LES of Coherent Vortices Embedded on an Impinging Jet

Wen Wu, Ugo Piomelli

Department of Mechanical and Materials Engineering

Queen's University

Kingston, Ontario, Canada)

VORTICAL STRUCTURES AND WALL TURBULENCE
Monteporzio Catone, September 20-12, 2014

TURBULENCE SIMULATION TSM LAB AND MODELLING LABORATORY

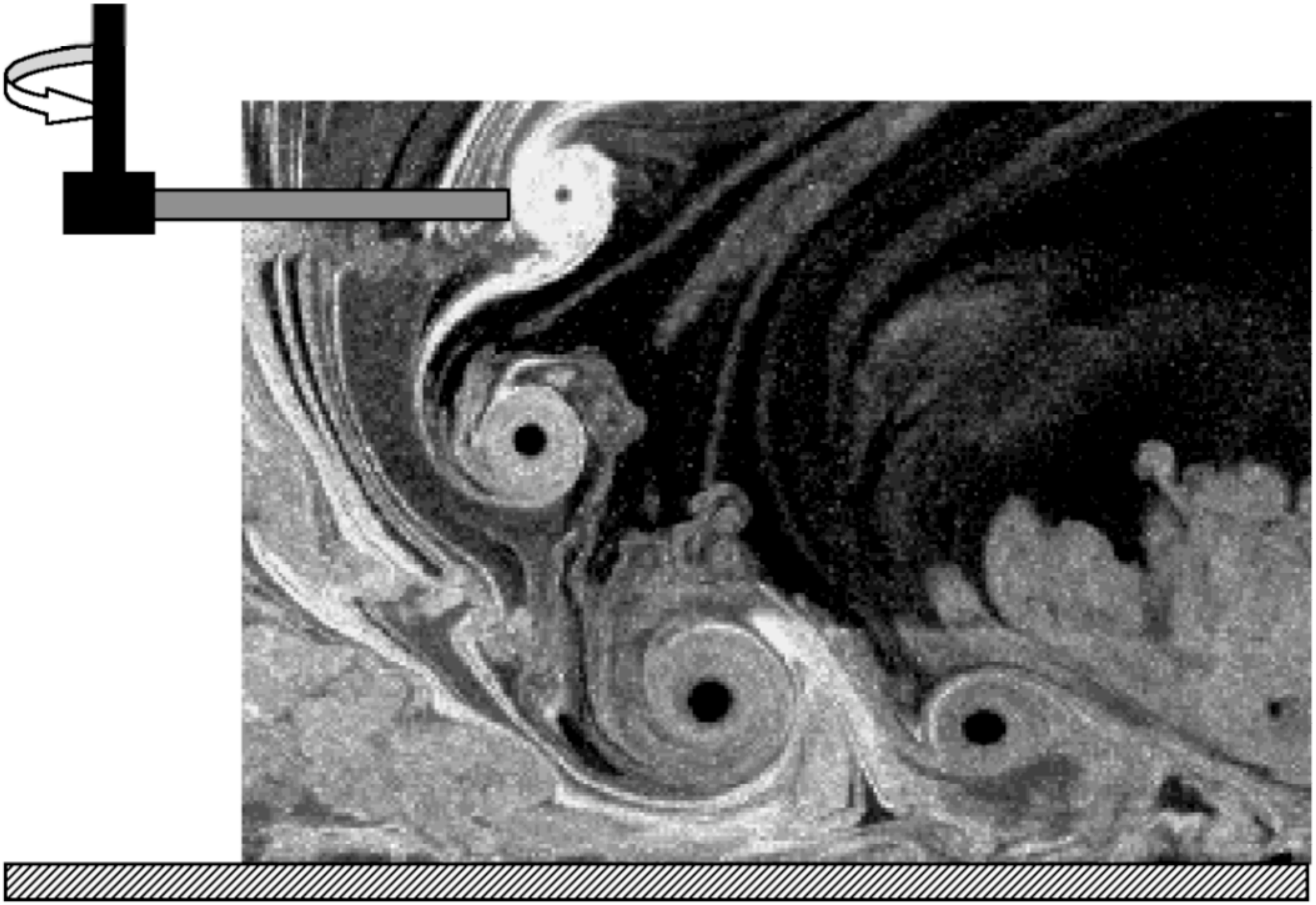
Research sponsored by AFOSR

Queen's UNIVERSITY

Motivation

- Impinging jets occur in
  - *Heat transfer applications*
  - *Meteorology (downdrafts)*
  - *Helicopter aerodynamics*

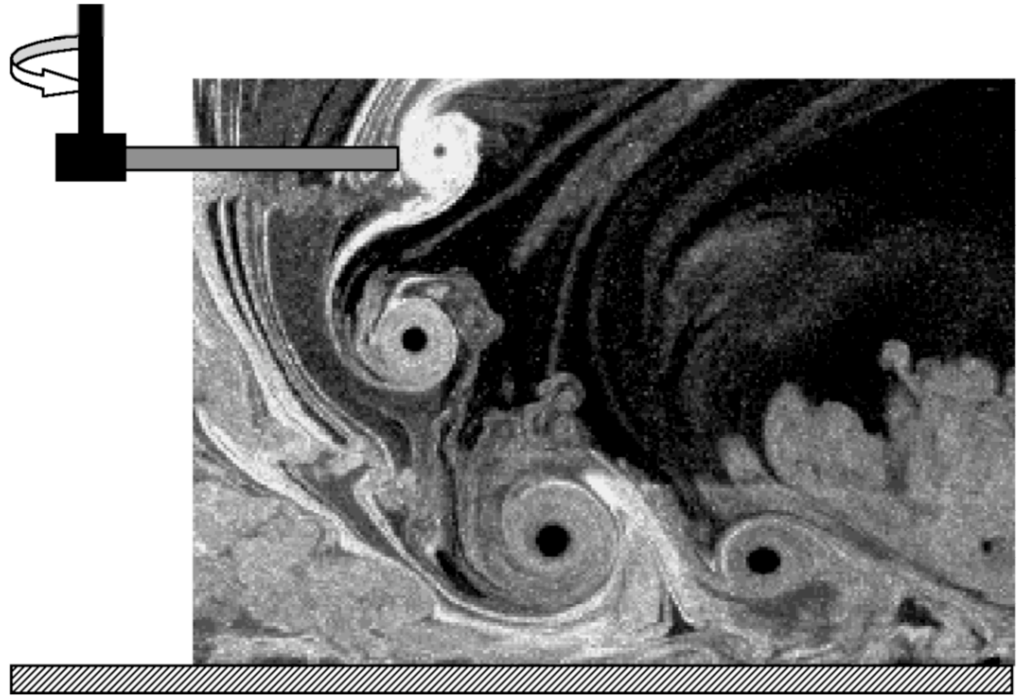
Motivation



From T. Lee, J. G. Leishman, and M. Ramasamy, (2008)

Motivation

- The interaction of the vortices with the ground
  - *Changes the turbulent flow field near the wall.*
  - *Results in the development of secondary vortices, which interact with the primary ones*
  - *Changes the vortex development and decay.*
  - *May result in particle lifting and suspension.*



From T. Lee, J. G. Leishman, and M. Ramasamy, (2008)

- It is important to develop models that relate the impinging jet (i.e., rotor wake) and vortex characteristics to the particle dynamics.
  - *Existing models are usually inviscid (vortex line)*

Objectives

- Study the interaction between the vortices and the near-wall turbulence.
  - *Moderate Reynolds number*
- Quantify the vortex decay in a turbulent wall-bounded flow.
  - *Moderate Reynolds number*
  - *High Reynolds number*
- Understand the physical mechanisms responsible for vortex decay.
- Develop lower level models that account for both viscous and turbulent effects.

