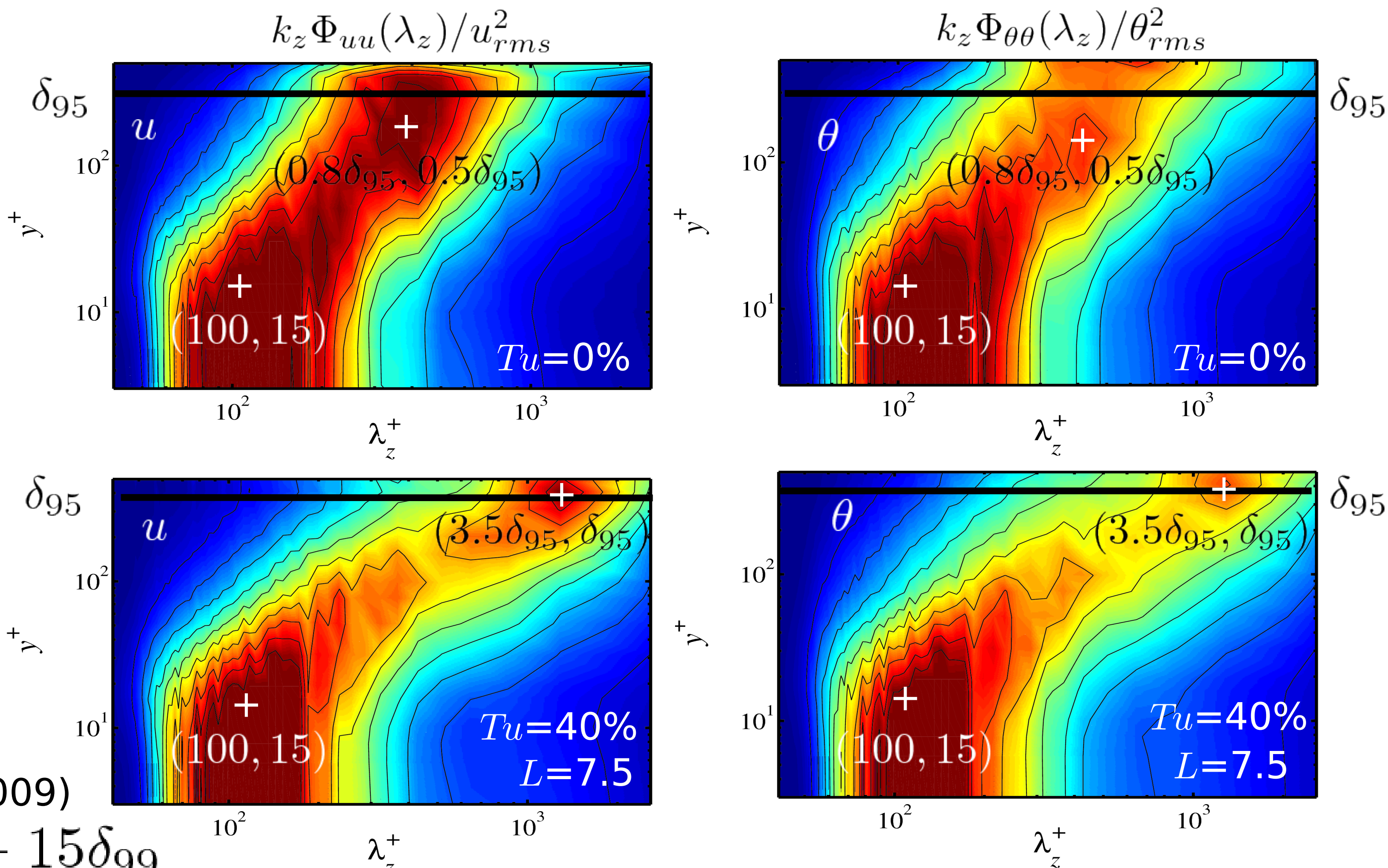


Péneau *et al.*, 2000

Free-Stream Turbulence

Premultiplied spanwise energy spectra of u and θ at $Re_\theta = 900$



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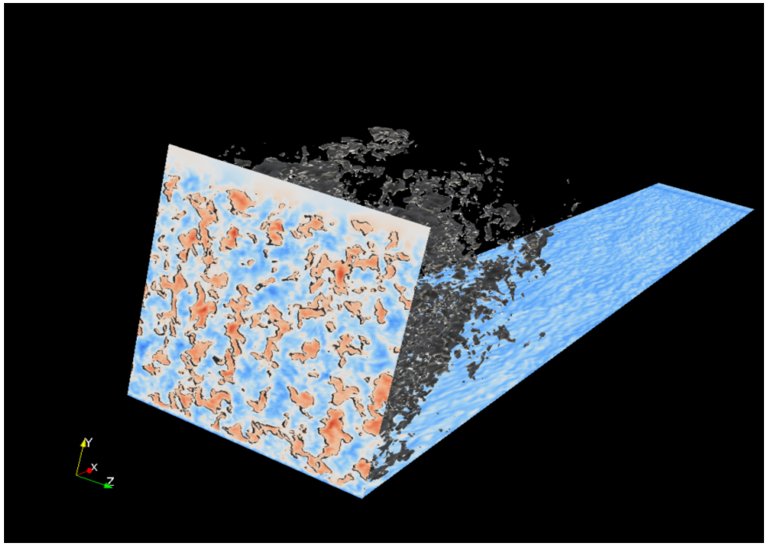
Sharp *et al.* (2009)

$$\lambda_x \sim 6\delta_{99} - 15\delta_{99}$$

Conclusions & Outlook



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- A series of LES of TBL with FST has been performed, the newly implemented LES models give good results at a low cost (5%-10%)
