STREAKY STRUCTURES IN A SINUSIODALLY-TEMPERED VERTICAL TURBULENT PIPE FLOW

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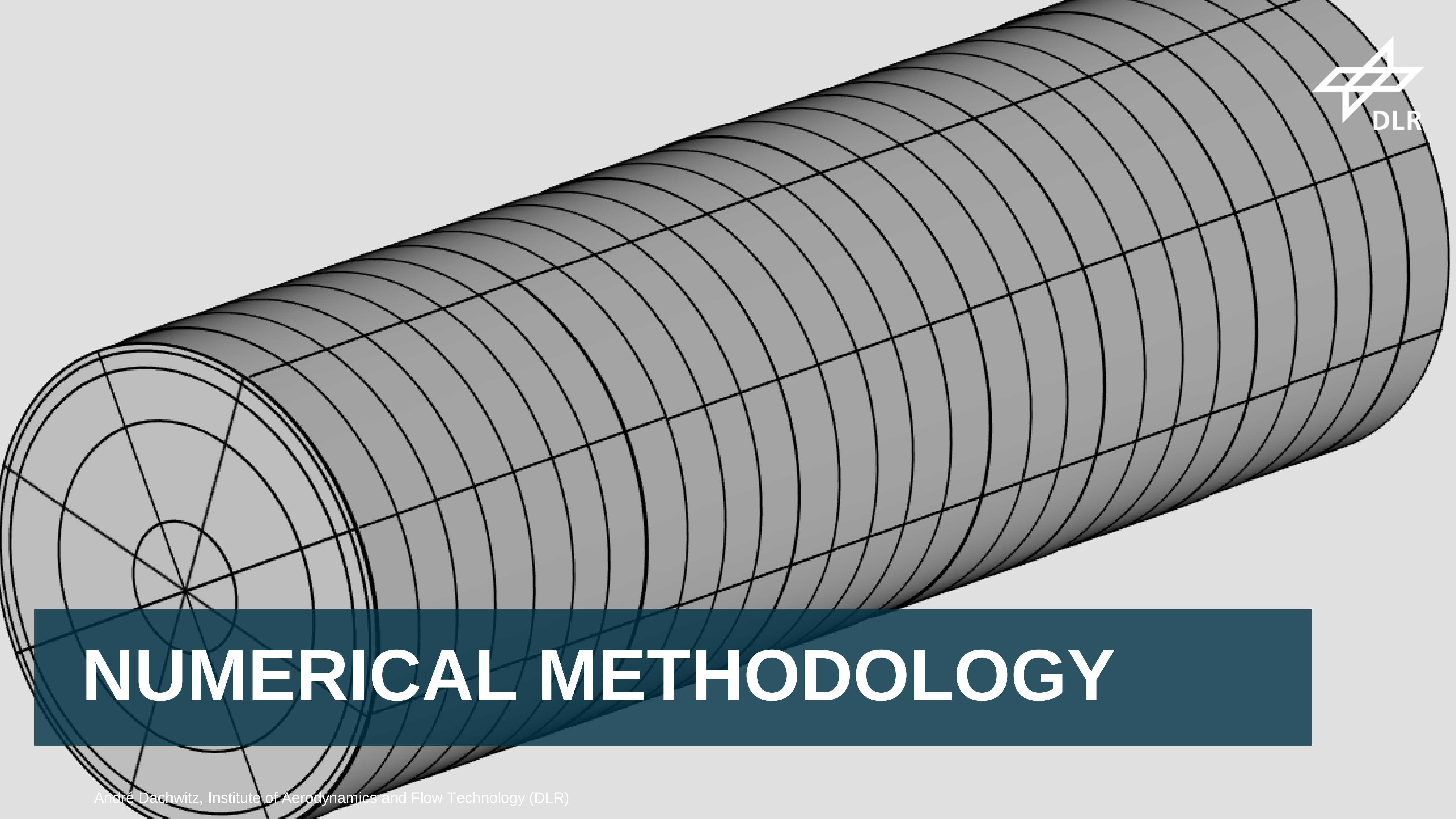
MOTIVATION

Motivation

- Flows are often forced through channels or arrays of tubes to absorb heat from surfaces.
- Heating the pipe wall can cause relaminarisation in buoyancy aided flows.[1]
- Relaminarisation also causes a decrease in the turbulent heat flux and therefore less thermal energy.[2]
- For vertical Pipes thermal effects are also not to be neglected for $Ri > 10^{-5}$.[3]
- We want to investigate the buoyancy-induced changes in the size and intensity of the streaks in a pipe flow with circumferentially-varying wall temperature.