METHODOLOGY

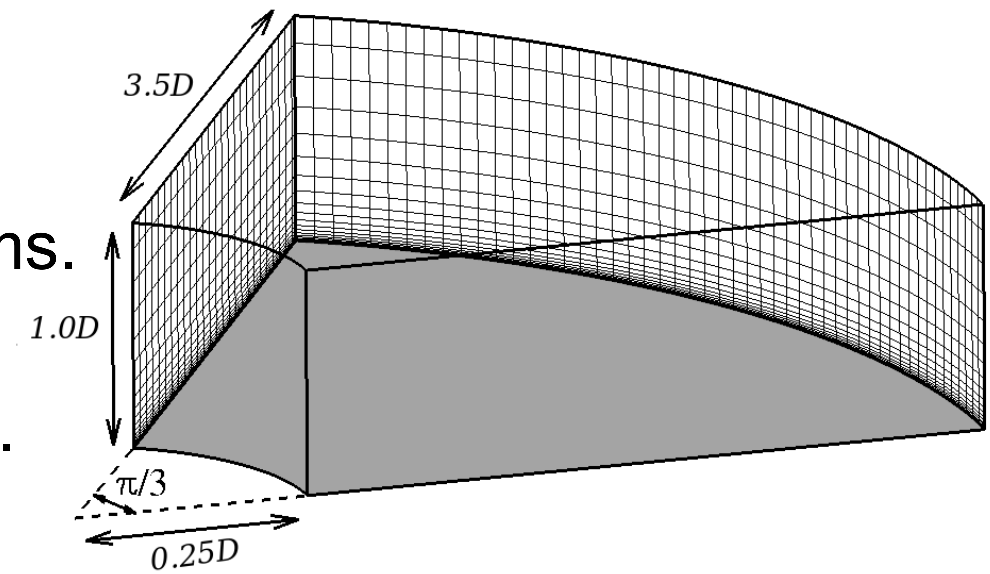
- Strategy:
  - *Develop a vortex-generation method that is*
    - Non-intrusive, Controllable
  - *Simulate increasingly realistic configurations*
    - 2D impingement
    - Axisymmetric impingement
    - Axisymmetric wall jet
  - *Perform hierarchical model validation:*
    - LES to validate Hybrid RANS
  - *Extend to high Re*
  - *Study decay laws and develop lower-level models*

Methodology

- Numerical solution of the filtered Navier-Stokes equations.
- Staggered grid.
- Second-order accurate in space and time.
- Central differences on all terms.
- Axi-symmetric configuration that does not include the axis.
- Inlet condition:

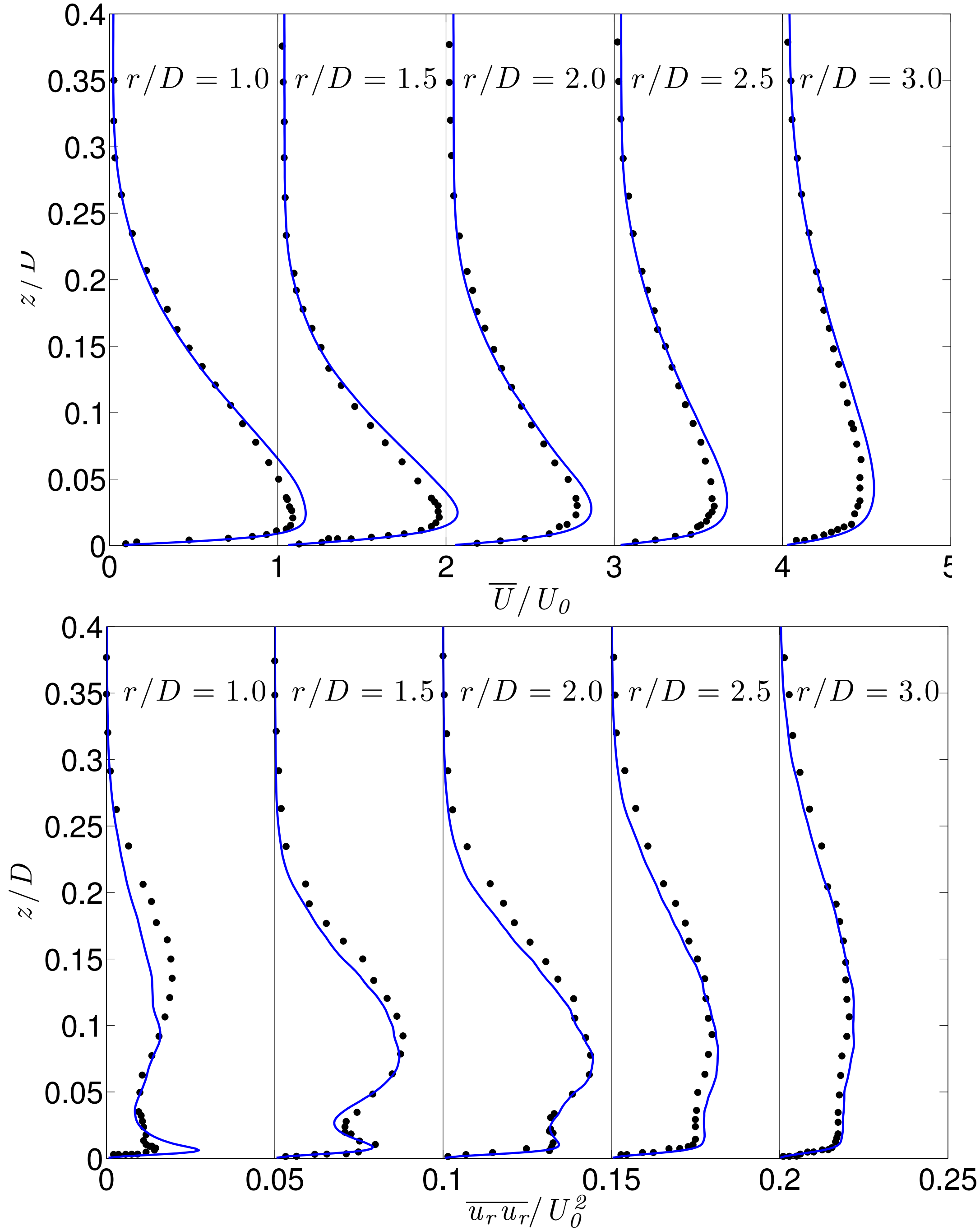
$$\langle U_{jet} \rangle = U_o + A\sin(2\pi t/T)$$

- Synthetic turbulence added at the jet exit and the inner radial boundary.
- $Re = U_{jet} D_{jet}/\nu = 66,000$



Validation

- Impinging jet experiment by Cooper, Jackson, Launder & Liao (1993)
- Verified grid requirements
- Verified domain size



Phase Averaging

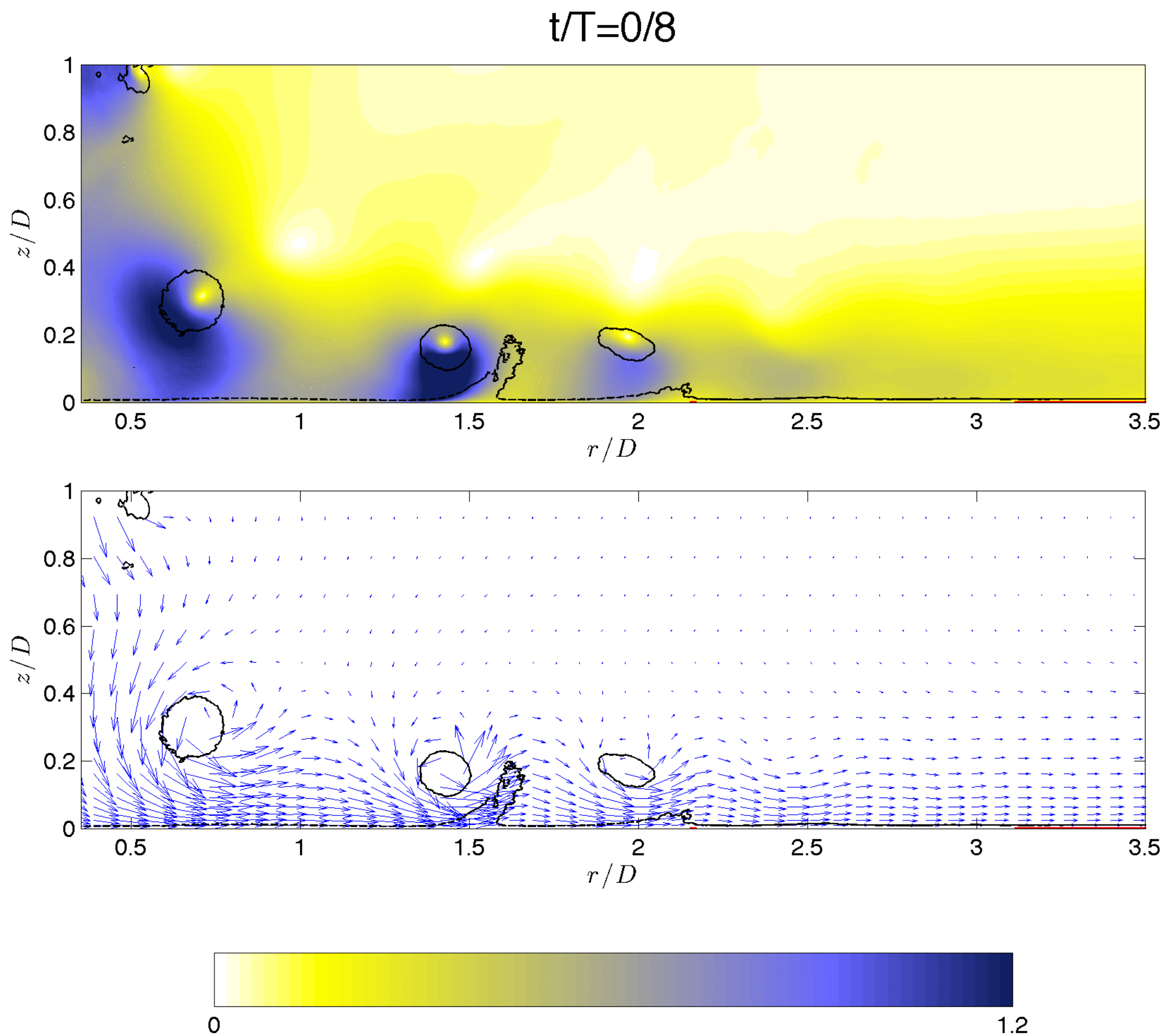
$$\langle f(\mathbf{x}, \phi) \rangle = \frac{1}{N} \sum_{n=1}^{N} f(\mathbf{x}, t_n + T)$$