- Increased c_f and St with increasing Tu are observed, for small L, St grows faster than c_f → Reynolds analogy factor grows with Tu
- The increase is due to footprints of the large-scale motions near the boundary layer edge
- Depression of the wake region is associated with the lower intermittency due to FST
- DNS will be performed, more detailed analysis will be done, in particular compare to results without FST at high Reynolds number

Comparison of TBL and Channel for Heat Transfer

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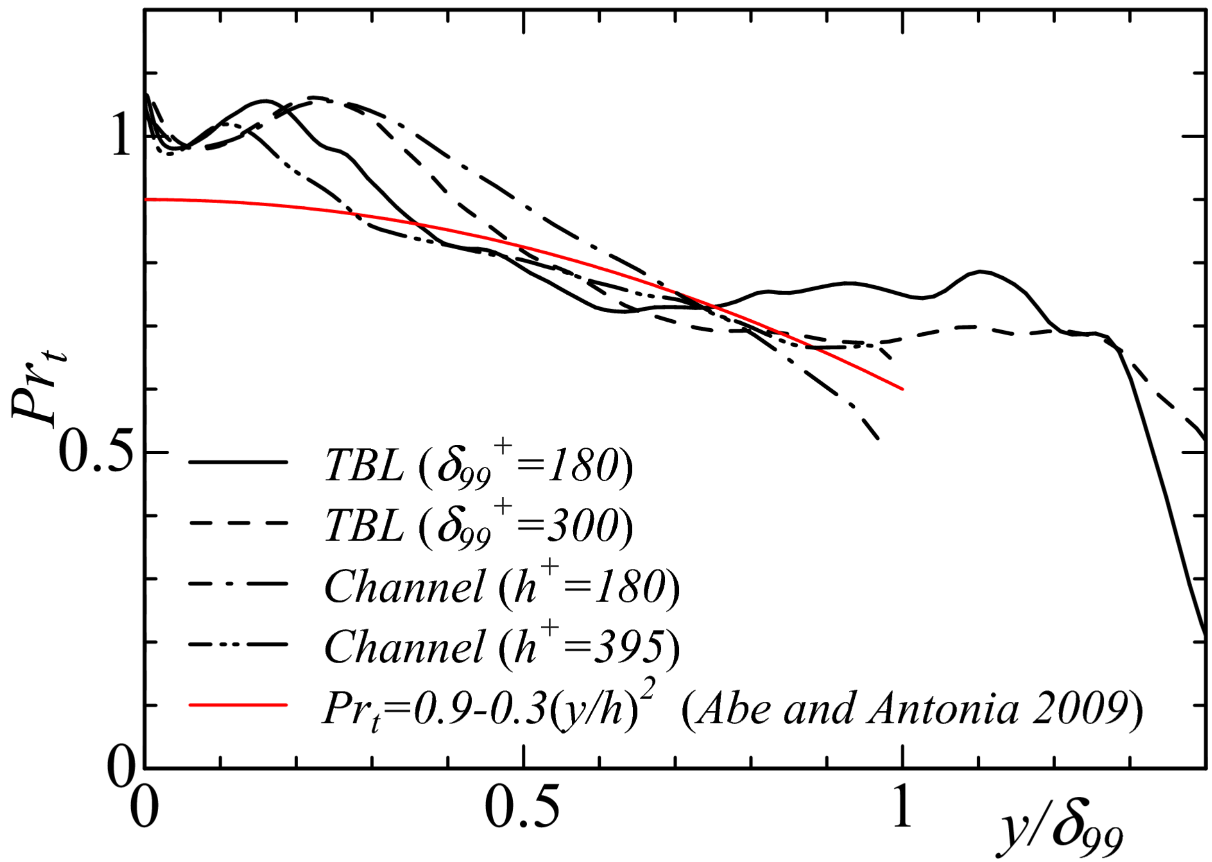
Preliminary result