[1] R. Narasimha and K.R. Sreenivasan. Relaminarization of Fluid Flows. Advances in Applied Mechanics, vol. 19, pp. 221-309, 1979
[2] E. Marensi, S. He and A.P. Willis. Suppression of Turbulence and Travelling Waves in a Vertical Heated Pipe. Journal of Fluid Mechanics, vol. 919, pp. 17-29, 2021
[3] J.D. Jackson and W. B. Hall. Forced Convection Heat Transfer to Fluids at Supercritical Pressure. Turbulent forced convection in channels and bundles, vol. 2, pp. 563-576, 1979.



NUMERICAL METHODOLOGY

Numerical Methodology

Incompressible Navier-Stokes Equations

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} + \nabla p = \frac{1}{Re_b} \nabla^2 \vec{u} + \frac{Gr}{{Re_b}^2} \theta \delta_{1i}$$

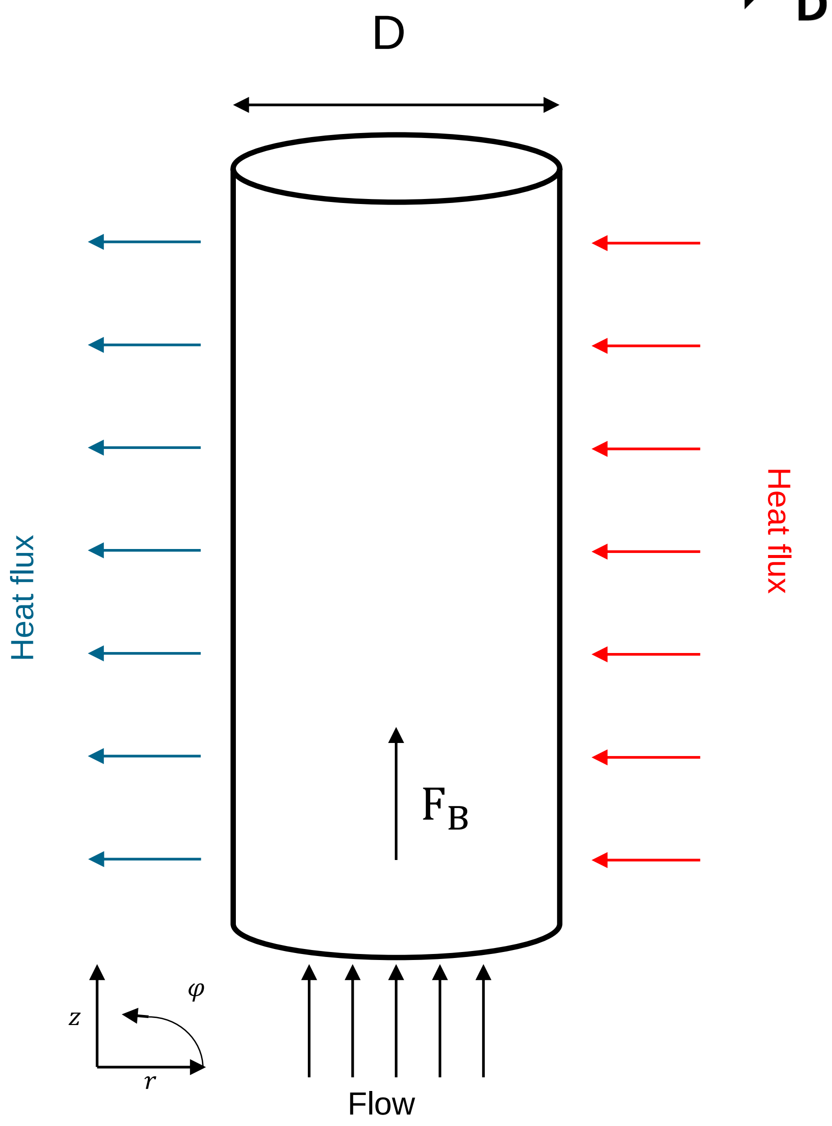
$$\nabla \vec{u} = 0$$

Boussinesq Approximation

$$\hat{\rho}\hat{g} \approx \hat{\rho}_0 \hat{g} \hat{\beta}_0 (\hat{T} - \hat{T}_0)$$

Boundary Conditions

- No-slip and impermeability boundary condition at the wall.
- Periodic boundary condition with regard to homogeneous direction.