$$f = \overline{F} + \widetilde{f} + f' = \langle f \rangle + f'$$

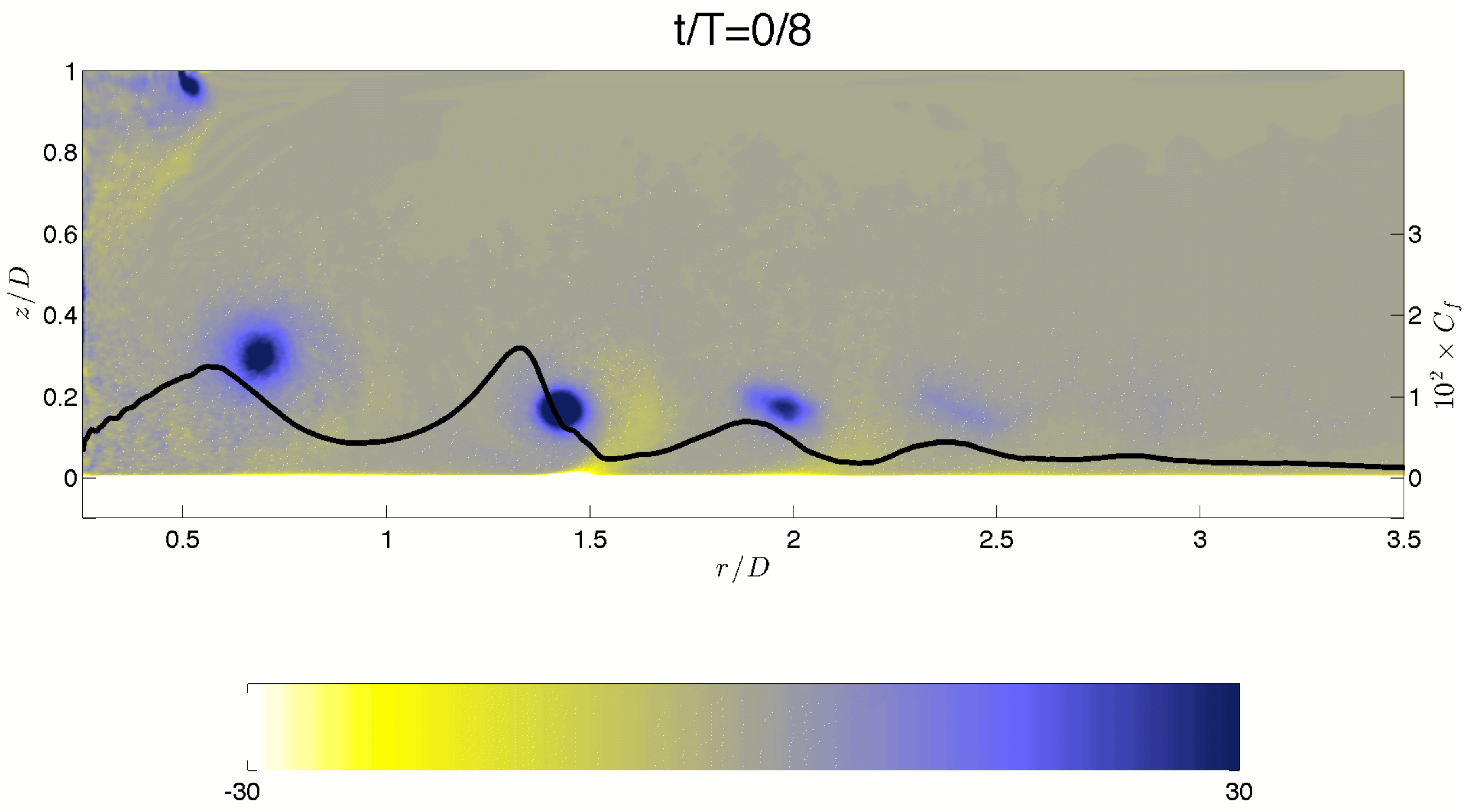
- $\overline{F}$: Time average
- $\widetilde{f}$: Periodic
- f': Stochastic
- $\langle f \rangle$: Phase average

$$\langle u_i u_j \rangle - U_i U_j = \langle u_i \rangle \langle u_j \rangle + \langle u_i' u_j' \rangle$$

