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Slide of the Seminar

Large-Eddy Simulations in Dune Dynamics Research

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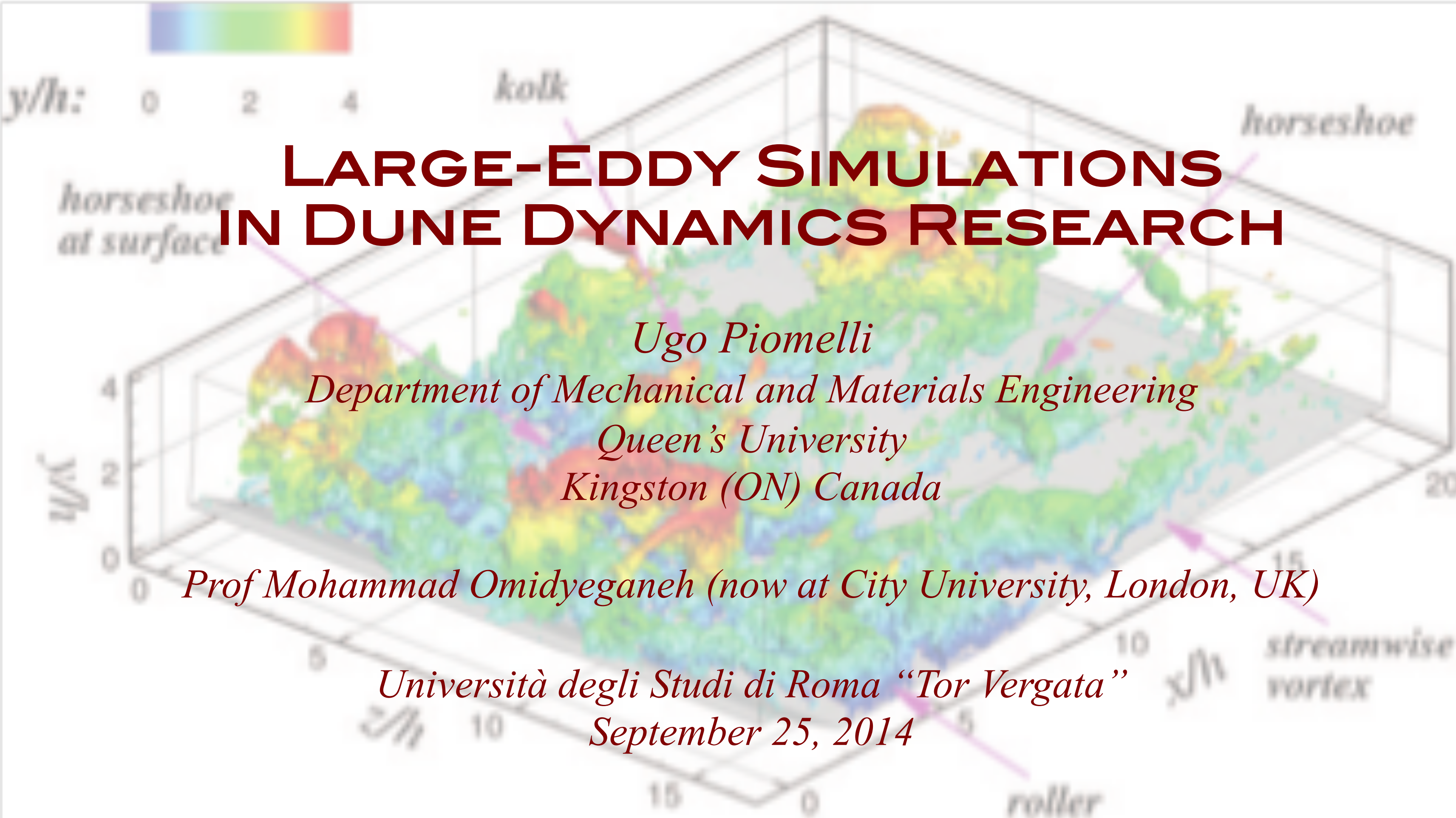

Large-Eddy Simulations in Dune Dynamics Research

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Queen's University

Turbulence Simulation TSM Lab and Modelling Laboratory

Outline

- Motivation
- Reynolds-averaging vs. Filtering
- Dune simulations
  - *Methodology*
  - *Examples*
    - 2D dunes: Boil generation
    - 3D dunes: Streamwise vorticity
    - Barchan dunes: Unsteady separation
- Outlook

Motivation

- Interaction of a flow field with a mobile sand bed results in bed deformation.
- The shape depends on:
  - *Flow properties (Re, Fr, etc.)*
  - *Sand type*
  - *Amount of sand available*
- For unidirectional mean flow, high Reynolds numbers (rivers)

  ⇒ *Transverse dunes*

Motivation

- Interaction of a flow field with a mobile sand bed results in bed deformation.
- The shape depends on:
  - *Flow properties (Re, Fr, etc.)*
  - *Sand type*
  - *Amount of sand available*
- For unidirectional mean flow, high Reynolds numbers (rivers)

  $\Rightarrow$ *Transverse dunes*
- Limited sediment supply (desert)

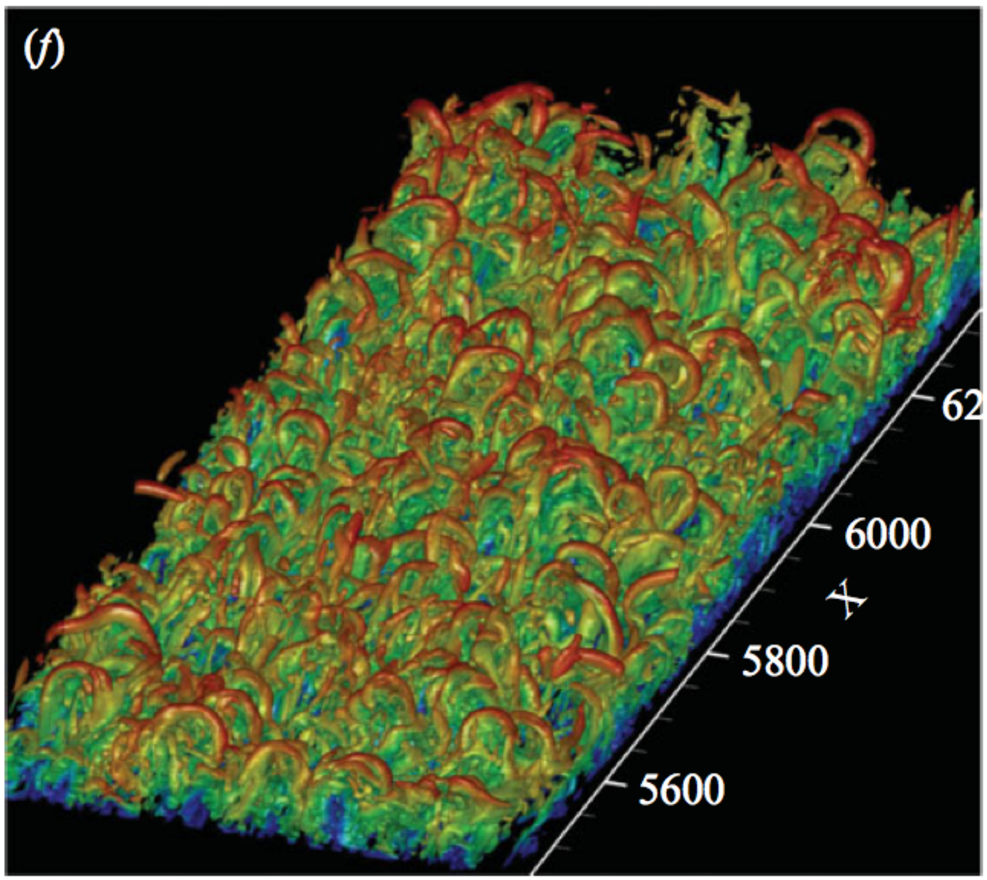
  $\Rightarrow$ *Barchan dunes*

Motivation

- In dunes, turbulence affects bed morphology and sediment transport.
  - *Flooding*
  - *Silting*
- Field and laboratory experiments can highlight many of the important turbulent phenomena.
  - *Mean flow*
  - *Instantaneous flow structure*
- Experiments have limitations:
  - *Control of boundary conditions*
  - *Access to full field*
  - *Near-wall measurements*
- Improved numerical models are required to complement the experiments.

Turbulence Simulations

- Turbulence contains vorticity
- Vorticity is concentrated in small regions, in which the fluid motion is coherent $\Rightarrow$ eddies.



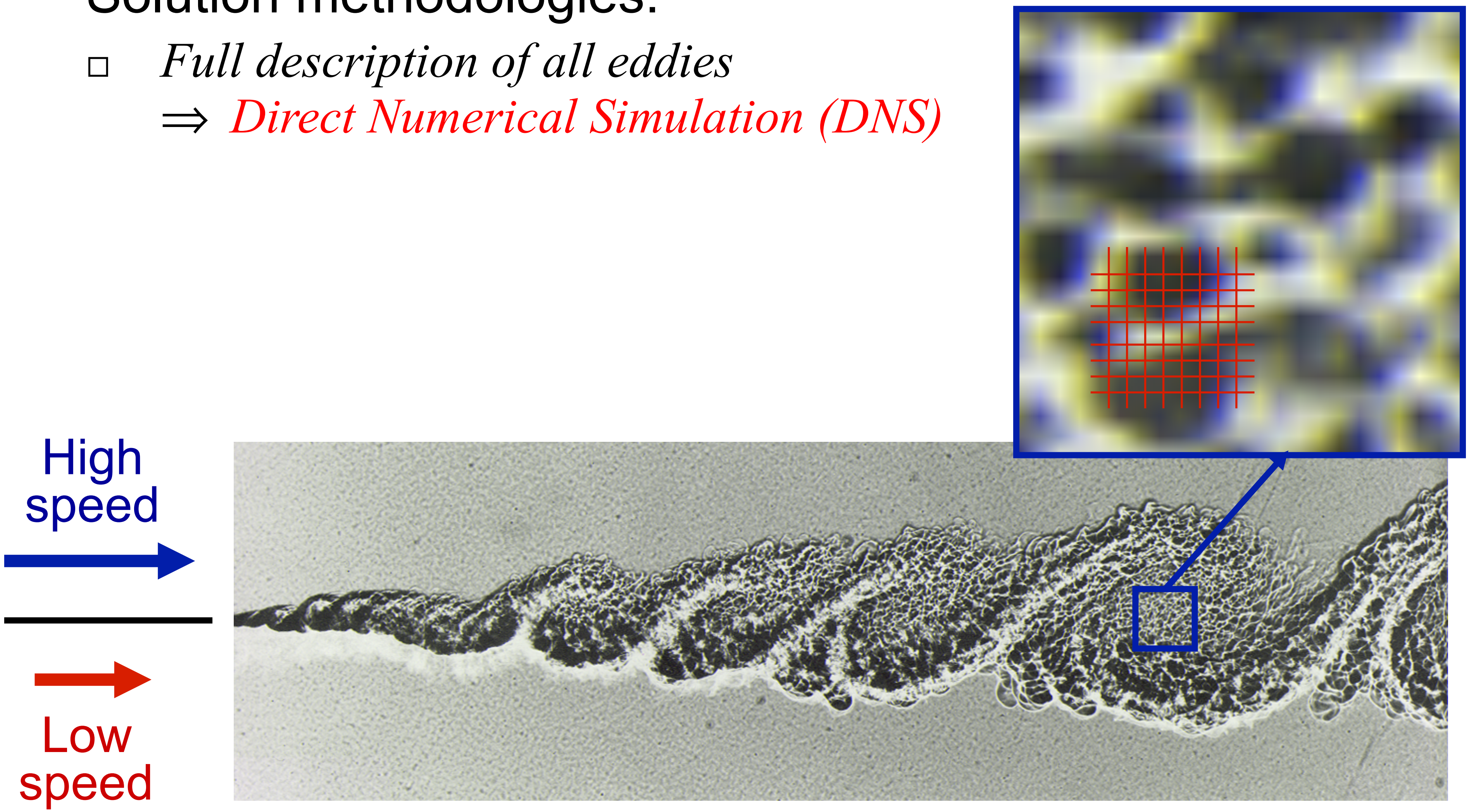
Visualization of the turbulent eddies in the boundary layer over a flat plate.

Wu, X. and Moin, P. (2009).

- Turbulence contains vorticity
- Vorticity is concentrated in small regions, in which the fluid motion is coherent $\Rightarrow$ eddies.
- Large eddies are responsible for mixing ($\Rightarrow$ momentum, energy transport).
- Small eddies are responsible for viscous dissipation

Simulation Methodologies

- Turbulent transport is due to the vortical motions (eddies).
- Solution methodologies:
  - *Full description of all eddies* ⇒ *Direct Numerical Simulation (DNS)*

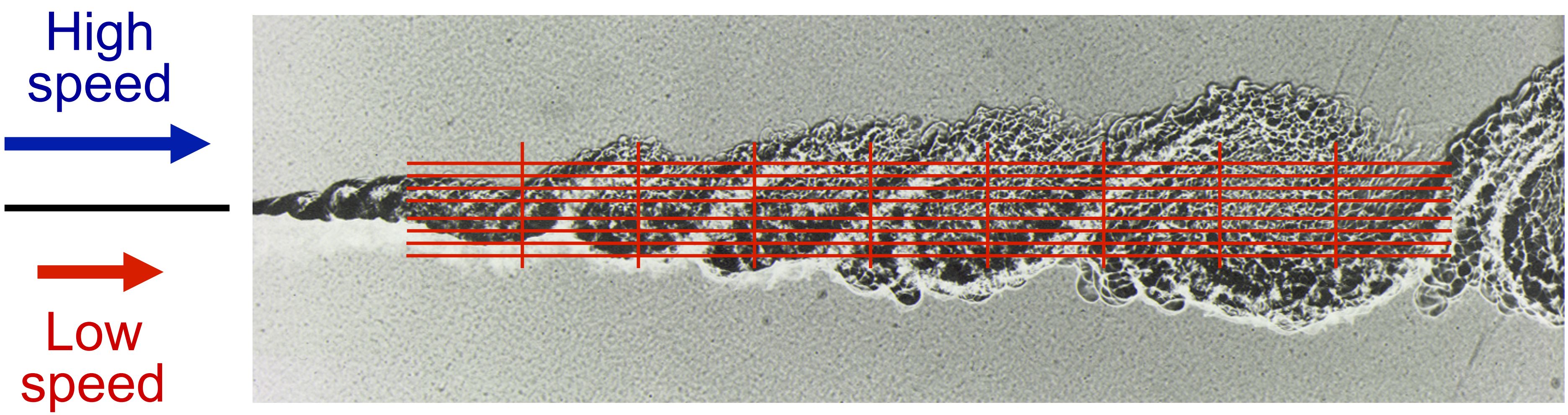


SIMULATION METHODOLOGIES

- Turbulent transport is due to the vortical motions (eddies).
- Solution methodologies:
  - *Full description of all eddies (DNS)*
  - *Statistical description of all eddies*