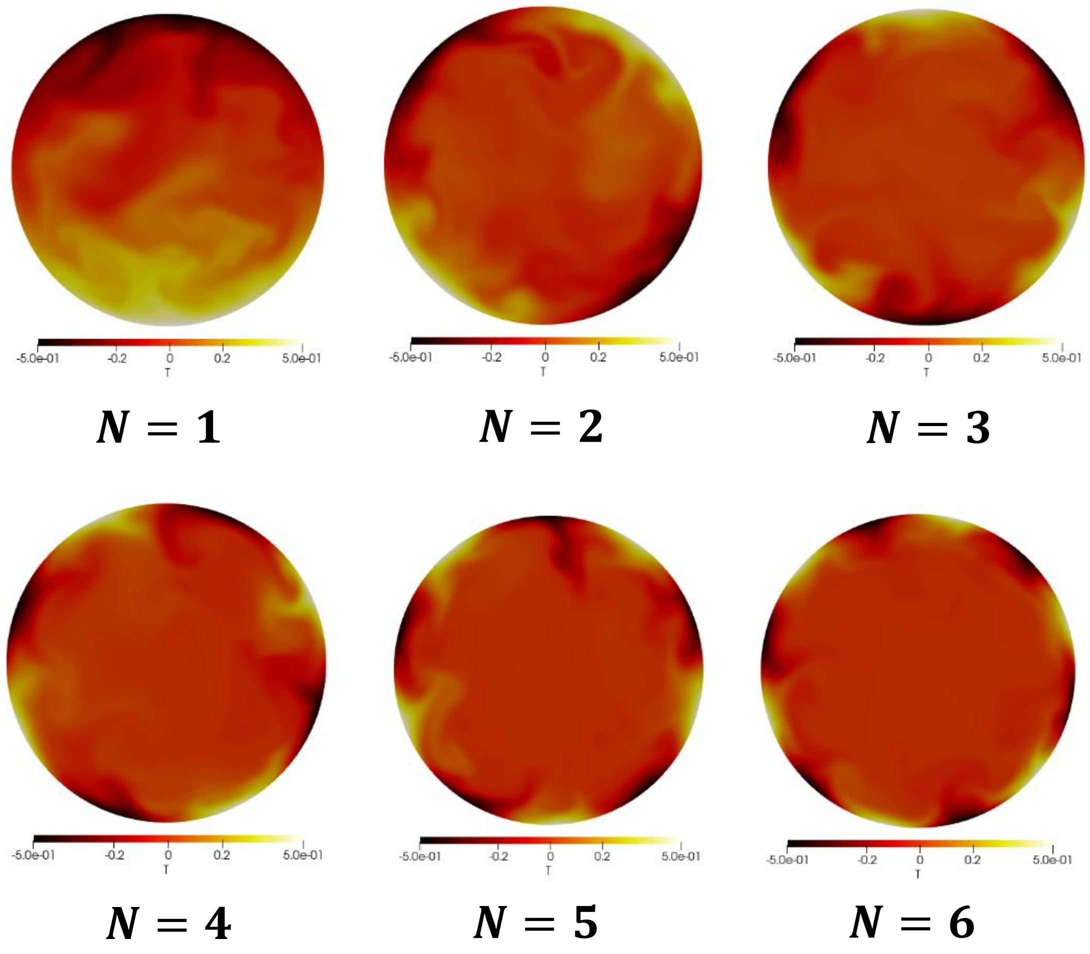
Energy Equation and Thermal Boundary Condition

Energy Equation

$$\frac{\partial \Theta}{\partial t} + \vec{u} \cdot \nabla \Theta = \frac{1}{Pr Re_b} \nabla^2 \Theta$$

Thermal Boundary Condition

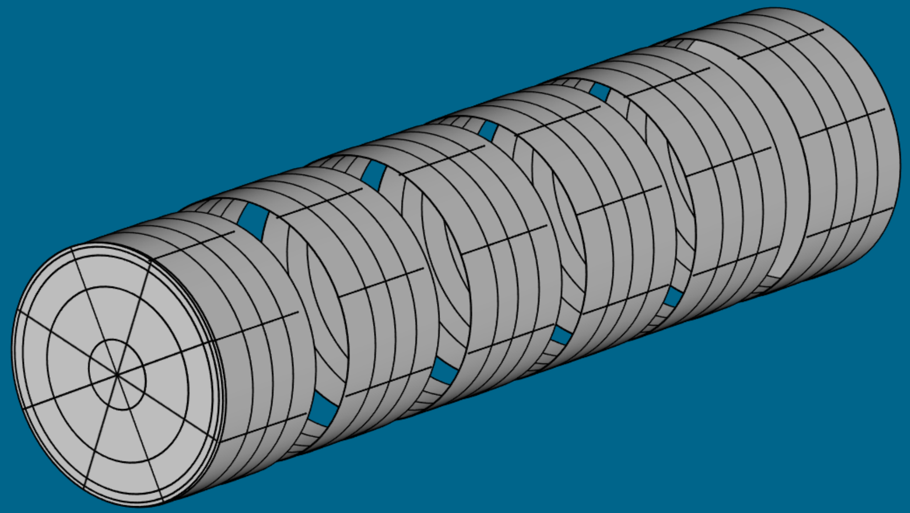
$$\Theta_w = sin(N \varphi) \quad N = 0, \dots, 7$$