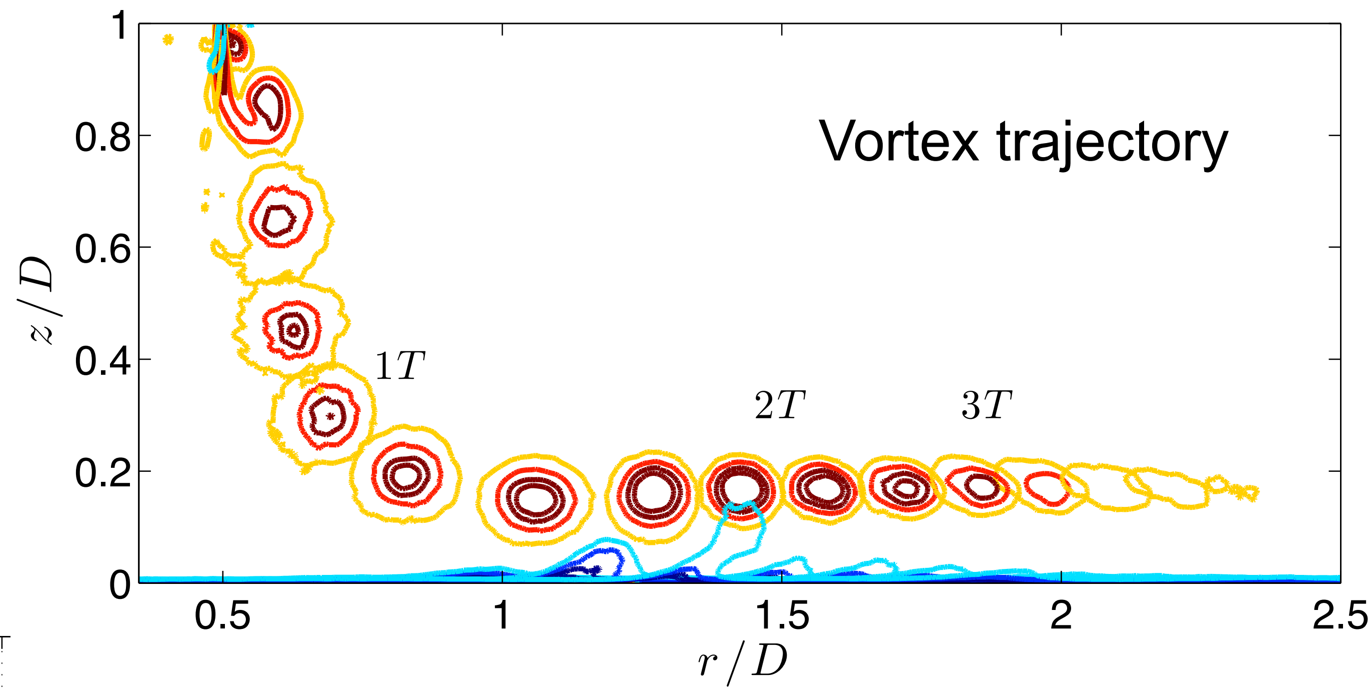
Phase-averaged Velocity

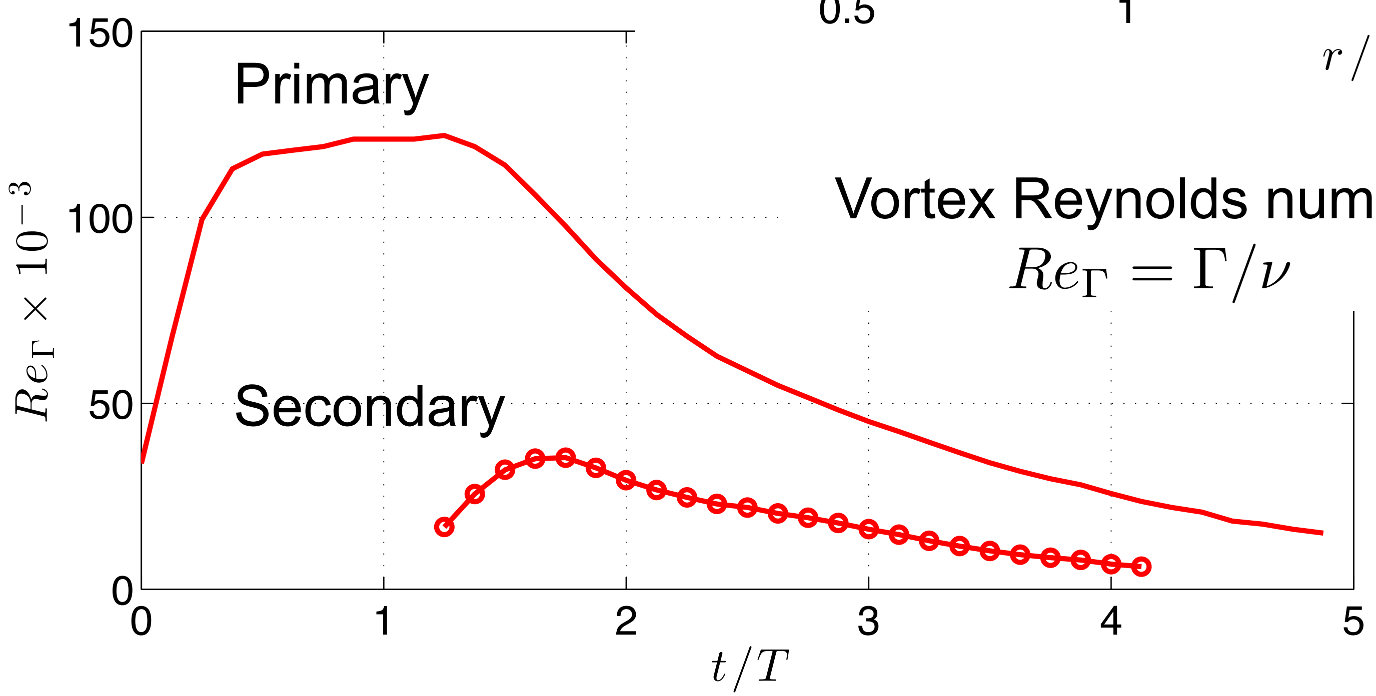


Phase-averaged Vorticity and C_f



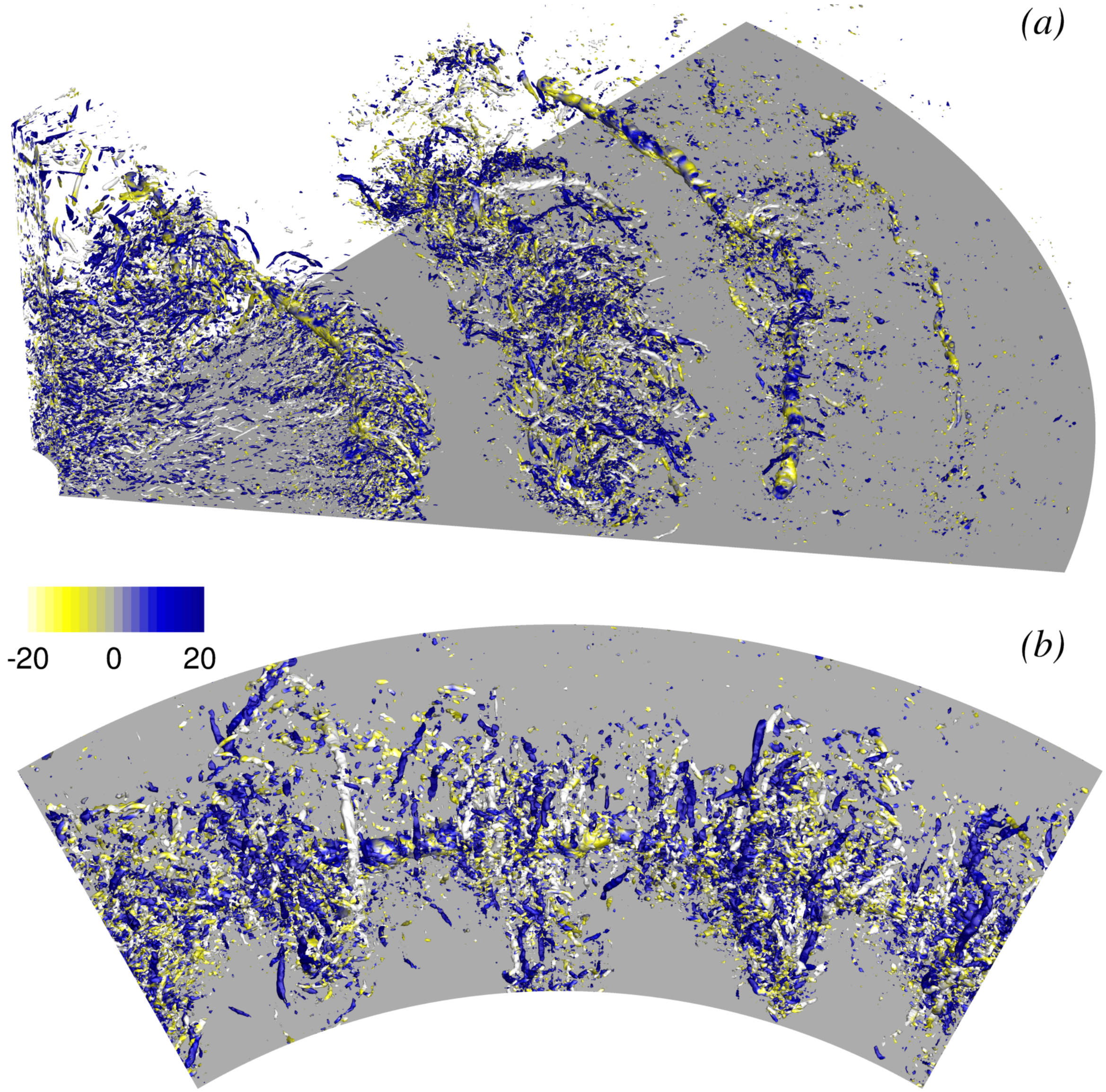
Phase-averaged Vorticity and C_f





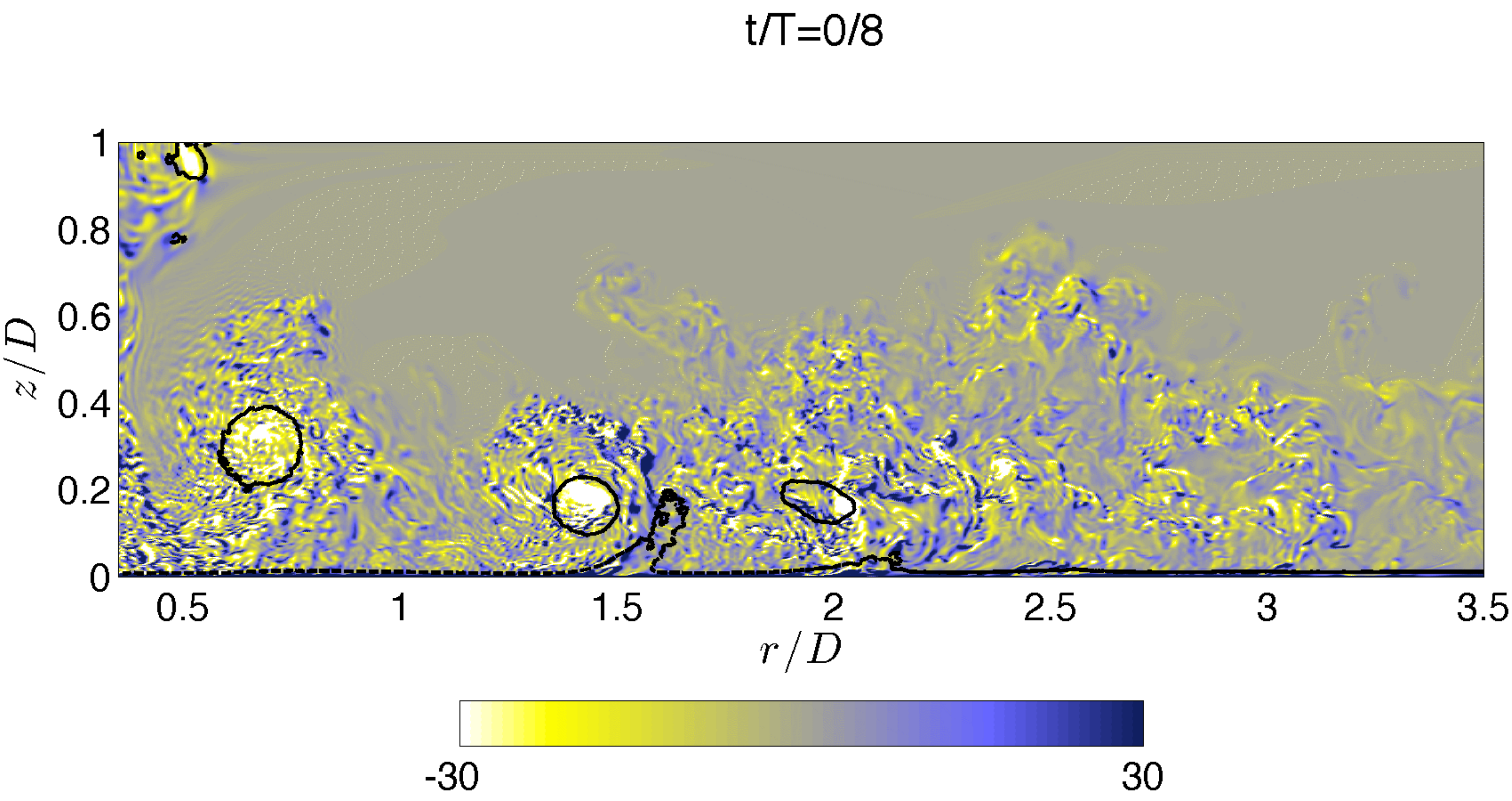
Instantaneous Field

Contours of $Q = -\frac{1}{2}\frac{\partial \overline{u}_j}{\partial x_i}\frac{\partial \overline{u}_i}{\partial x_j} = \frac{1}{2}\left(\overline{\Omega}_{ij}\overline{\Omega}_{ij} - \overline{S}_{ij}\overline{S}_{ij}\right)$ coloured by ω_r



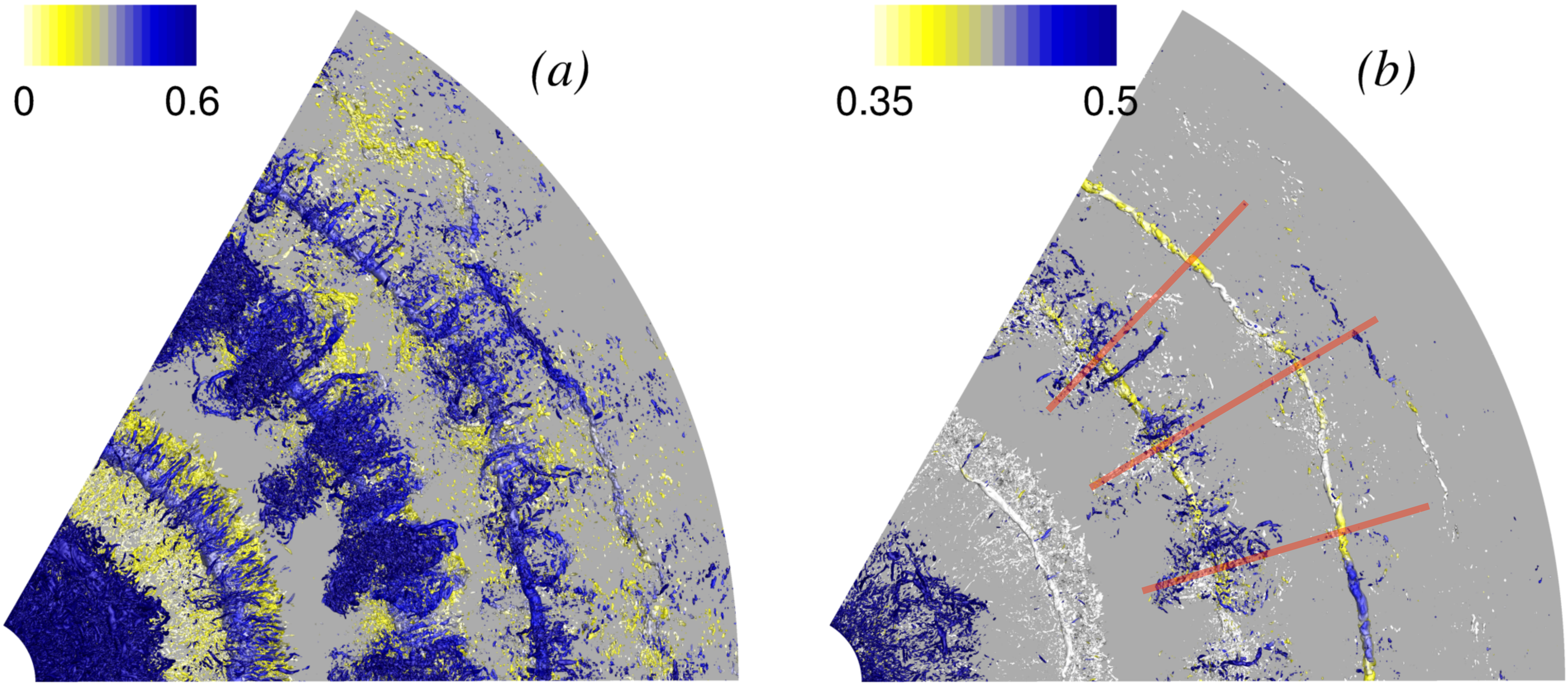
Stochastic Azimuthal vorticity ω'_θ

Queen's University



Instantaneous Field

- Azimuthal instability.
  - *Contributes to development of three-dimensionality.*



Contours of $Q = -\frac{1}{2}\frac{\partial \overline{u}_j}{\partial x_i}\frac{\partial \overline{u}_i}{\partial x_j} = \frac{1}{2}\left(\overline{\Omega}_{ij}\overline{\Omega}_{ij} - \overline{S}_{ij}\overline{S}_{ij}\right)$ coloured by z

Budget of $\langle \omega_\theta \rangle$

$$\frac{D\langle \boldsymbol{\omega} \rangle}{Dt} = \frac{\partial \langle \boldsymbol{\omega} \rangle}{\partial t} + \langle \mathbf{u} \rangle \cdot \nabla \langle \boldsymbol{\omega} \rangle =$$

$$\langle \boldsymbol{\omega} \rangle \cdot \nabla \langle \mathbf{u} \rangle$$

Vortex stretching by phase-averaged flow

$$+\nabla \times (\nabla \cdot \langle \boldsymbol{\tau}_{tot} \rangle)$$

Viscous and SGS diffusion

$$+\langle \boldsymbol{\omega}' \cdot \nabla \mathbf{u}' \rangle - \nabla \cdot \langle \mathbf{u}' \boldsymbol{\omega}' \rangle$$