Turbulent Prandtl Number

$$\nu_t = -\frac{\langle u'v' \rangle}{\frac{\partial \langle u \rangle}{\partial y}}$$ Turbulent eddy viscosity

$$\alpha_t = -\frac{\langle v'\theta' \rangle}{\frac{\partial \langle \theta \rangle}{\partial y}}$$ Turbulent eddy diffusivity



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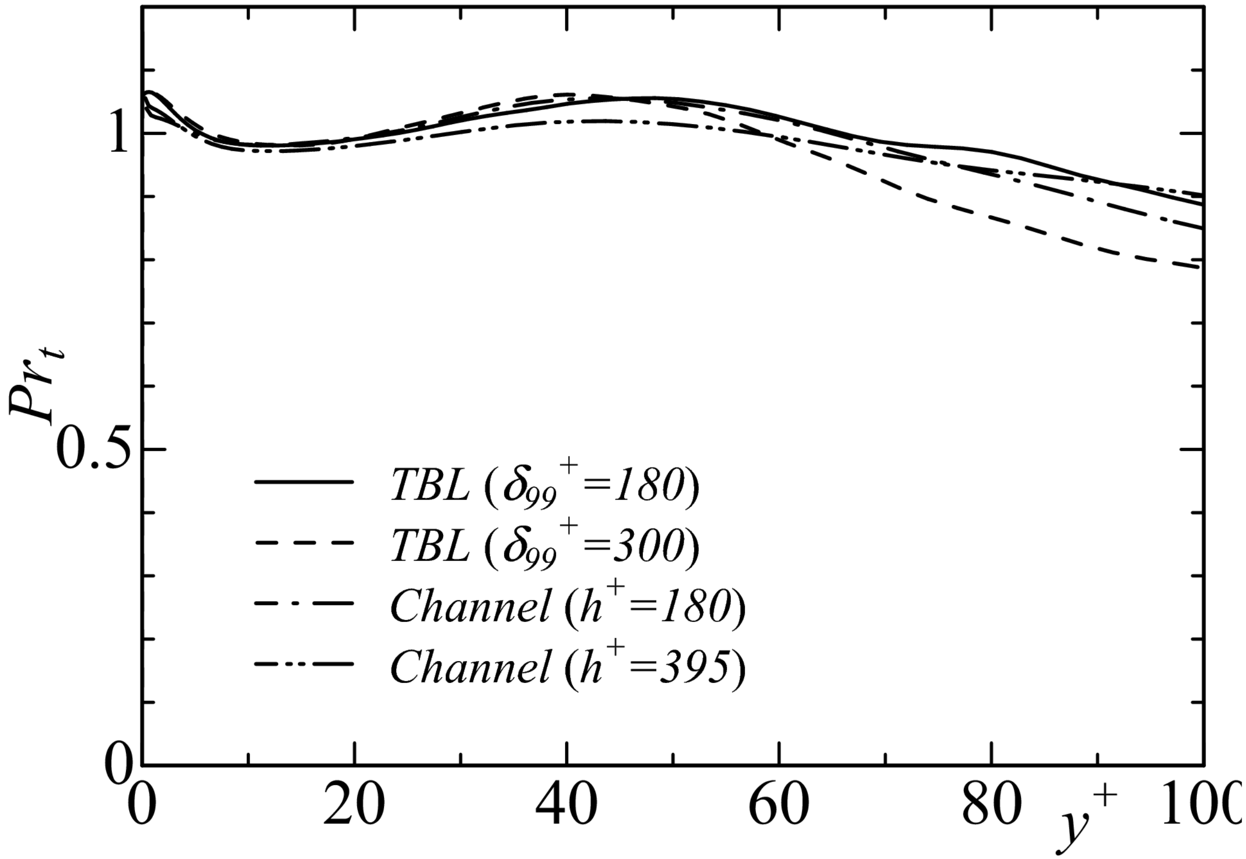
Turbulent Prandtl Number