    ⇒ *Solution of the Reynolds-Averaged Navier-Stokes (RANS) equations*

    ⇒ *A turbulence model is required to account for the effect of all the eddies*

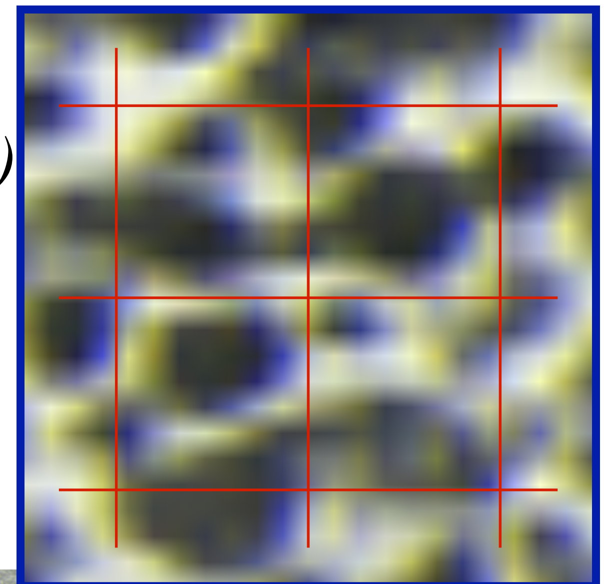


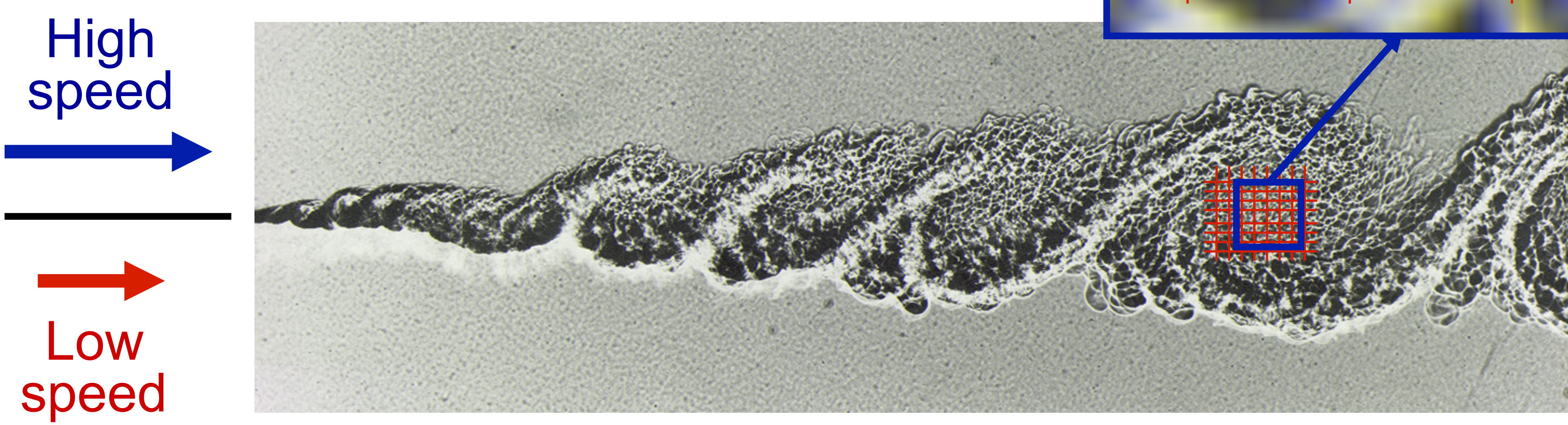
Simulation Methodologies

- Turbulent transport is due to the vortical motions (eddies).
- Solution methodologies:
  - *Full description of all eddies (DNS)*
  - *Statistical description of all eddies (RANS)*
  - *Partial description of the eddies*

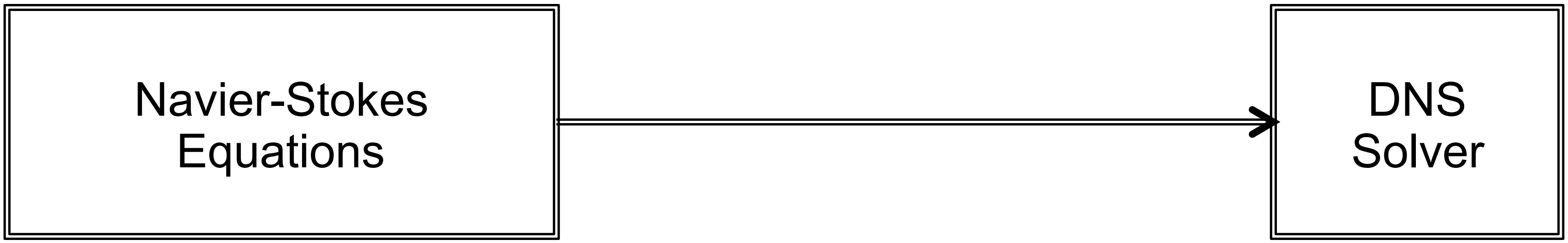
    ⇒ *Large-Eddy Simulation (LES)*

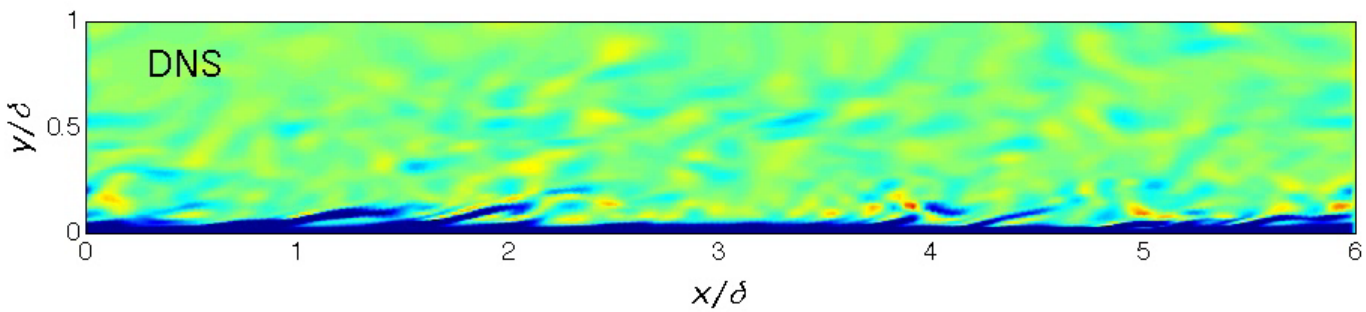
    ⇒ *A model is required to account for the effect of the small eddies*





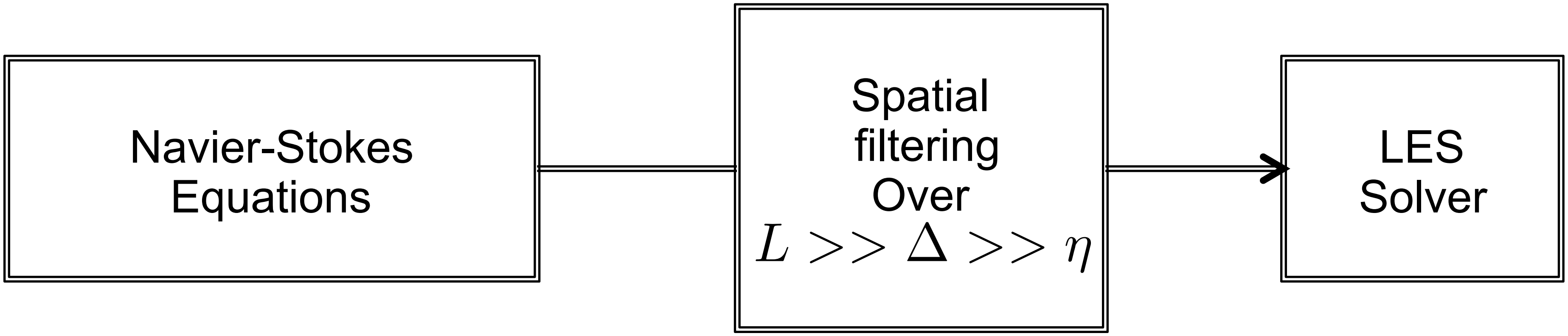
Direct Numerical Simulation

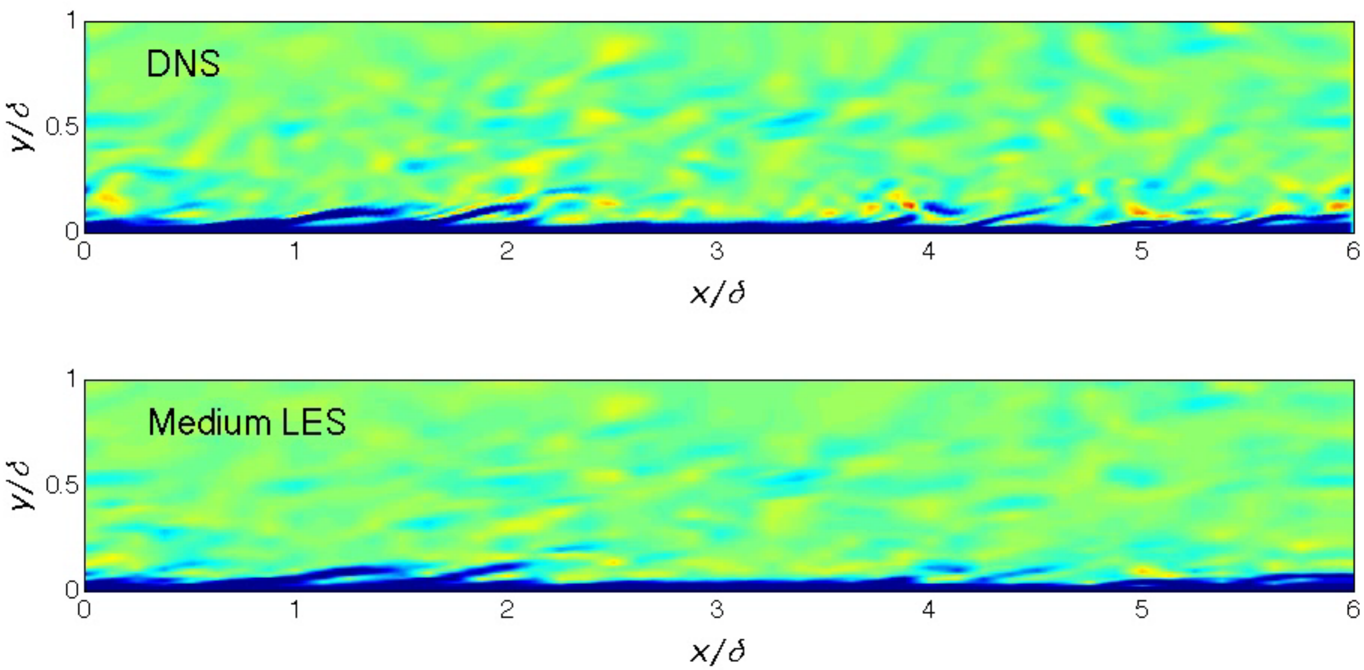




Vorticity contours, Channel flow, Re=7000

Large-Eddy Simulation

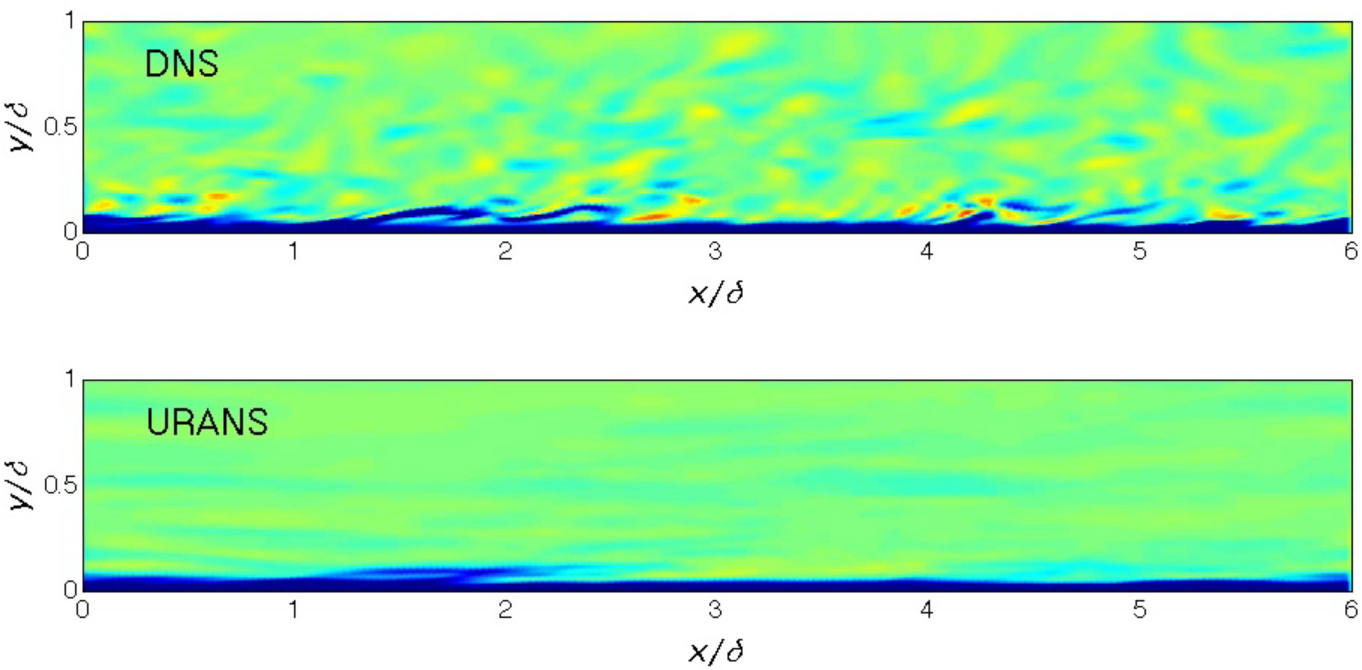




Vorticity contours, Channel flow, Re=7000

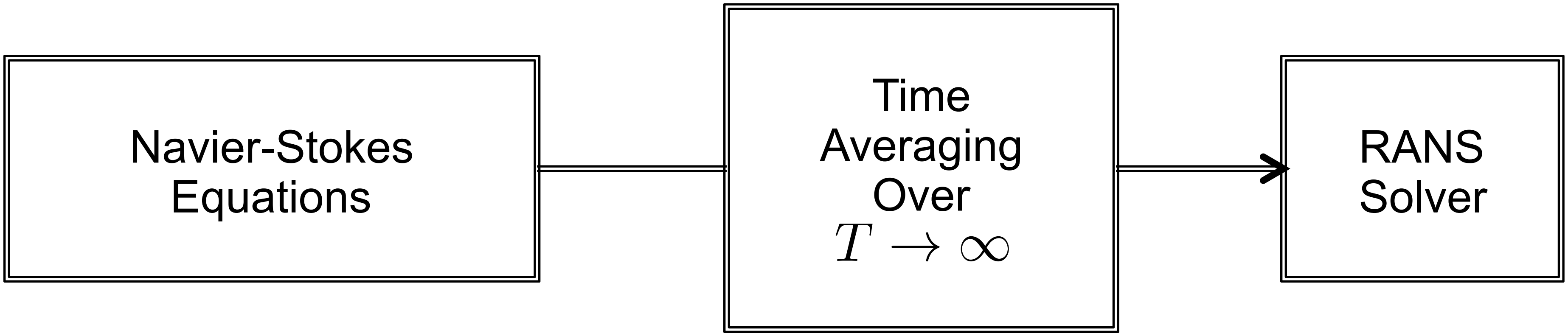
Unsteady Reynolds-Averaged NS Simulation

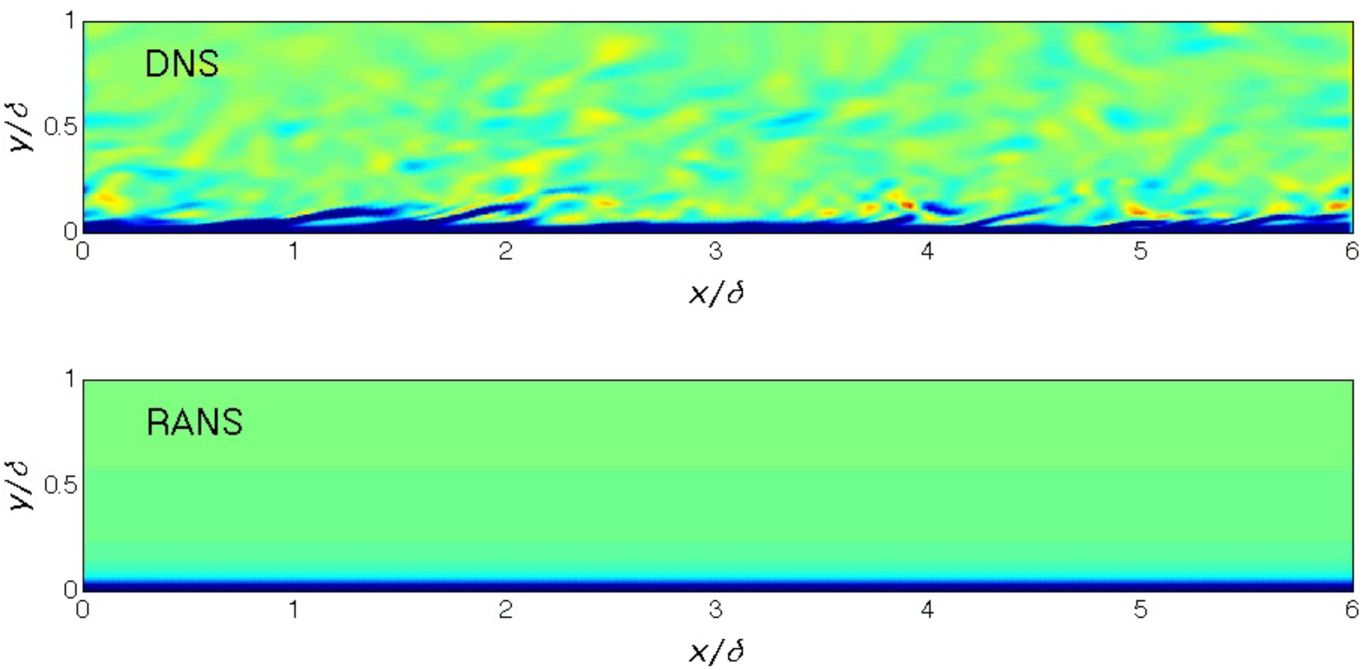
Navier-Stokes Equations → Time Averaging Over $T >>$ LETOT → URANS Solver