Vortex stretching by fluctuating field

Turbulent vorticity diffusion

$$-\nabla \times (\nabla \cdot \langle \mathbf{u}' \mathbf{u}' \rangle)$$

Budget of $\langle \omega_\theta \rangle$

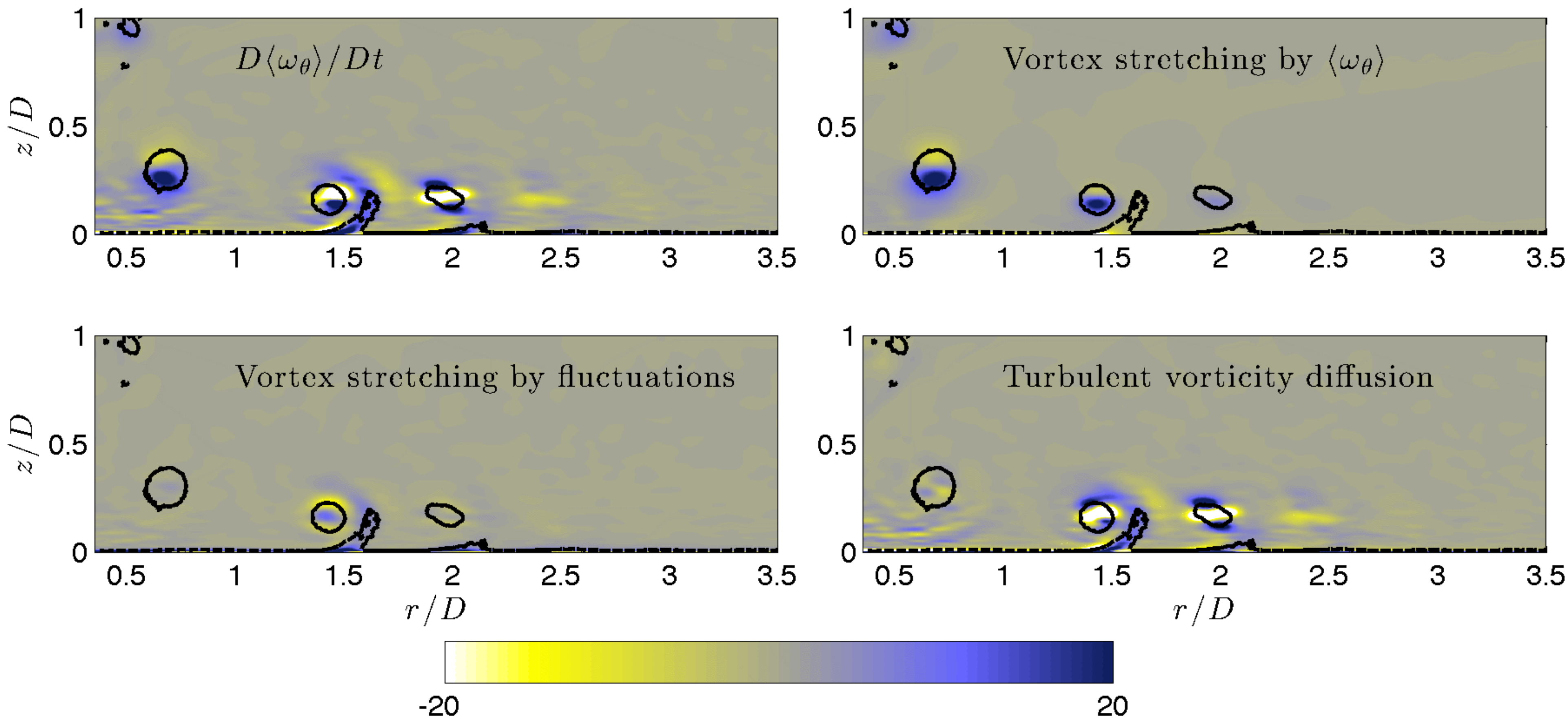
$$\frac{D\langle \boldsymbol{\omega} \rangle}{Dt} =$$ Vortex stretching by phase-averaged flow + ~~Viscous and SGS diffusion~~ + Vortex stretching by fluctuating field + Turbulent vorticity diffusion

Budget of $\langle \omega_\theta \rangle$

$$\frac{D\langle \boldsymbol{\omega} \rangle}{Dt} =$$ Vortex stretching by phase-averaged flow

+ Vortex stretching by fluctuating field + Turbulent vorticity diffusion

t/T=0/8



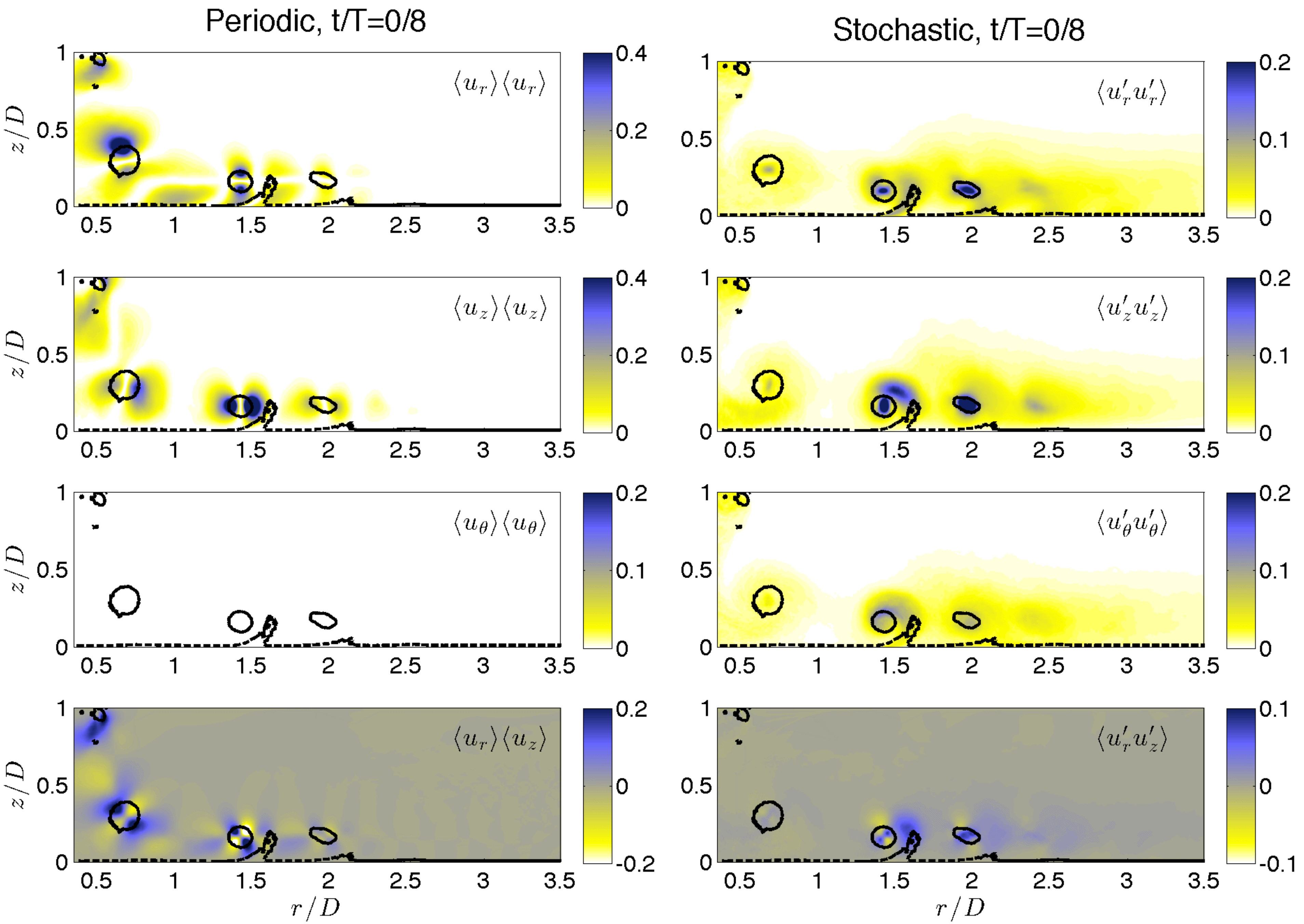
Budget of $\langle \omega_\theta \rangle$

$$\frac{D\langle \boldsymbol{\omega} \rangle}{Dt} = $$ Vortex stretching by phase-averaged flow