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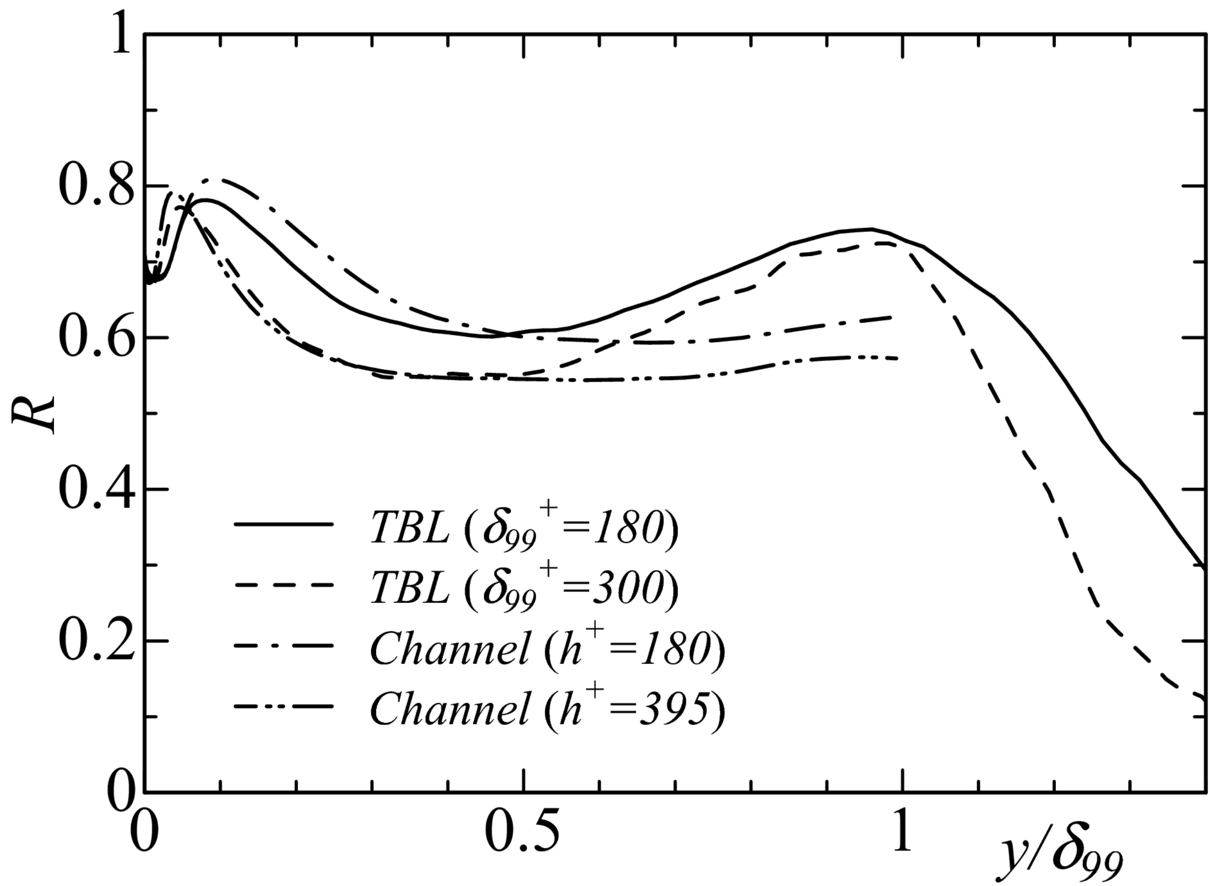
Time Scale Ratio