Numerical Set-up

FLOWSI solver

- 4th-order finite volume method in space
- 2nd-order semi-implicit Euler-leapfrog scheme in time
- MPI parallel



N	Re_b	Pr	Gr	L/D	$N_z \times N_\varphi \times N_r$	$\Delta r^+_{min}, \Delta r^+_{max}$	Δz^+	$R^+\Delta\varphi$
0	4328	0.71	$-$	21	$1536 \times 256 \times 90$	$0.17, 3.81$	4.14	3.72
$1, 7$	4328	0.71	$1.87 \cdot 10^7$	21	$1536 \times 256 \times 90$	$0.17, 3.81$	4.14	3.72

Bulk Reynolds Number: $Re_b = \frac{u_b D}{\nu}$

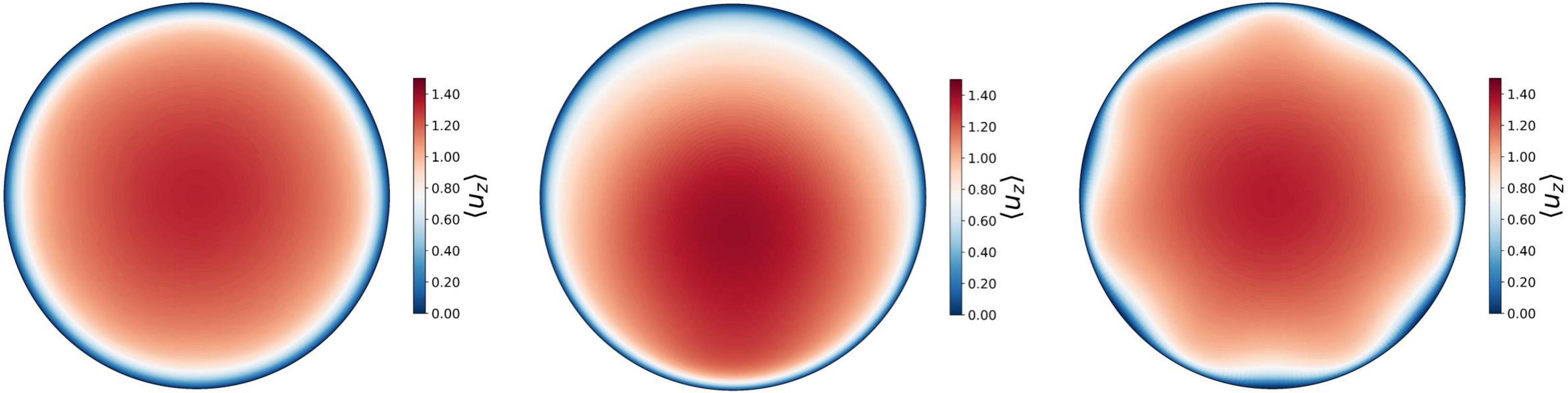
Friction Reynolds Number: $Re_\tau = \frac{u_\tau D}{\nu}$

Prandtl Number: $\mathrm{Pr} = \frac{\nu}{\alpha}$

Grashof Number: $Gr = \frac{g\ \beta \Delta T D^3}{\nu^2}$

RESULTS

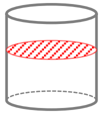
Mean Streamwise Velocity Fields (N = 0, 1, 7)