Vorticity contours, Channel flow, Re=7000

Reynolds-Averaged NS Simulation



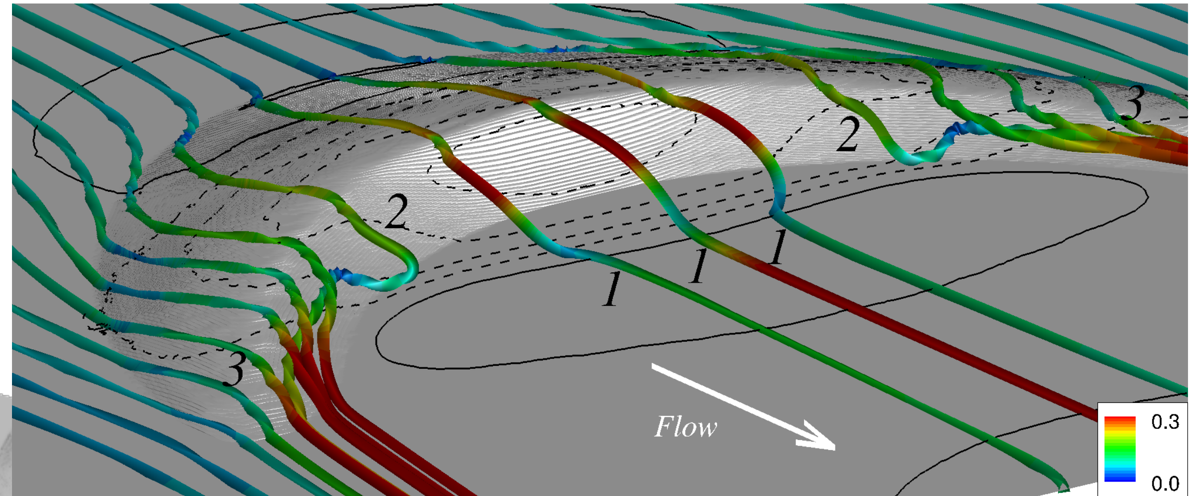


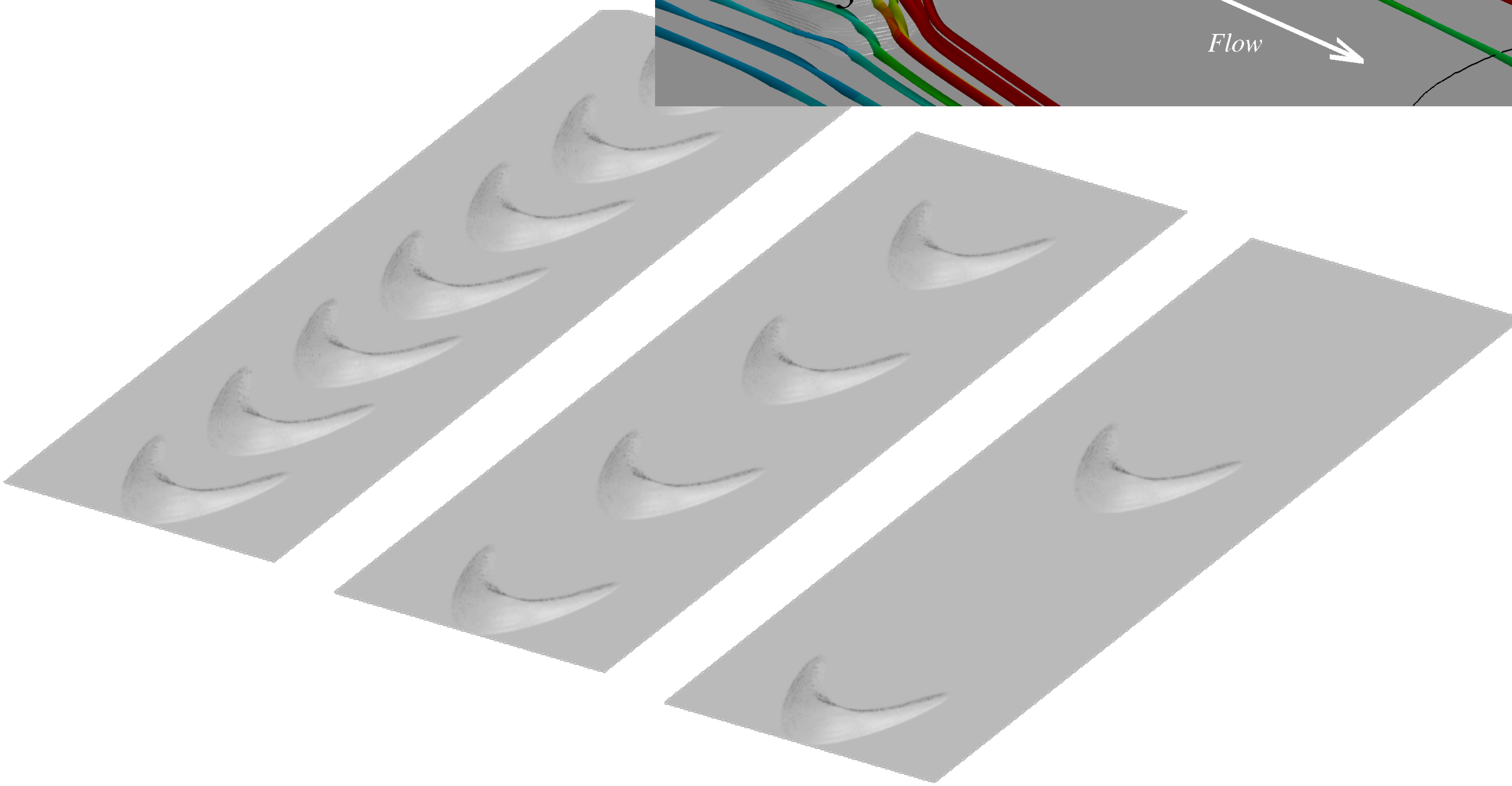
Vorticity contours, Channel flow, Re=7000

RANS/URANS vs LES

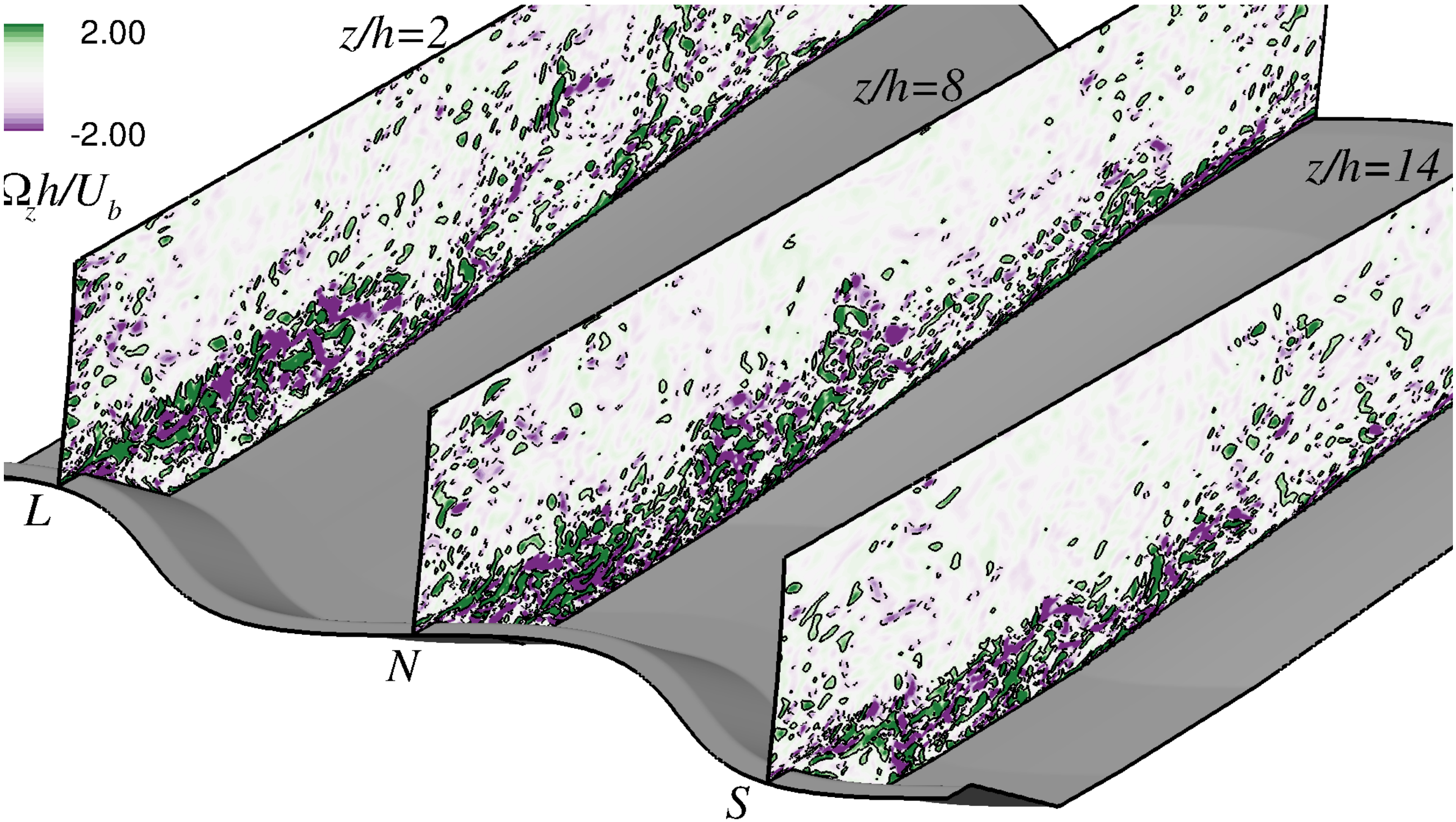
- Reynolds-Averaged Navier-Stokes solutions
  - *Are relatively inexpensive:* $Cost \propto Re^{0.6}$
  - *Average out the turbulent eddies and model their effect using strong empiricism.*
  - *Work well in flows close to the calibration cases.*
  - *Are less accurate in cases with physical complexities*
    - Mean 3D flow
    - Unsteady separation and reattachment
    - Streamline curvature
    - Favorable pressure gradients
    - Return to equilibrium after a perturbation is imposed.

RANS/URANS vs LES





RANS/URANS vs LES



RANS/URANS vs LES

- Large-Eddy Simulations
  - *Are expensive: Cost $\propto$ Re$^{3.6}$*
  - *Average out only the smallest turbulent eddies and model their effect using less empiricism*
  - *Can be accurate in cases with physical complexities*
    - Mean 3D flow
    - Unsteady separation and reattachment
    - Streamline curvature
    - Favorable pressure gradients
    - Return to equilibrium after a perturbation is imposed.

    ...if the grid is sufficiently fine
  - *Yield 3D, time-dependent fields*
    - Allow a complete view of the flow.

    ...at laboratory scale

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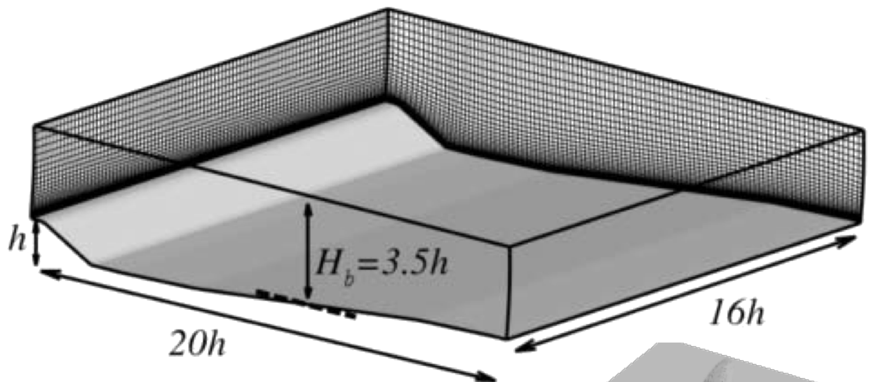
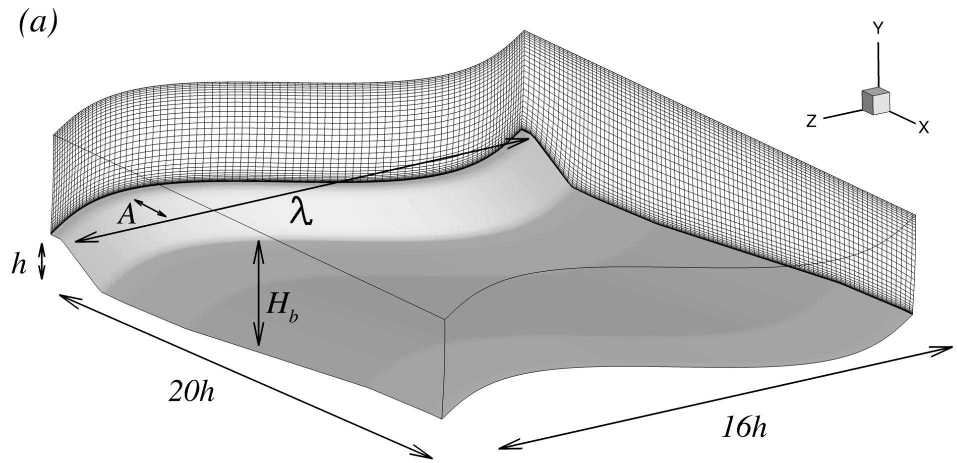
LES of Flows Over Dunes

- Curvilinear code
  - *2^{nd}-order accurate in time and space.*
  - *Central differences on all terms*
  - *Lagrangian Dynamic subfilter-scale model*
- The model has been extensively validated in engineering and geophysical flows.
- Grids between 6×10^6 and 41×10^6 points.
  - *Up to* 16,000 *CPU-hours per simulation*