$$R = \frac{k_\theta / \varepsilon_\theta}{k/\varepsilon}$$



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Thank you!

Free-Stream Turbulence

Influence of the FST on the Reynolds stress heat flux at $Re_\theta = 850$

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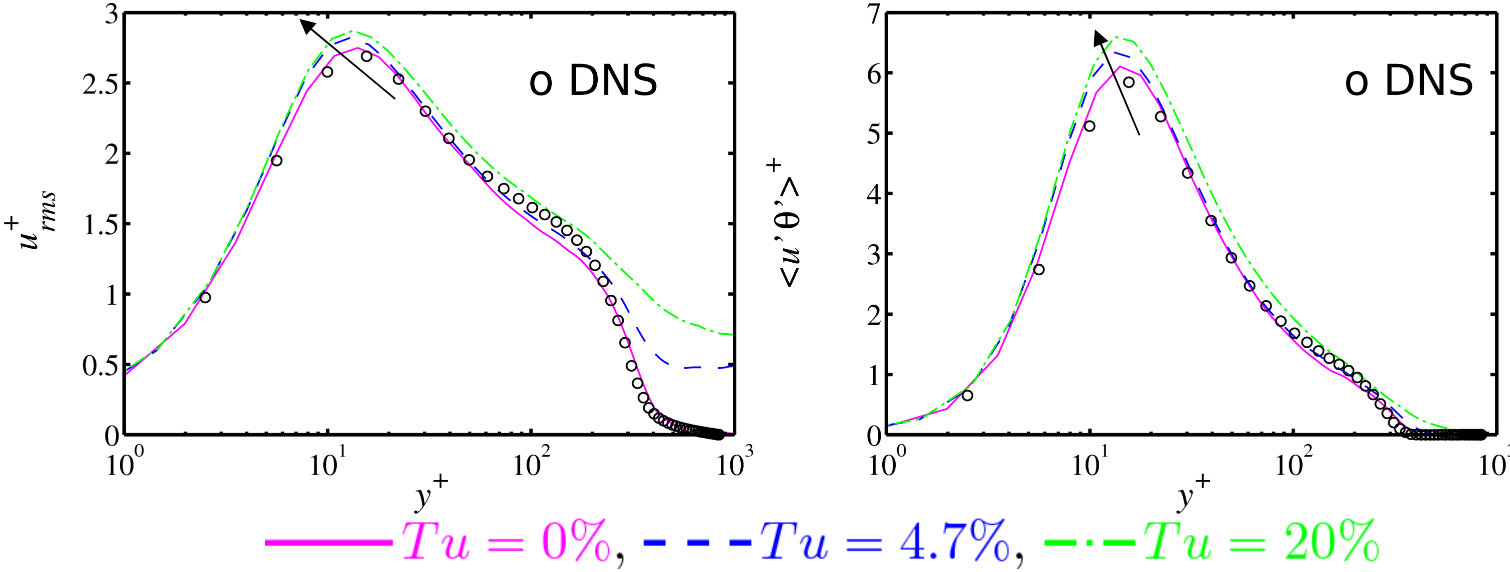
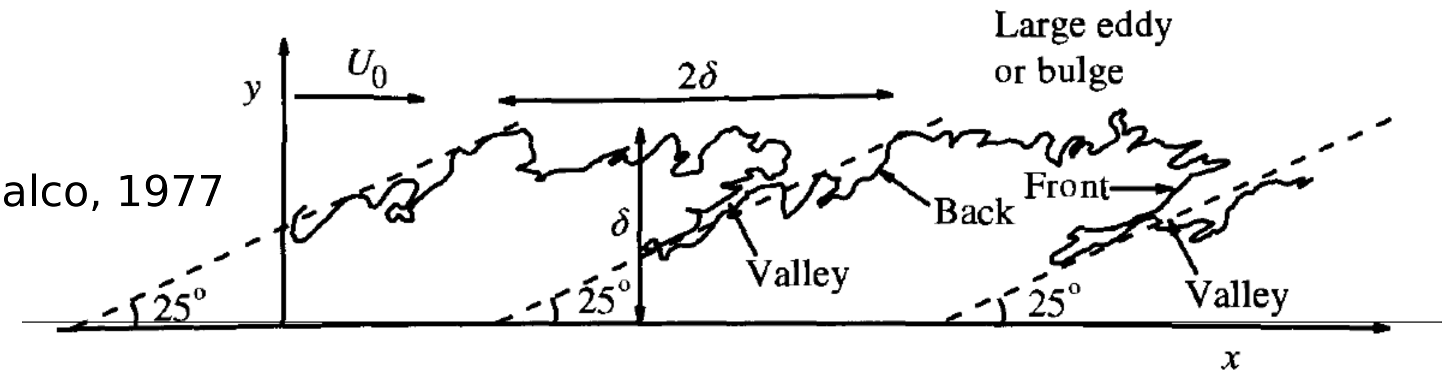