\+ Vortex stretching by fluctuating field + Turbulent vorticity diffusion

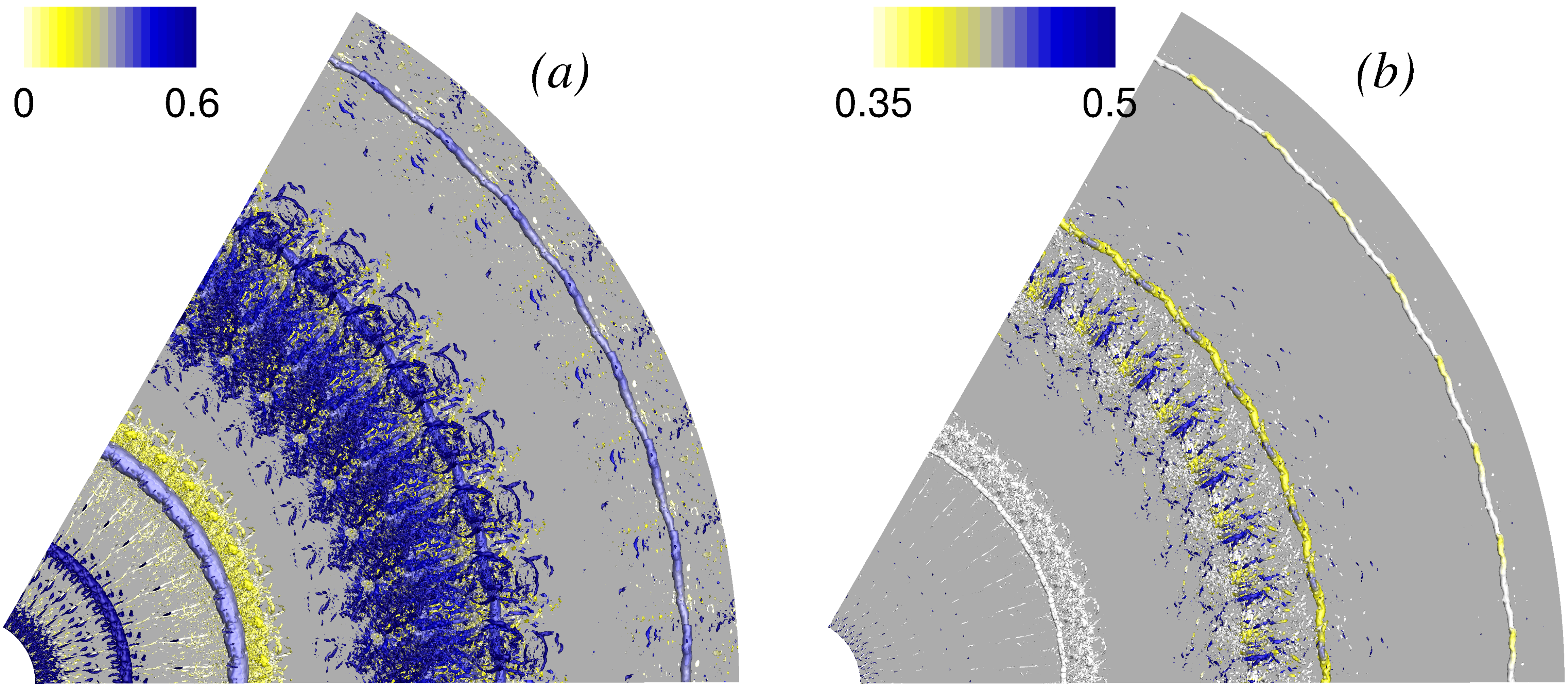
$$-\nabla \times (\nabla \cdot \boldsymbol{u}'\boldsymbol{u}')|_\theta = \frac{\partial}{\partial z \partial r}\left(\langle u_r' u_r' \rangle - \langle u_z' u_z' \rangle\right) - \frac{1}{r}\frac{\partial}{\partial z}\langle u_\theta' u_\theta' \rangle + \boxed{\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial r^2}\right)\langle u_r' u_z' \rangle}$$

Phase-Averaged Reynolds Stresses



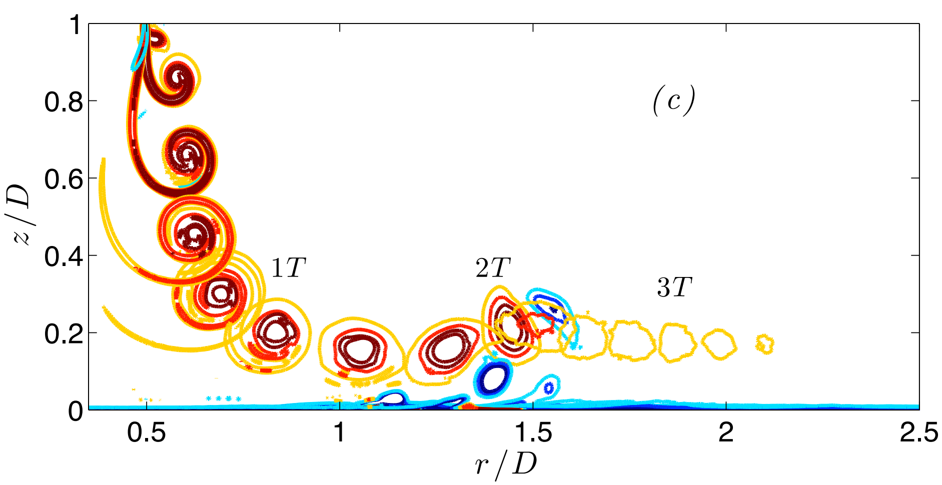
Other Tests

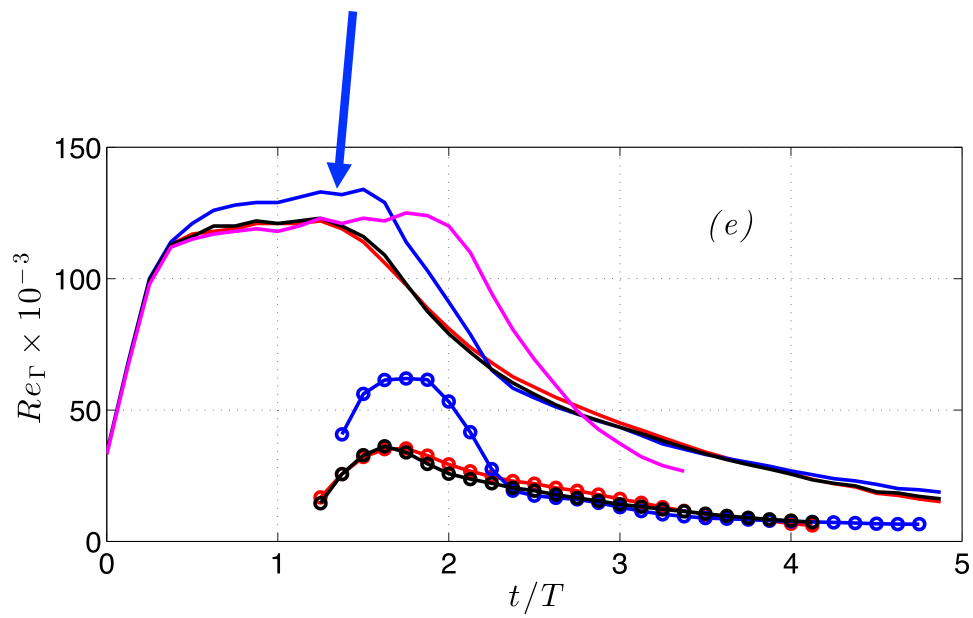
- Limit the development of the azimuthal instability (= maintain the vortex axi-symmetric)
  - *Delays primary-vortex decay by 5-10%.*