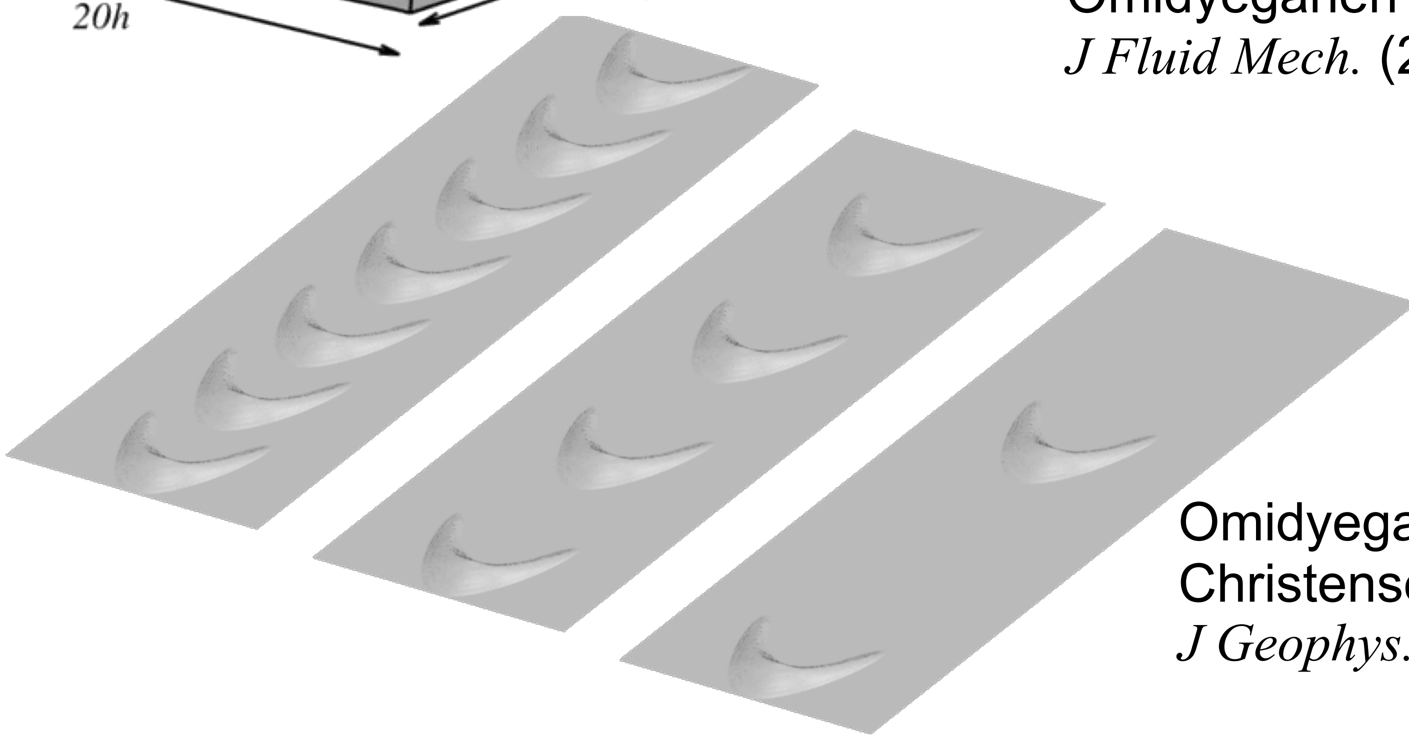
LES of Flows Over Dunes

Omidyeganeh & Piomelli
J of Turbulence (2010)





Omidyeganeh & Piomelli
J Fluid Mech. (2013a, 2013b)



Omidyeganeh, Piomelli,
Christensen & Best
J Geophys. Res. (2013)

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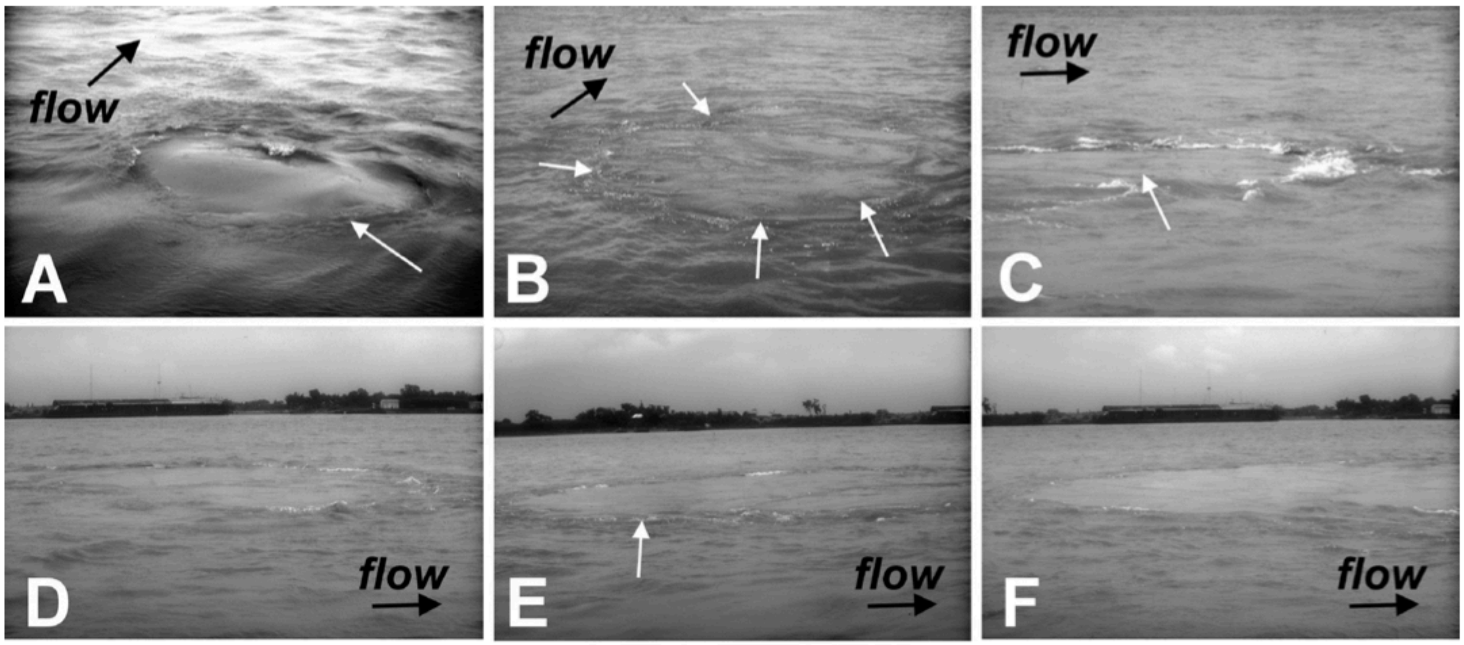
Boils

- “Boils” are eruptions at the water surface associated with large turbulent structures.



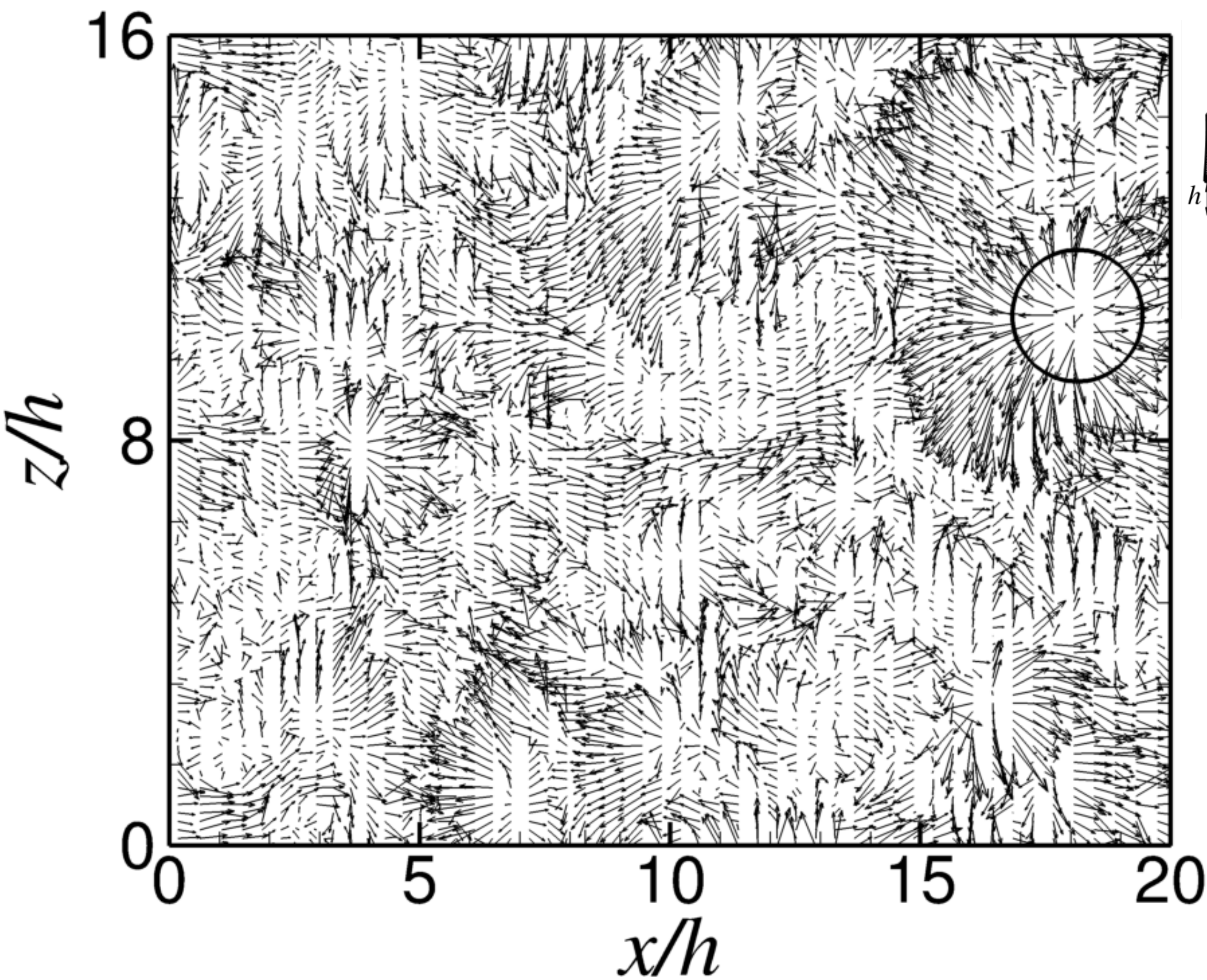
Photographs of vortex–free-surface interactions in the Jamuna River, Bangladesh.
From Best, J. (2005)

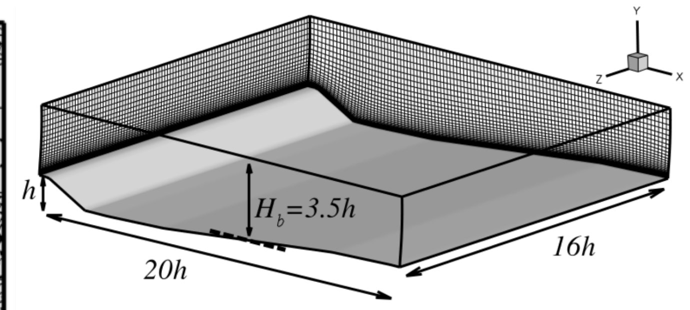
Boils

- "Boils" are eruptions at the water surface associated with large turbulent structures.
- Occur infrequently but generate significant Reynolds stress
- Are responsible for transport of fluid (sediment, nutrients, ….) from the bottom to the surface.
- Their genesis was unknown:
  - *Three conjectures:*
    - Oscillations of the reattachment line
    - Turbulent eddies from the stoss side
    - Eddies in the separated shear layer
- Full-field, time dependent information is needed to understand their dynamics.

Boil Identification

- Boils can be identified in the numerical simulations





Velocity vectors at the water surface. 2D dunes

Boil Identification

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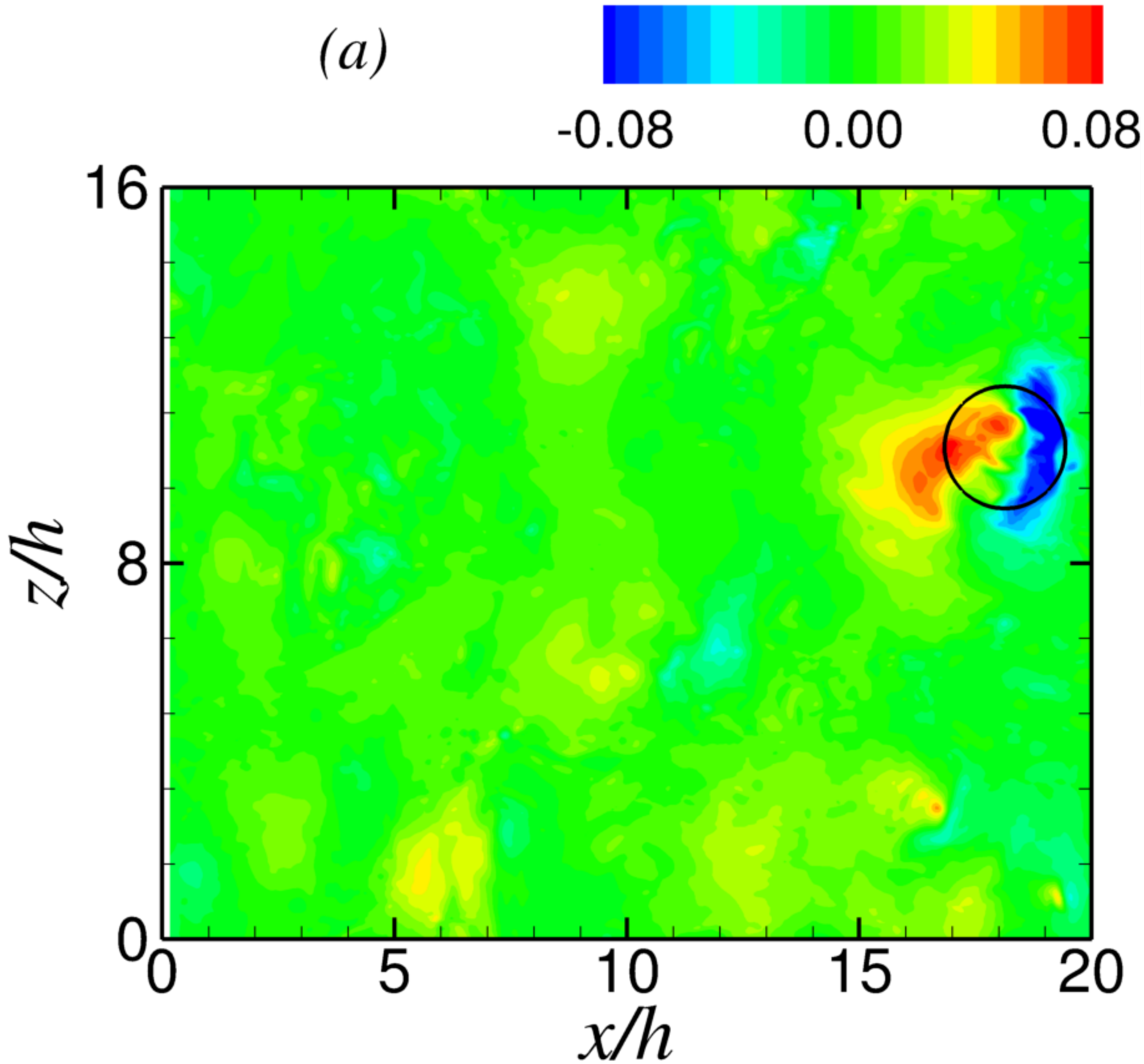
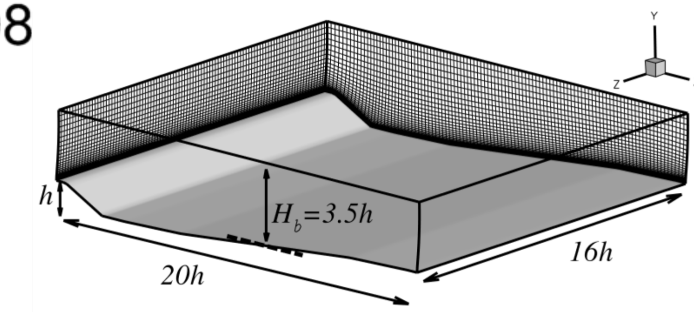
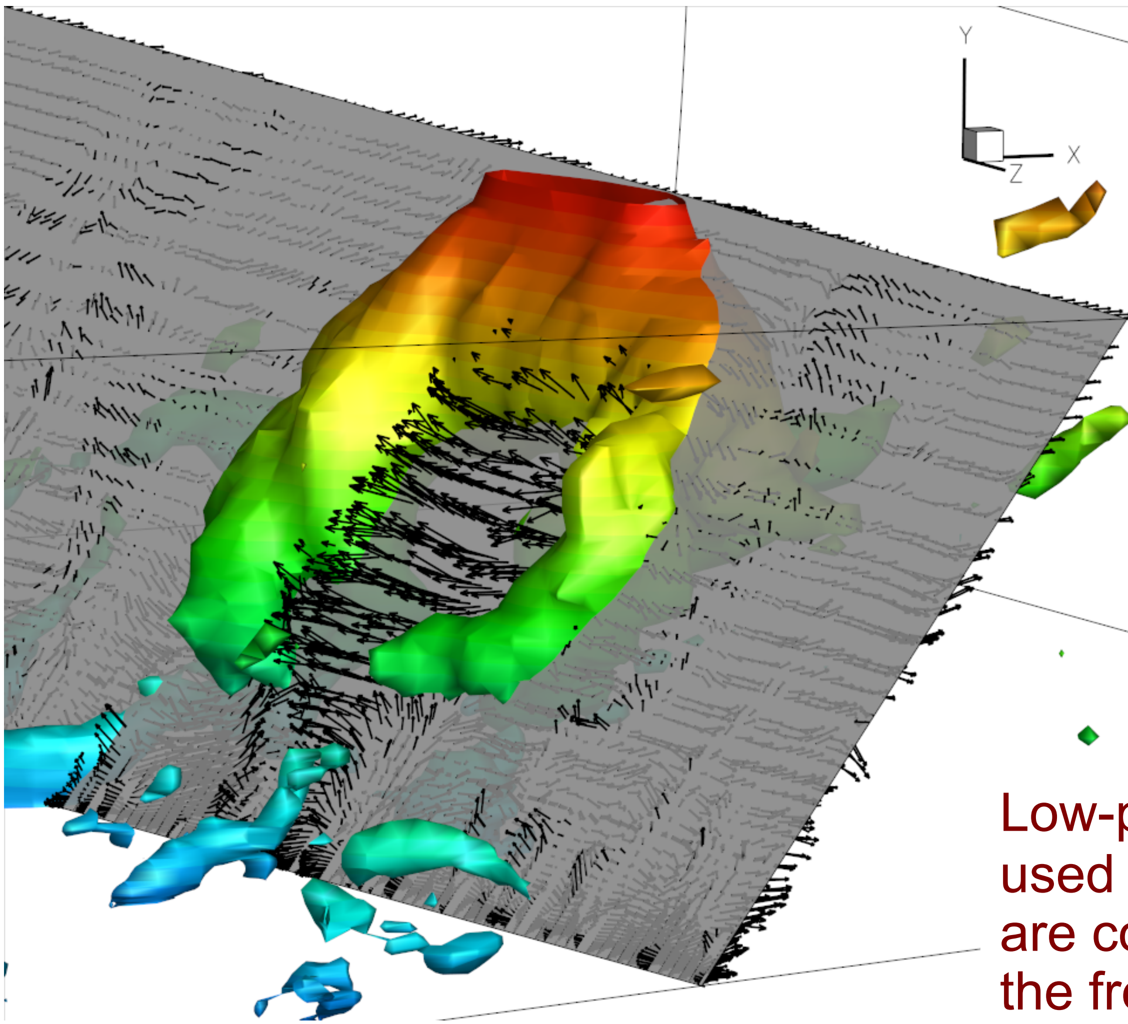