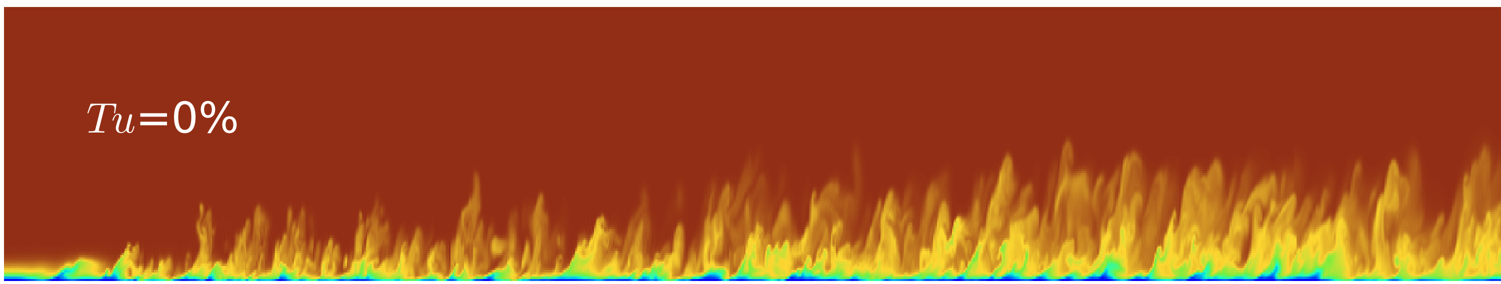
Peak moves towards the wall and increases with higher Tu