Other Tests

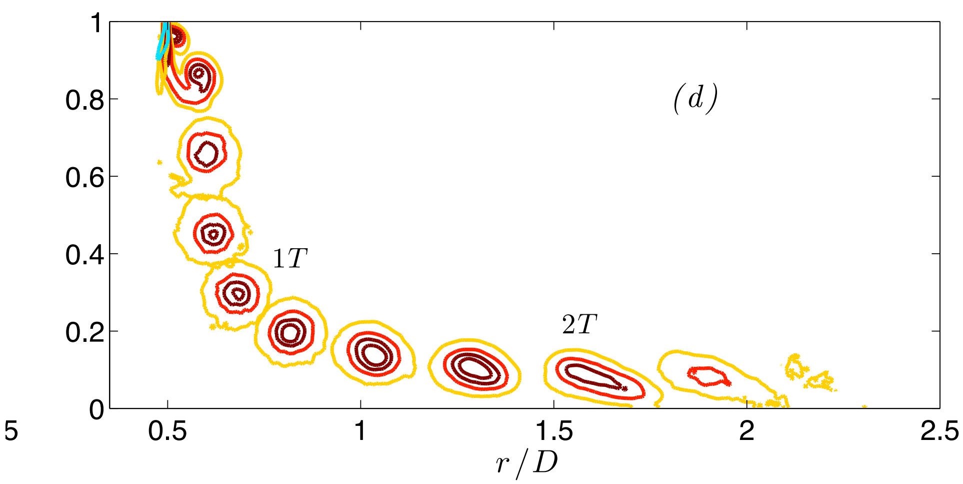
- Limit the development of the azimuthal instability (= maintain the vortex axi-symmetric)
- Use laminar flow at the inlet
  - *The primary vorticity is stronger before the interaction with the wall*
  - *The secondary vorticity is much stronger*
  - *The interaction generates Reynolds stresses that cause the primary vorticity to decay.*

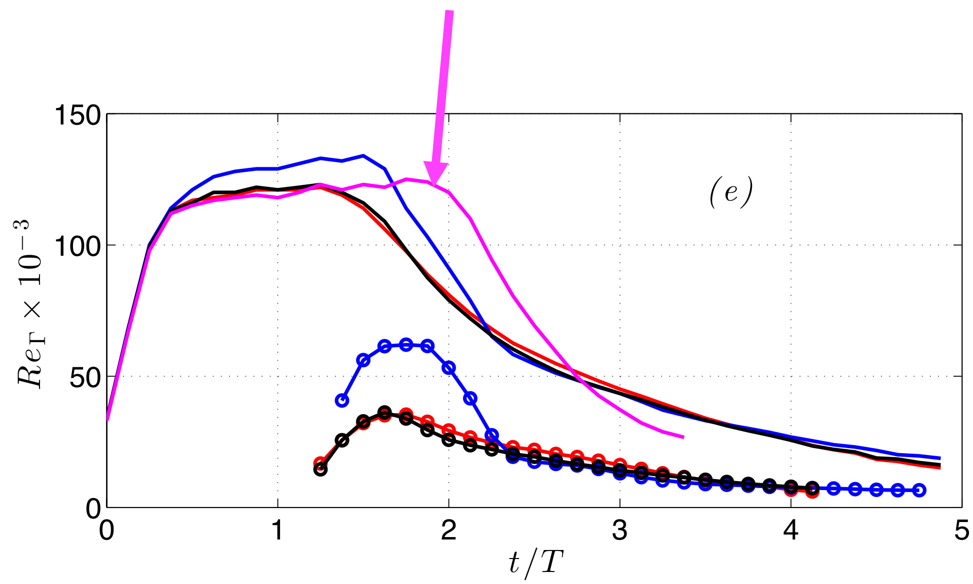




Other Tests

- Limit the development of the azimuthal instability (= maintain the vortex axi-symmetric).
- Use laminar flow at the inlet.
- Apply a free-slip condition at the wall.
  - *No secondary vorticity is generated.*
  - *Vorticity diffusion is caused by the eddies coming from the jet (amplified inside the vortex).*
  - *Decay starts later but is faster.*



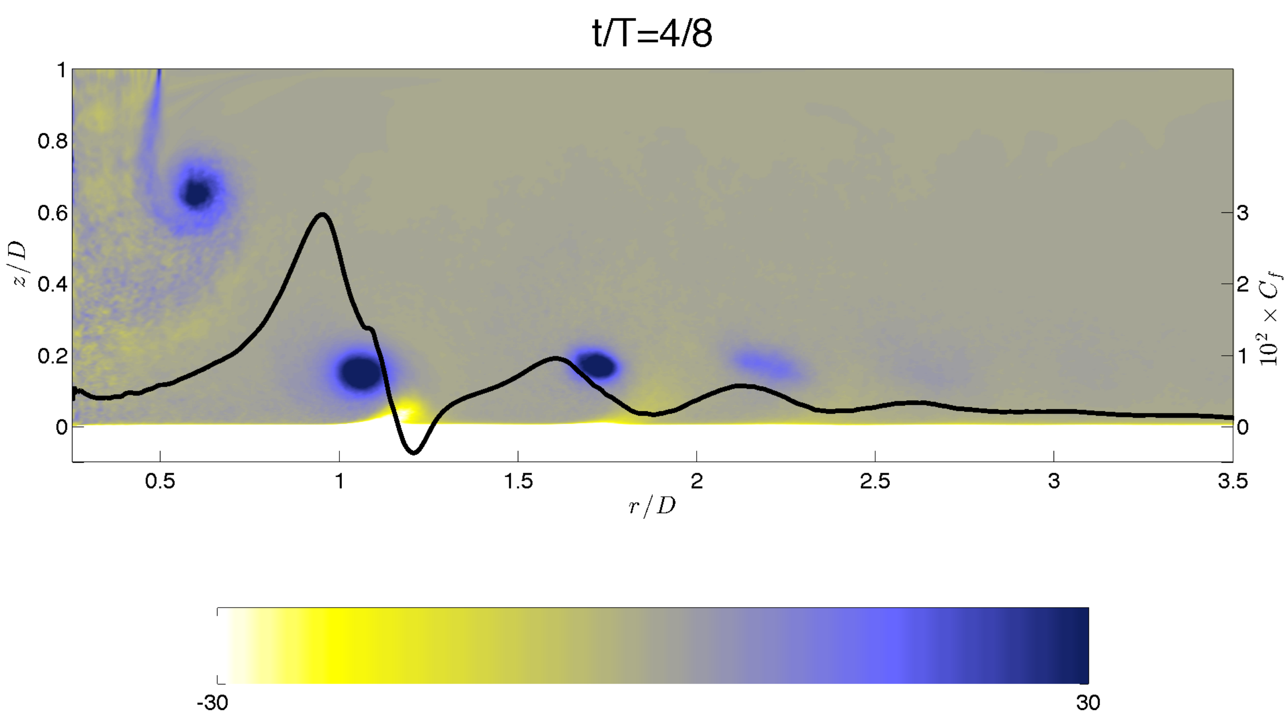


Modelling Considerations

- Design requires fast throughput, multiple configurations ➔ Not LES (not even hybrid RANS/LES).
- In the immediate future, RANS are going to be used to predict this flow in industrial applications.
- What are the requirements?

Modelling Considerations

- RANS are not adequate. URANS is the minimum.
- The wall stress is important
  - *Affects particle lift-up*
  - *Separation caused by Adverse Pressure Gradient (difficult to model accurately).*
  - *The interaction between primary and secondary vorticity is fundamental for the vortex evolution.*



Modelling Considerations

- RANS are not adequate. URANS is the minimum.
- The wall stress is important.
- Flow three-dimensionality is important
  - *The azimuthal instability speeds up the primary vortex decay.*
- Vortex decay depends on the **second derivatives** of the Reynolds shear stresses

$$\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial r^2}\right)\langle u'_r u'_z \rangle$$

Modelling Considerations

- RANS are not adequate. URANS is the minimum.
- The wall stress is important.
- Flow three-dimensionality is important
  - *The azimuthal instability speeds up the primary vortex decay.*
- Vortex decay depends on the **second derivatives** of the Reynolds shear stresses
- K-ε models predict excessive gradient transport in vortex cores (Liu et al 96)
- Reynolds number may be (???) unimportant

Conclusions

Queen's University

- Performed well-resolved LES of the interaction of a jet with embedded vortices and a wall
  - *Generation of secondary vorticity*
  - *Azimuthal instability of the primary vortex*
  - *Primary-secondary vortex interaction strongly affected by background turbulence*
  - *Shear stresses are the main cause for the vorticity decay*
  - *Turbulent vorticity diffusion is an extremely robust mechanism*