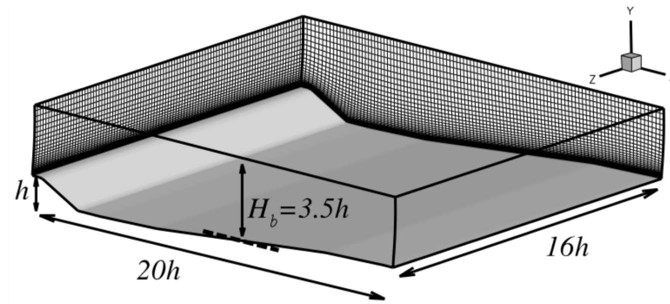


Pressure fluctuations at the water surface. 2D dunes

Boil Identification

- Boils can be identified in the numerical simulations and related too the vortical structures.



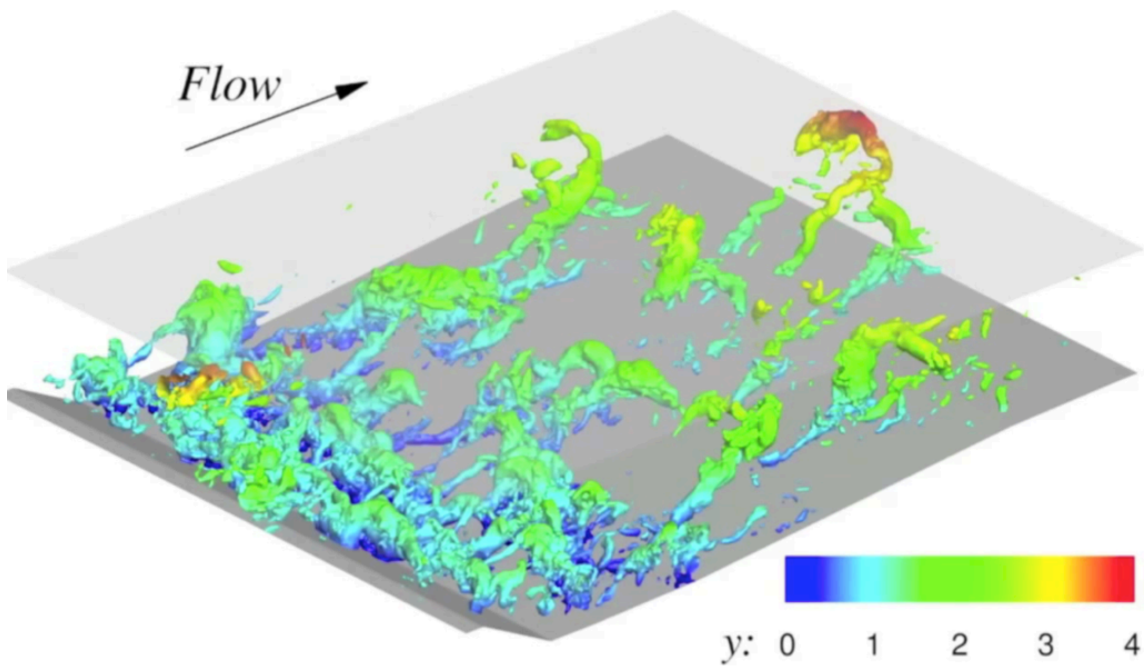


Visualization of a horseshoe vortex touching the water surface. 2D dunes.

Low-pressure isosurfaces are used to visualize the vortex, and are coloured by the distance to the free surface (0→4).

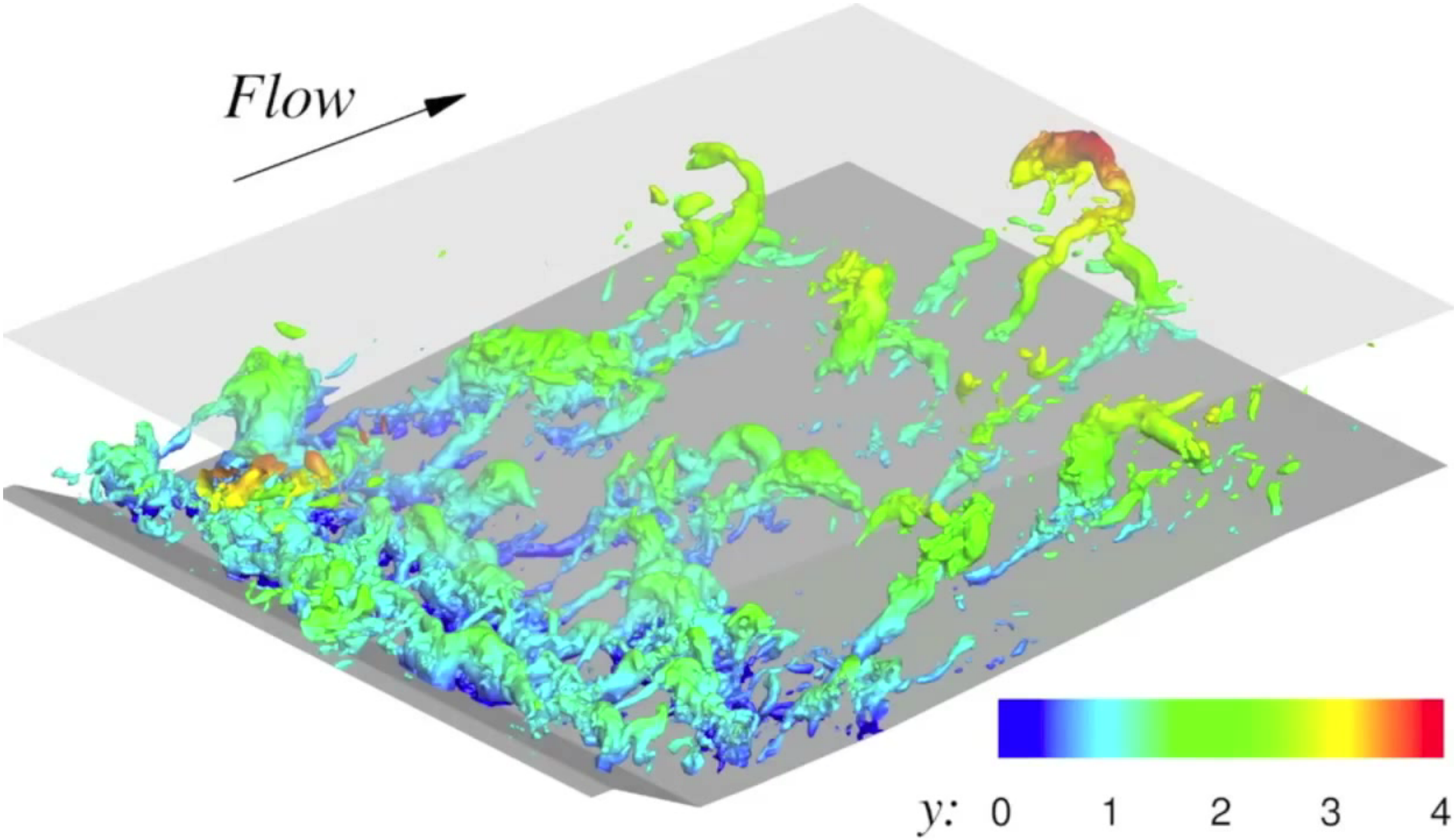
Boil Identification

- Boils can be identified in the numerical simulations and related too the vortical structures.
- Once the structures are identified, we can consider the full field.

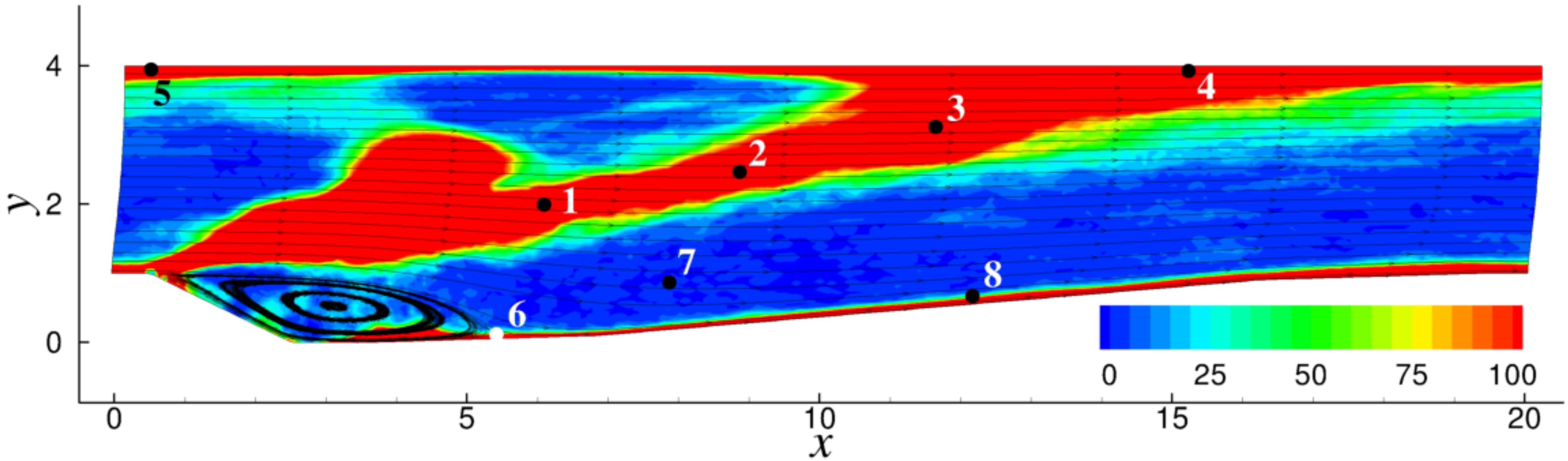


Low-pressure isosurfaces are used to visualize the vortex, and are coloured by the distance to the free surface (0→4).

Time History

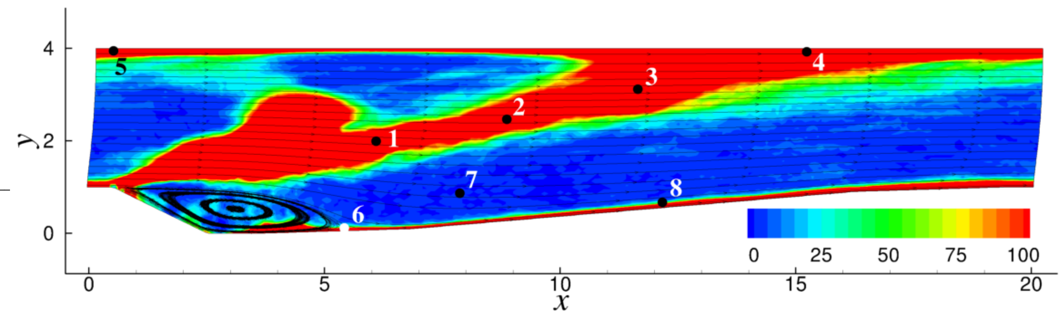


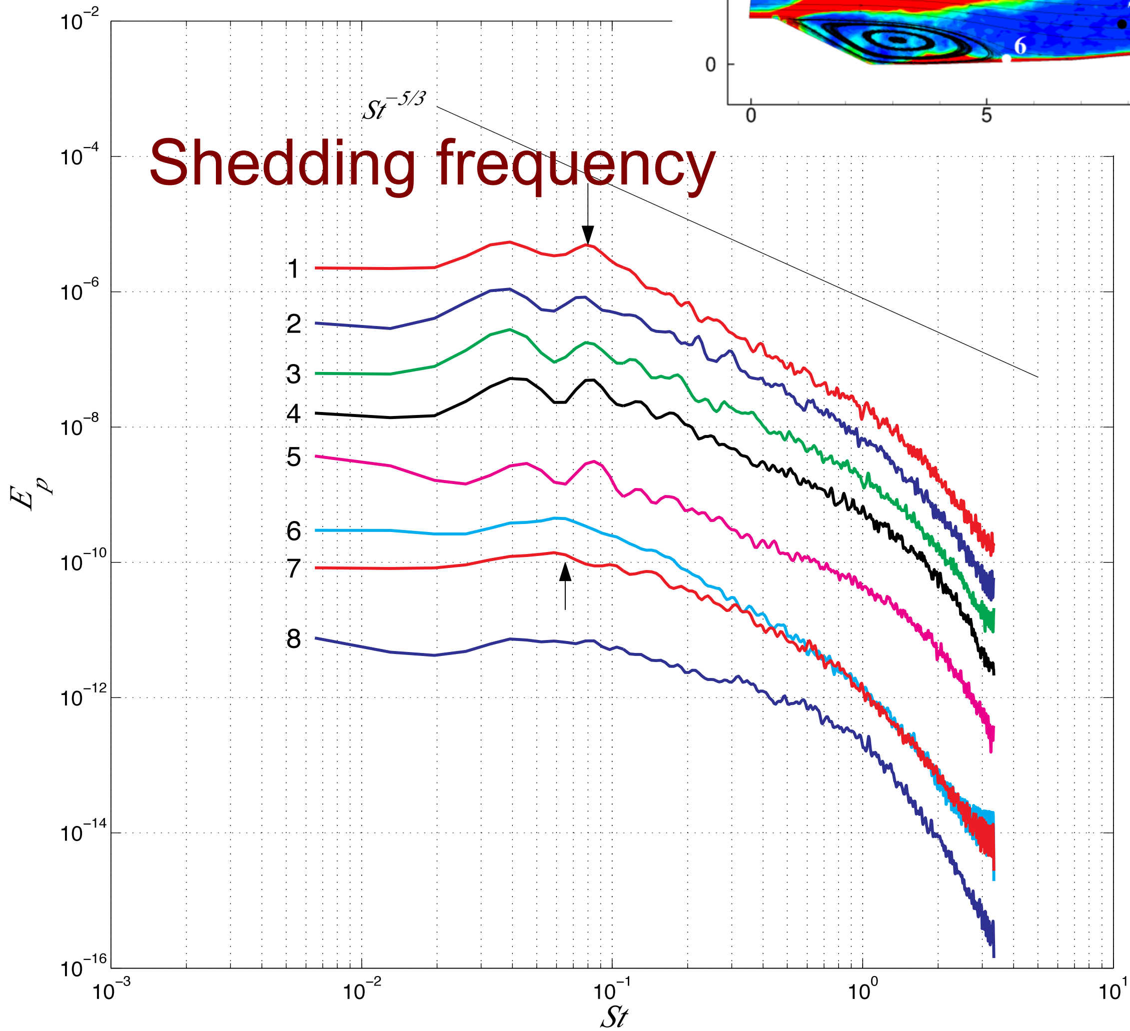
Quantitative Analysis



Frequency of horseshoe vortex appearance
(Low pressure + spanwise vorticity)