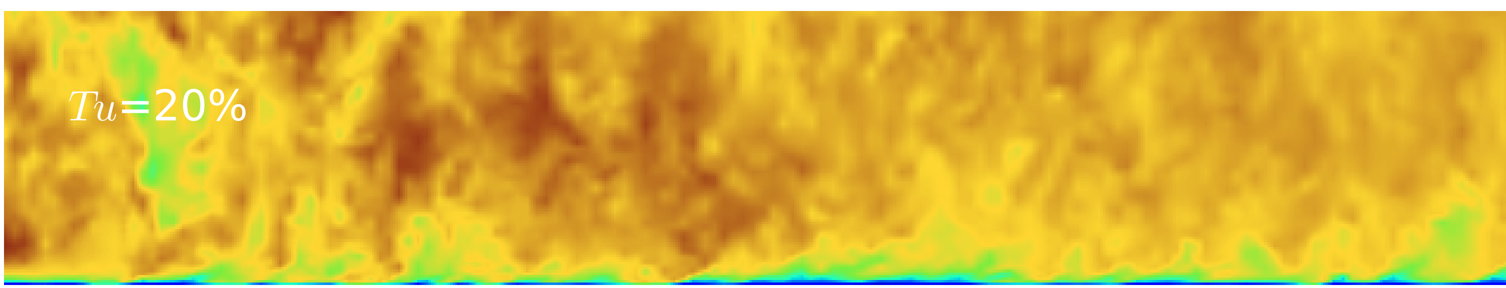
More increases in the free stream

Free-Stream Turbulence

Falco, 1977







Depression of wake region is due to the loss of intermittency

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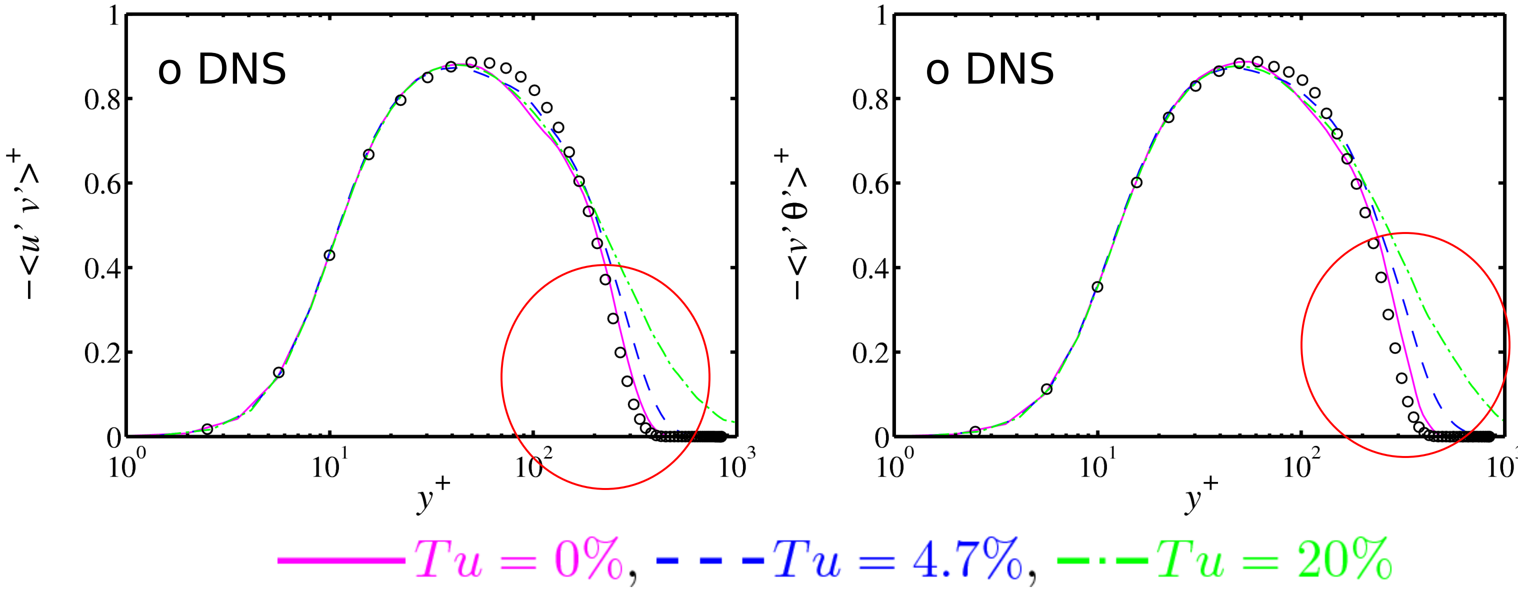
Free-Stream Turbulence



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The increase of c_f and St is connected to the large-scale structure resides in the outer region