Quantitative Analysis





Power spectra of pressure

Conclusions

- Performed LES of the flow over 2D dunes at laboratory scale
- Good agreement with experimental and numerical data
- Gortler-like vortices are formed on the stoss side (upward slope)
- Boils can be identified from velocity vectors, pressure and turbulent kinetic energy at the surface.
  - *They are associated with large horseshoe vortices*
    - Upwash between the legs of the vortex
    - TKE and Reynolds stress are much larger than the average (15-40 times)
    - They are due to the instability of the separated shear layer

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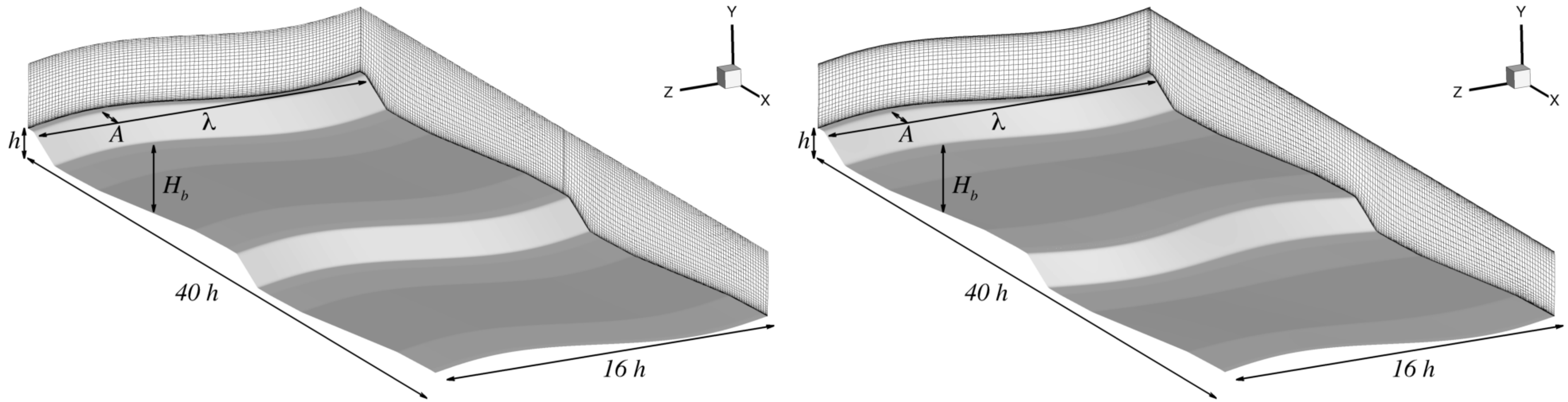
- Outlook

Motivation

- Real world: Dunes are three-dimensional.
- Effects of three-dimensionality on flow resistance, sediment transport, and turbulence production are not well known.
- Experiments on three-dimensional dunes lack precise measurements of skin friction and form drag, as well as spatially-resolved turbulence stresses.

Setup

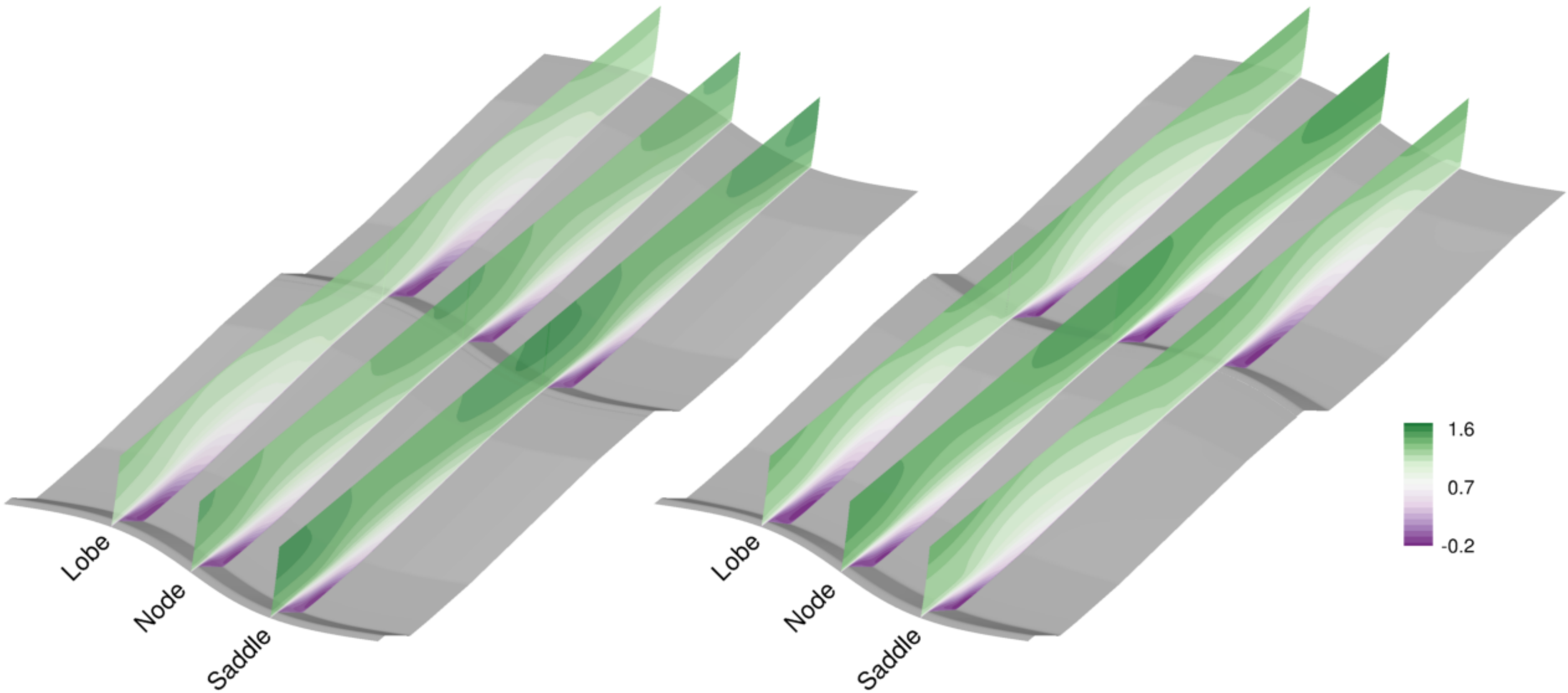
- Reynolds number: $\mathrm{Re} = \dfrac{U_b H_b}{\nu} = 18{,}900$
- Two configurations: in-phase and staggered



Cases	*A/h*	*λ/h*	$N_x \times N_y \times N_z$	Δs^+	Δn^+	Δz^+
In-phase	*1.0*	*16.0*	*512* x *96* x *256*	*22.0*	*0.7*	*18.1*
Staggered	*1.0*	*16.0*	*640* x *128* x *320*	*17.6*	*0.7*	*14.0*

Results

Mean streamwise velocity U

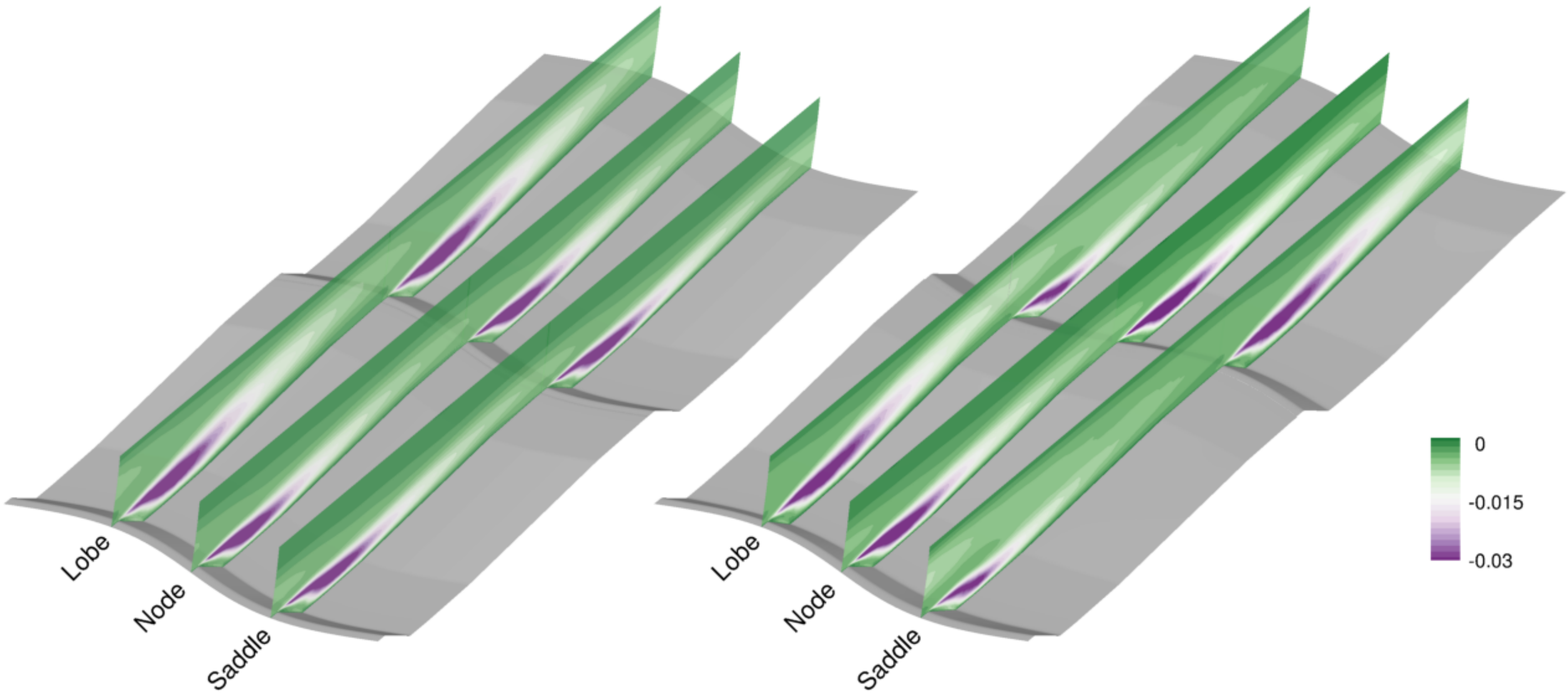


In-phase

Staggered

Results

Reynolds shear stress $\langle u'v' \rangle$

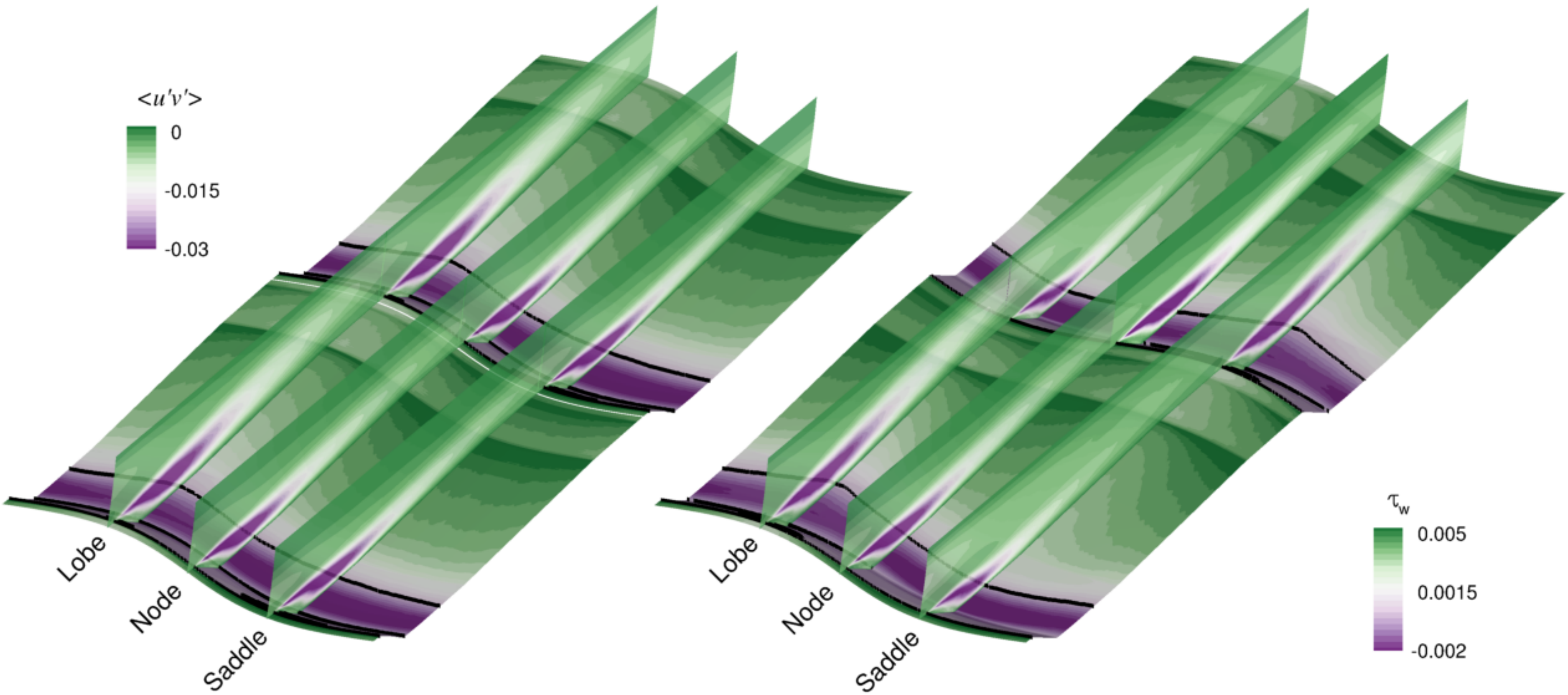


In-phase

Staggered

Results

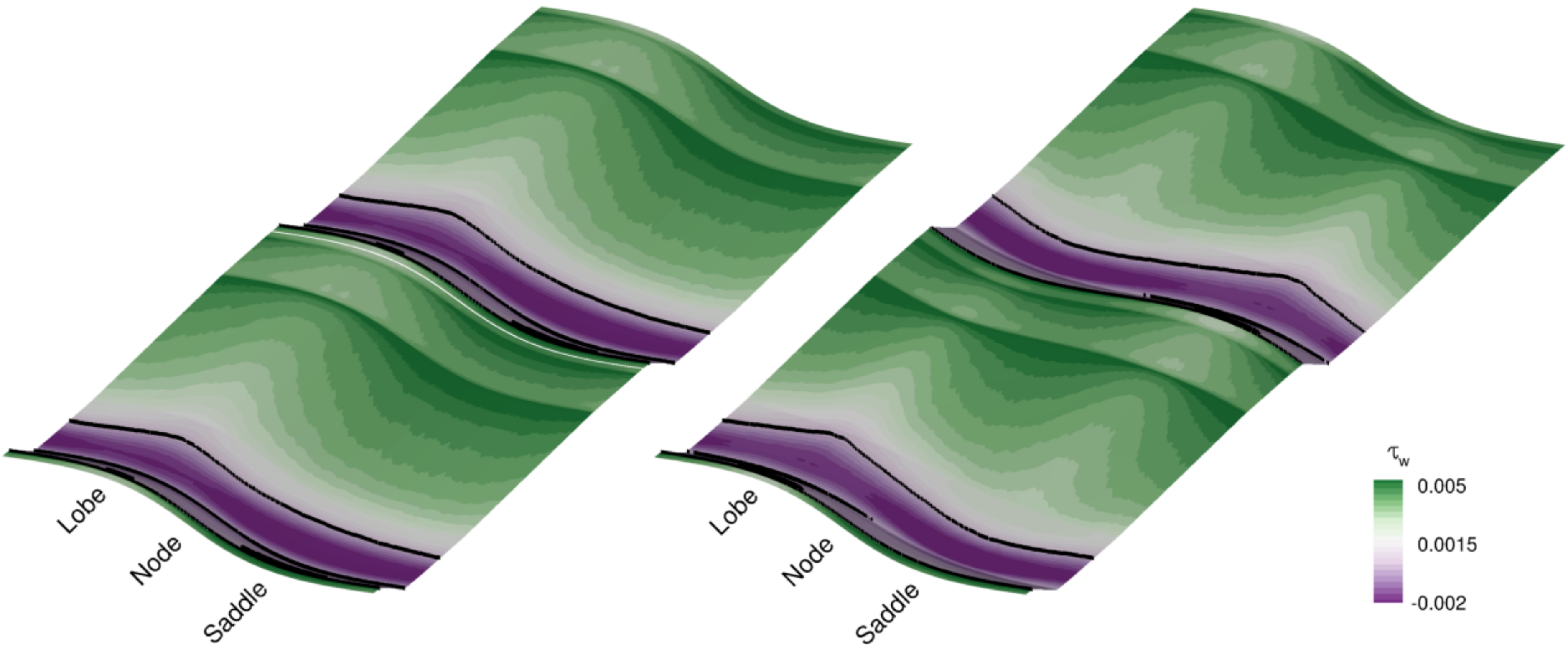
Reynolds shear stress $<u'v'>$ and wall stress τ_w



In-phase   *Staggered*

Results

Wall stress τ_w



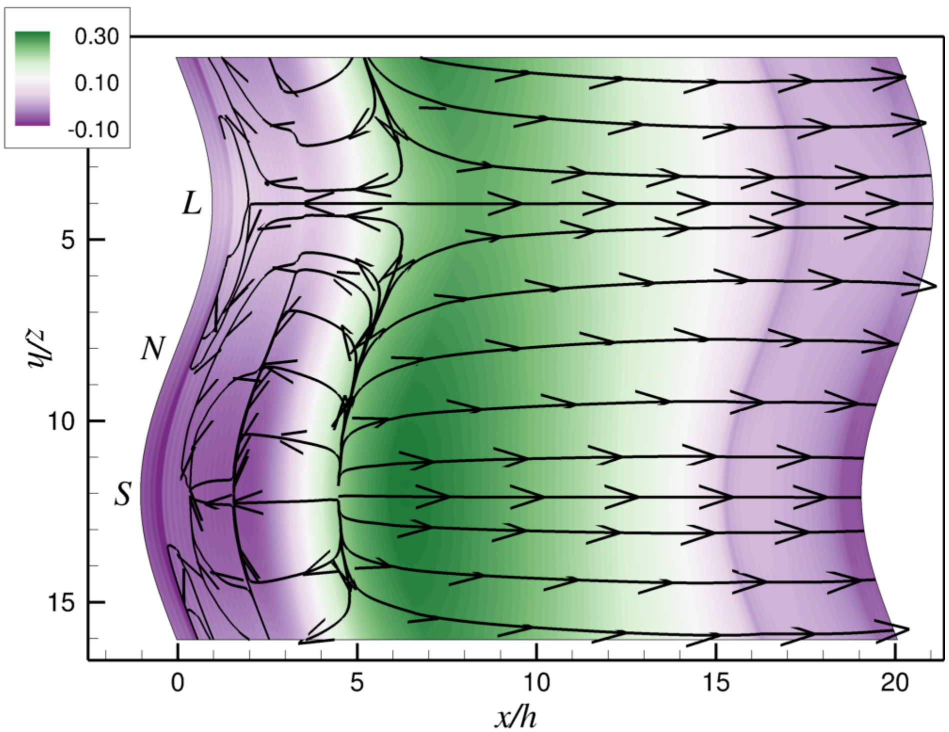
In-phase *Staggered*

Results

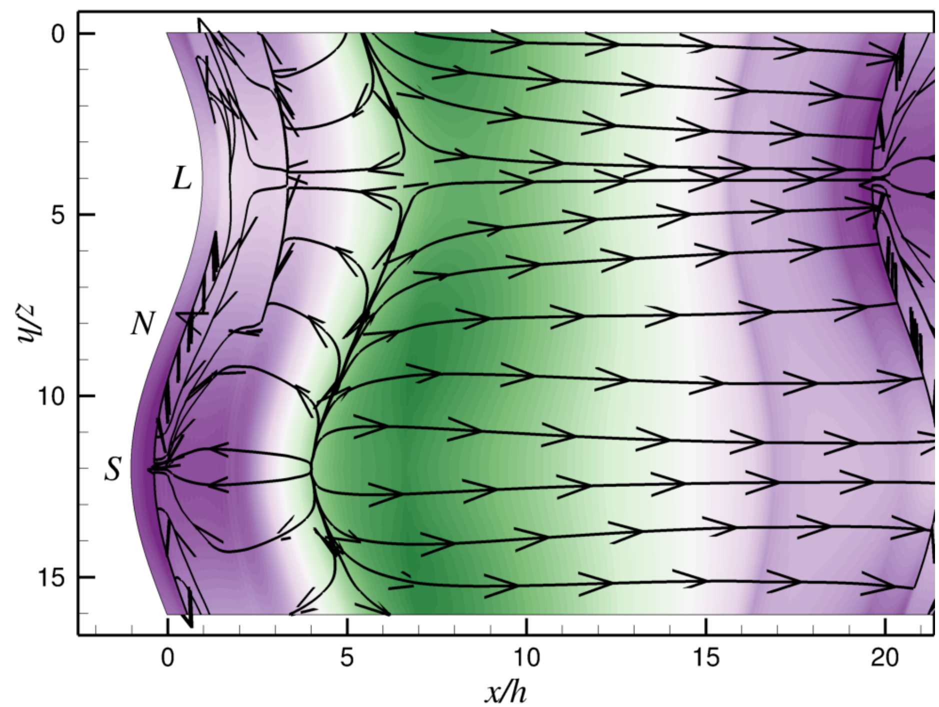
TURBULENCE SIMULATION TSM LAB AND MODELLING LABORATORY

- Lateral pressure gradient (from node to lobe) induces spanwise flow

Mean wall pressure and wall streamlines



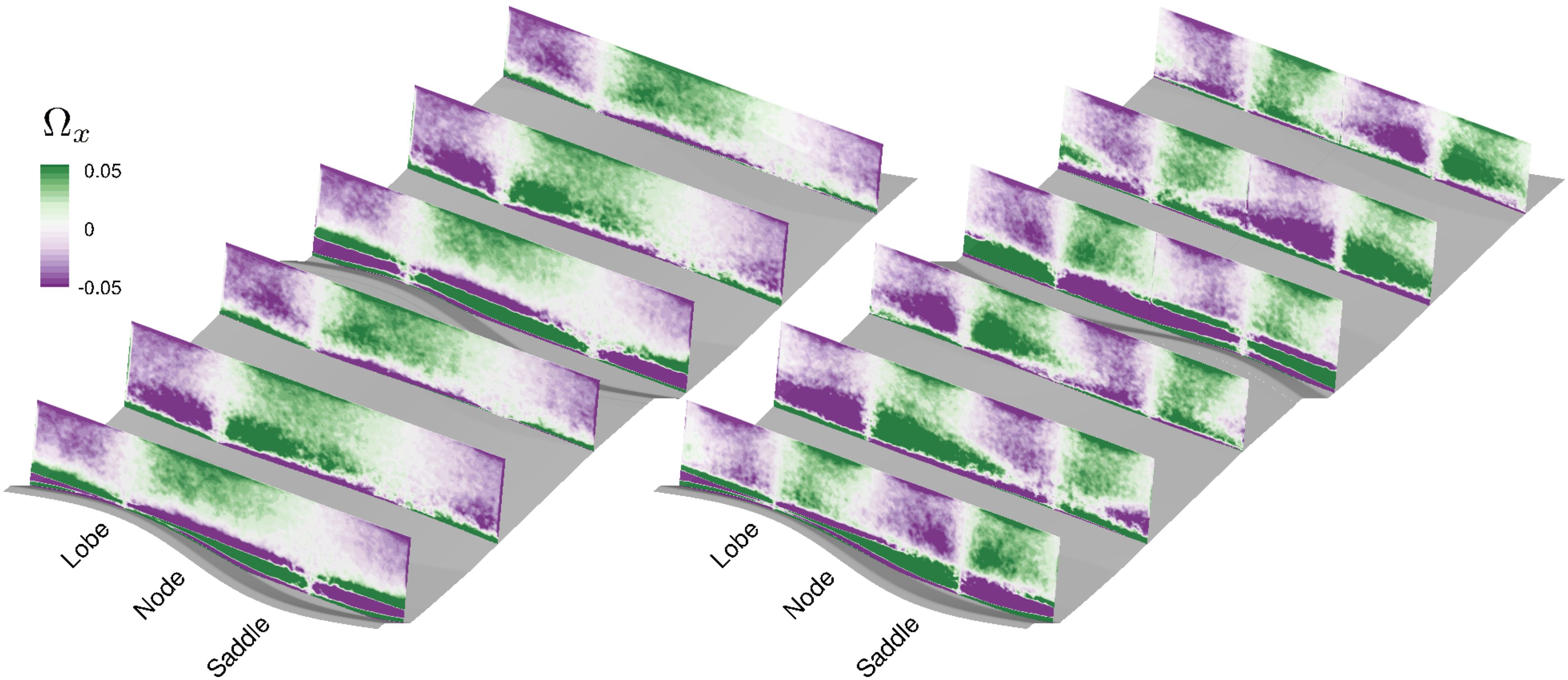
In-phase



Staggered

Results

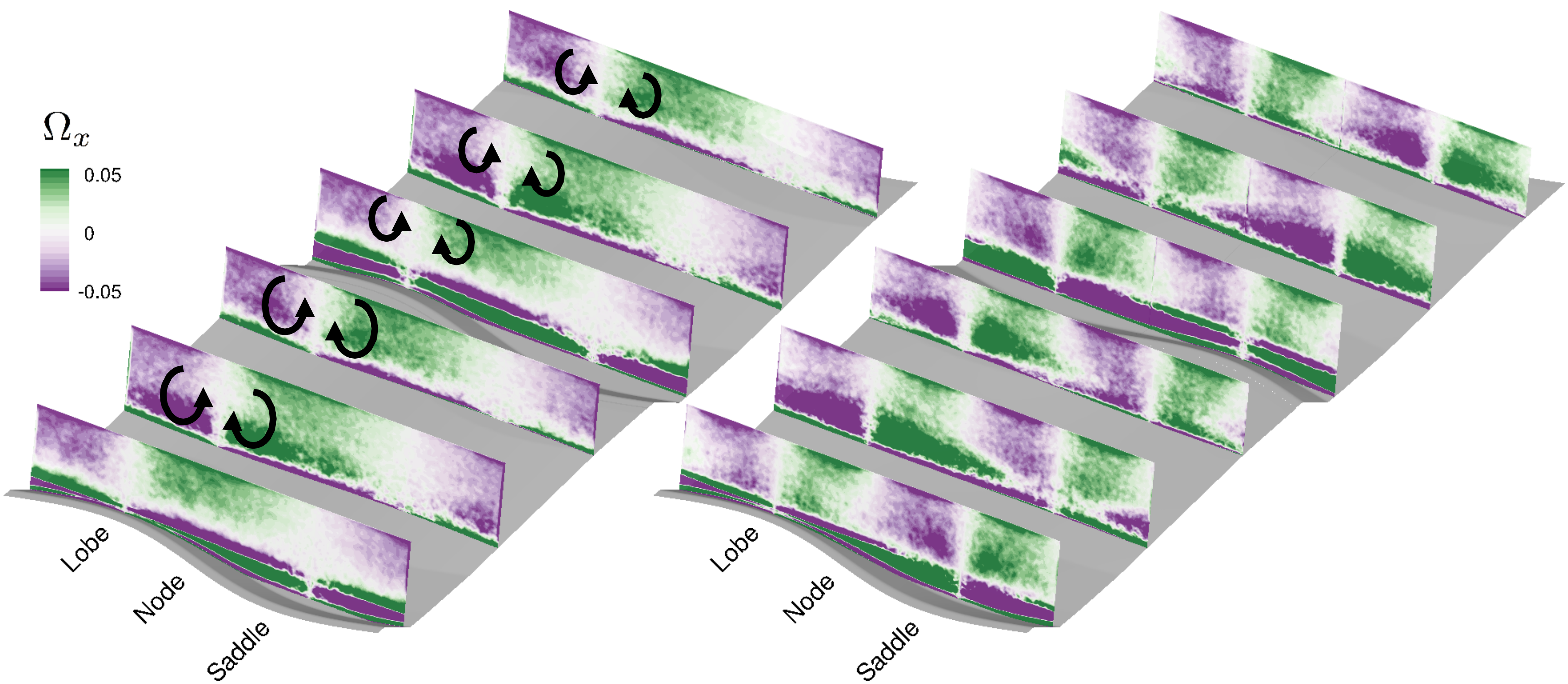
Mean streamwise vorticity Ω_x



In-phase *Staggered*

Results

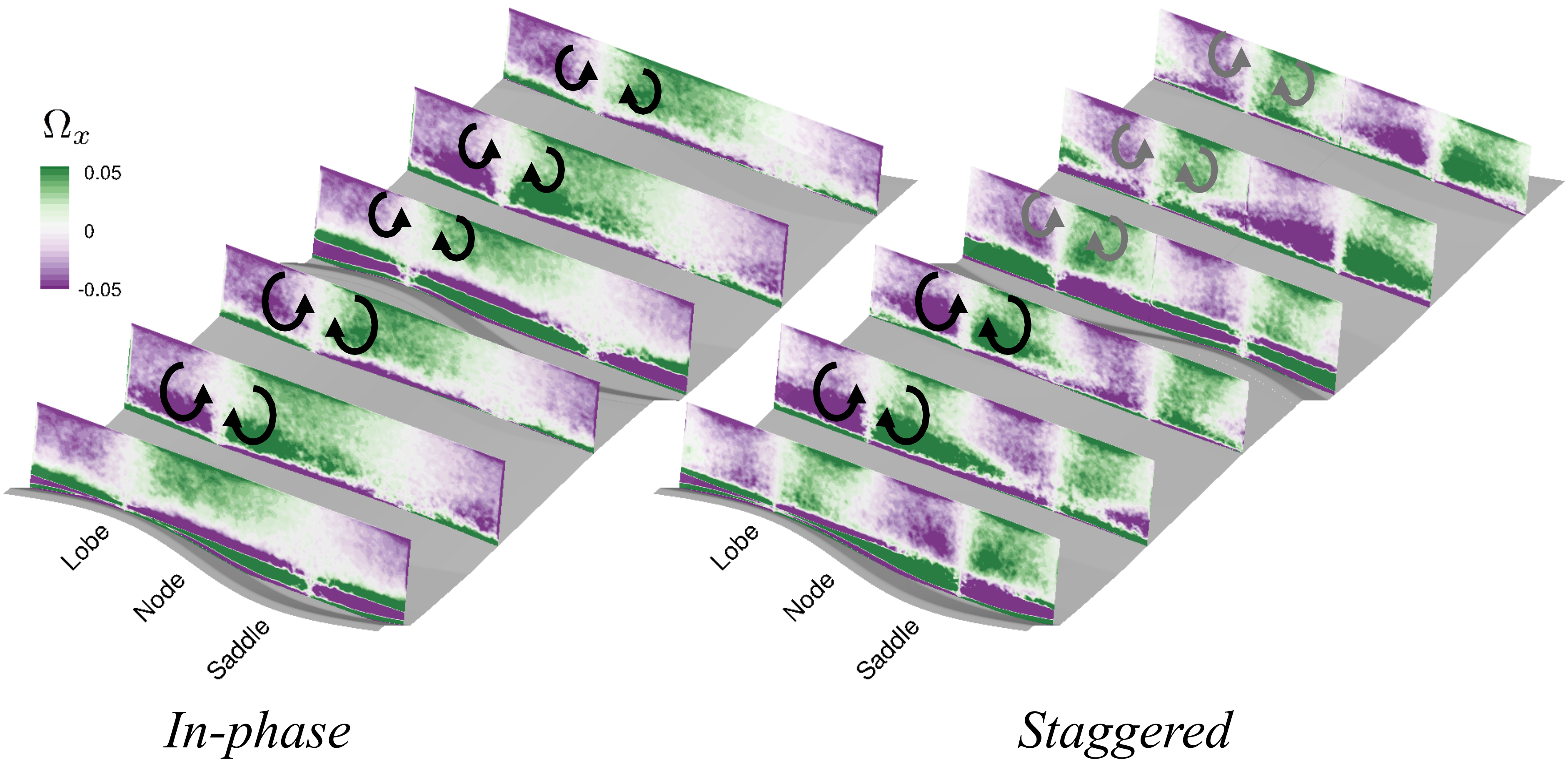
Mean streamwise vorticity Ω_x



In-phase *Staggered*

Results

Mean streamwise vorticity Ω_x



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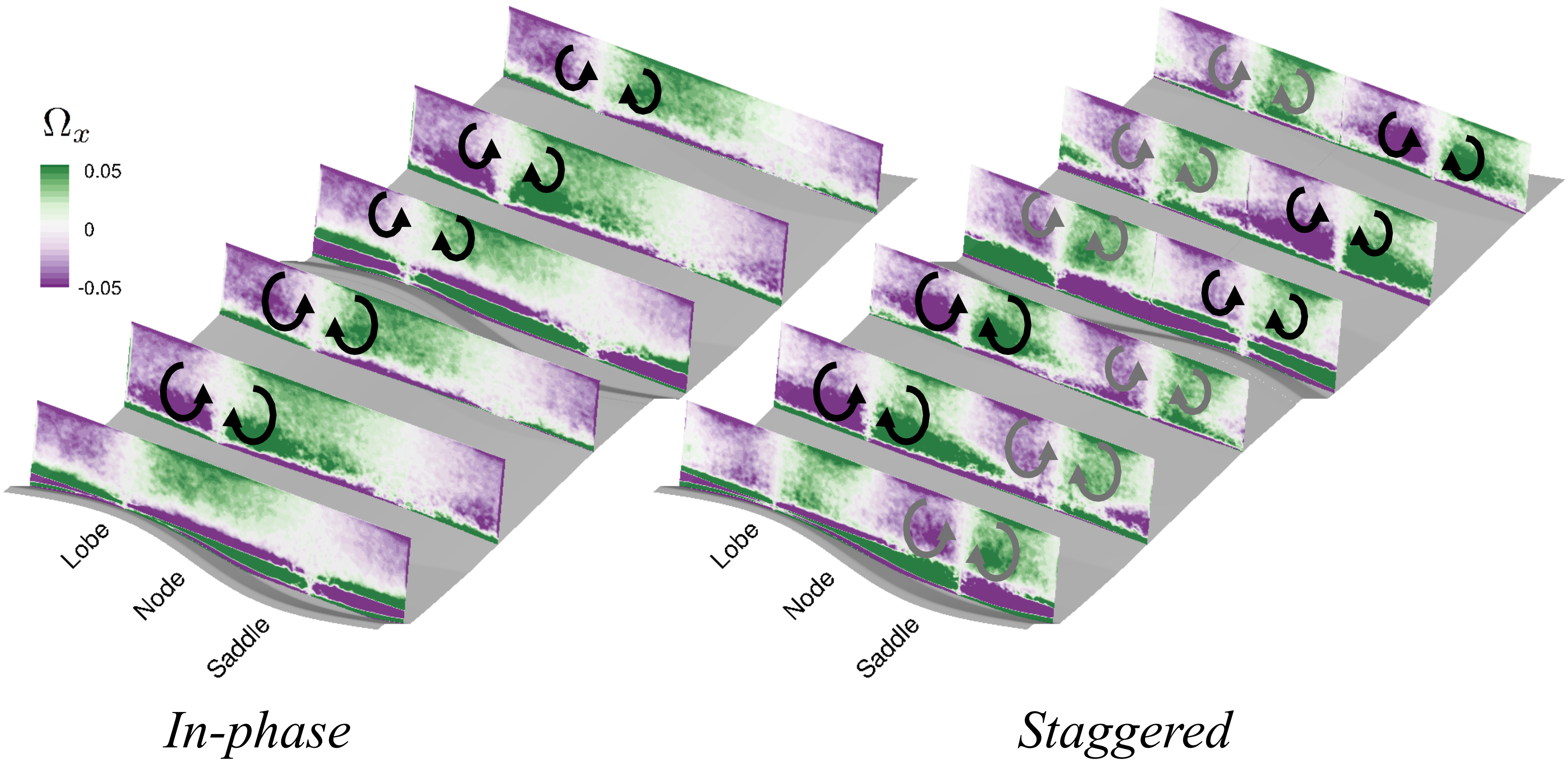
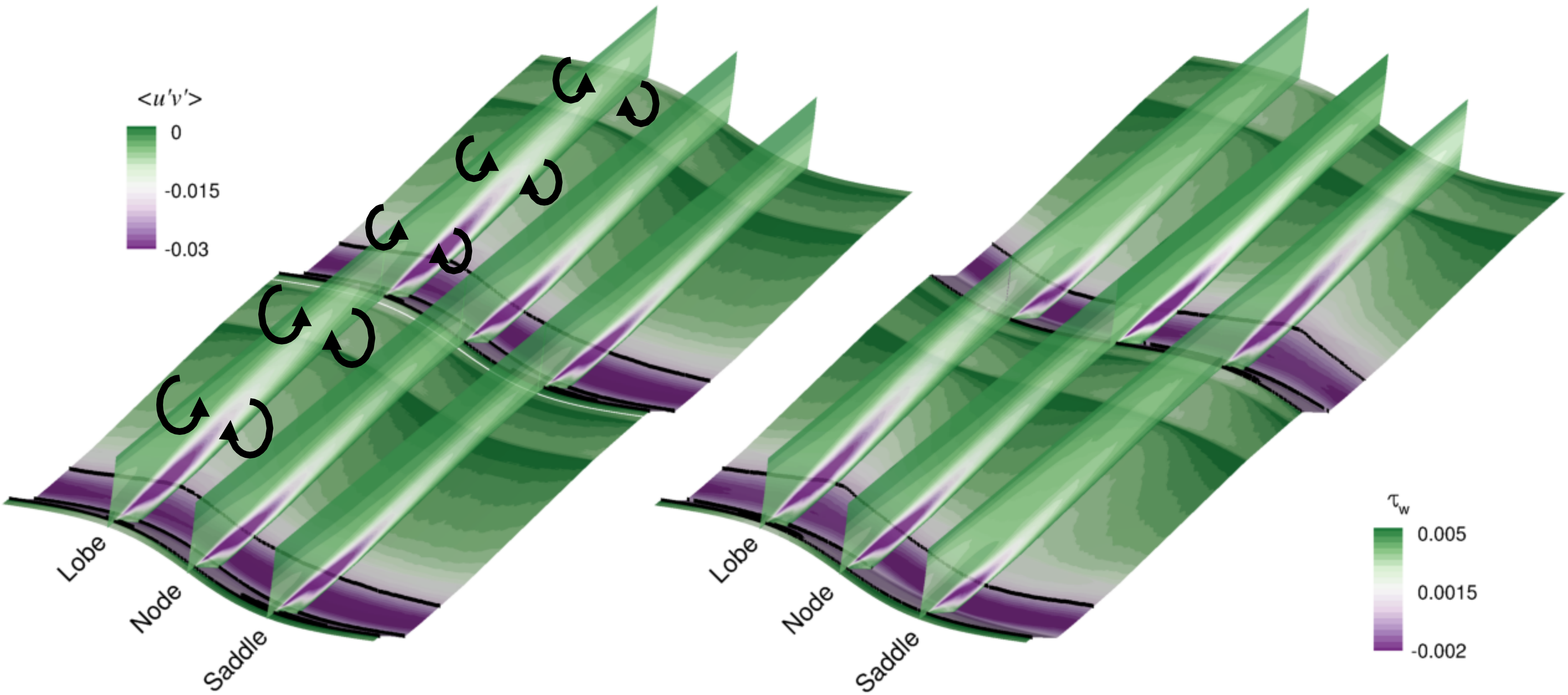
Mean streamwise vorticity Ω_x



Results

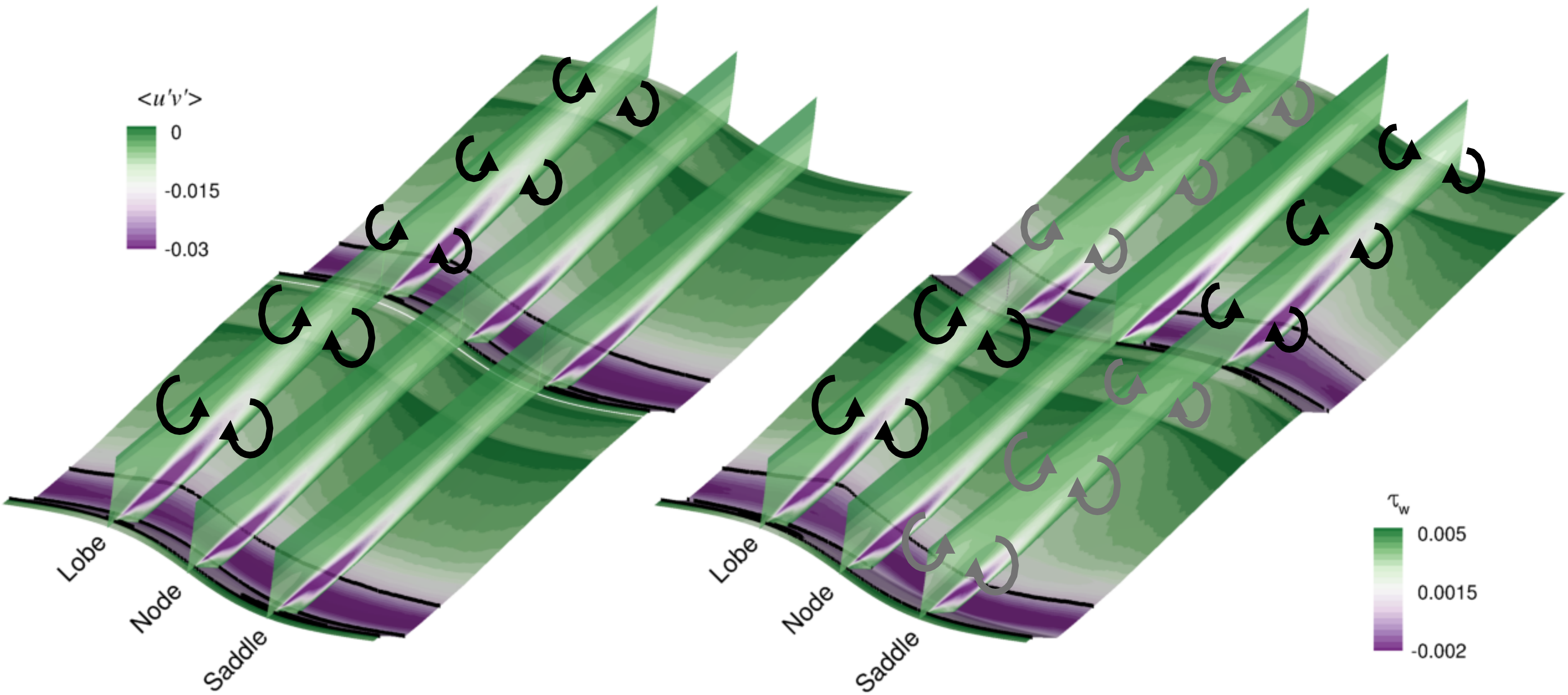
Reynolds shear stress $<u'v'>$ and wall stress τ_w



In-phase *Staggered*

Results

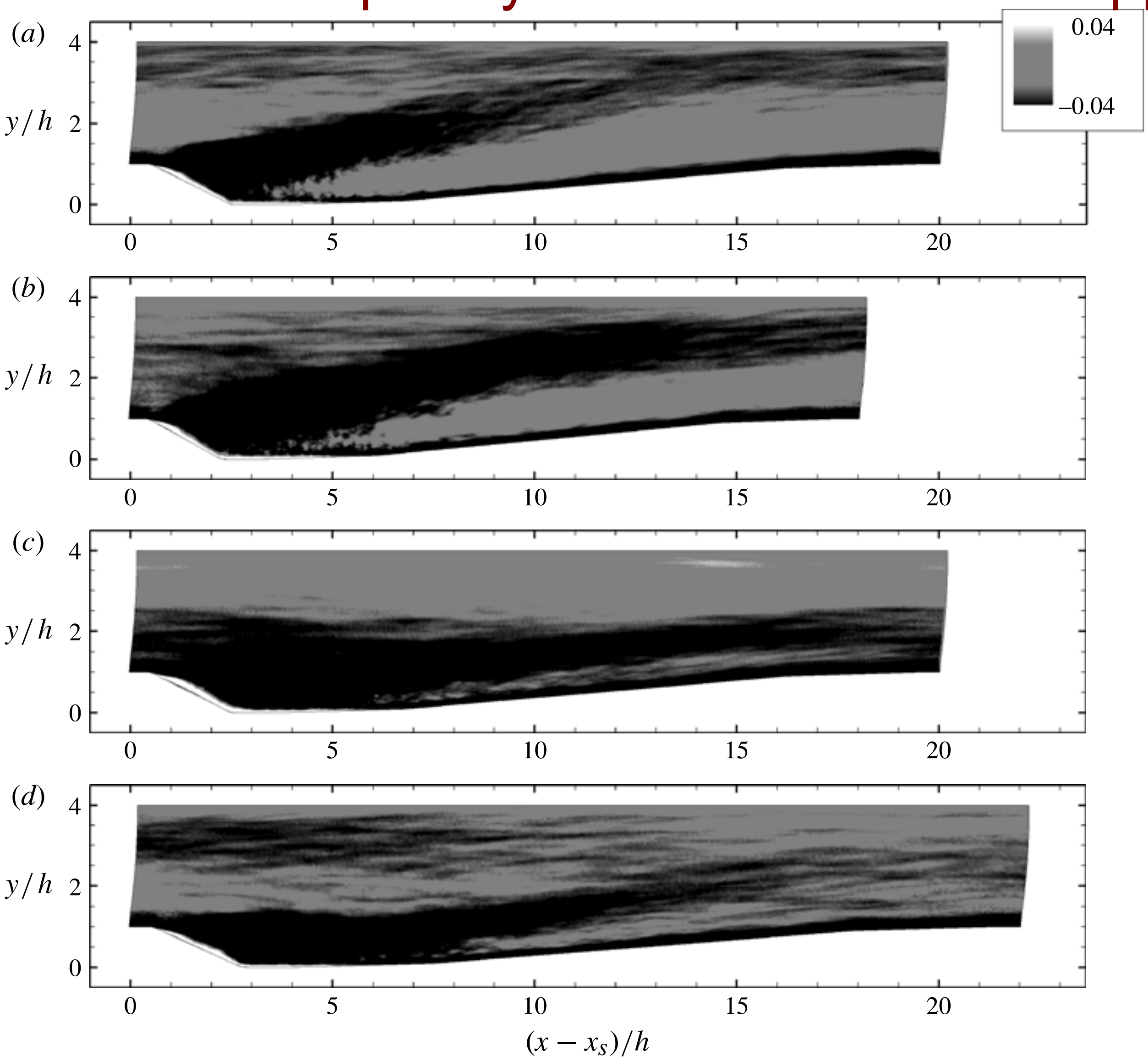
Reynolds shear stress $\langle u'v' \rangle$ and wall stress τ_w



In-phase *Staggered*

Results

Frequency of horseshoe vortex appearance



Lobe, in-phase

Lobe, staggered

Saddle, in-phase

Saddle, staggered

CONCLUSIONS

- The three-dimensional bed form induces mean secondary flow in the streamwise direction.
  - *Low-momentum fluid close to the bed moves from the saddle plane toward the lobe plane, generating a vortex pair.*
  - *The secondary flow affects the whole flow depth.*
  - *In the staggered configuration, there are two vortex pairs, one formed at the lobe and one advected over the saddle from the previous dune.*
- The spatial distribution of the separated-shear layer alters the flow across the channel.
  - *The upwash of slow fluid enhances the flow deceleration and acceleration in the lobe plane.*
  - *Advection displaces the shear layer and the horseshoe vortices upwards.*