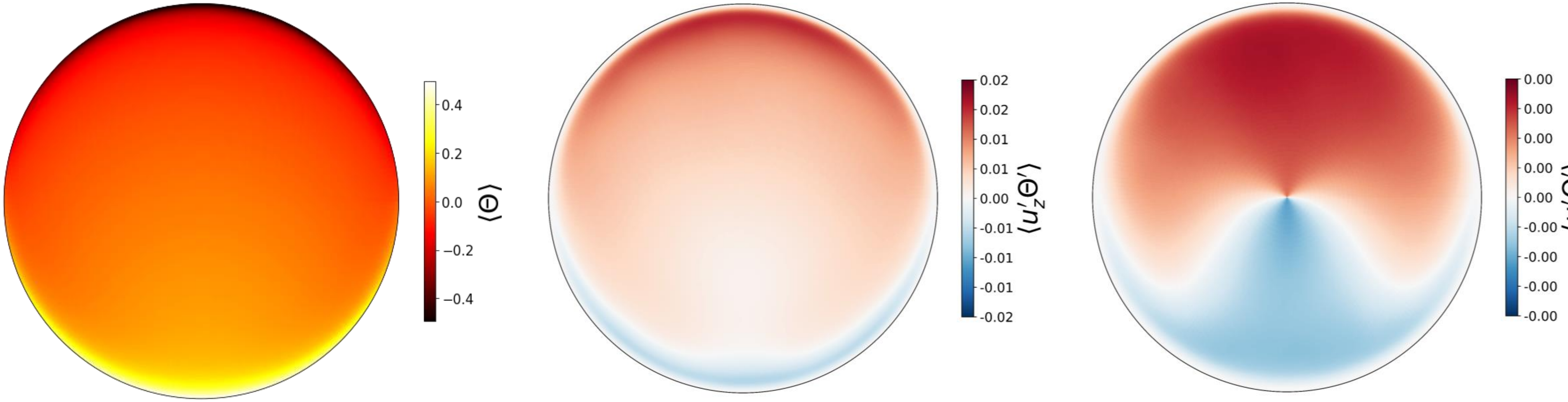
N = 0 | N = 1 | N = 7

- The isothermal streamwise velocity field is circumferentially-symmetric.
- For *N = 1* the maximum of the streamwise velocity is shifted to the heated wall.
- Larger velocity gradients at heated wall result in larger shear stress on the surface.
- For *N = 7* the streamwise velocity profile is star-shaped.

Mean Temperature and Turbulent Heat Flux

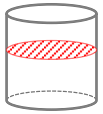


N = 1

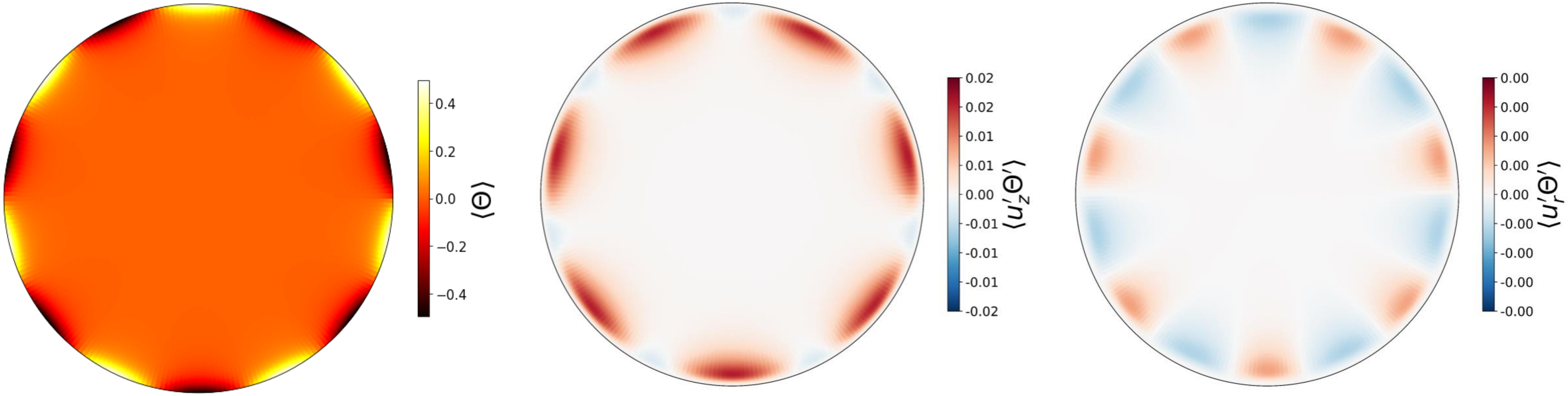


- Whole pipe affected by the heating.
- Larger turbulent heat flux at the colder wall than at the warmer wall.
- Mostly positive correlation between streamwise velocity and temperature fluctuations.
- In heated area the correlation is mostly negative for the radial turbulent heat flux.

Mean Temperature and Turbulent Heat Flux



N = 7

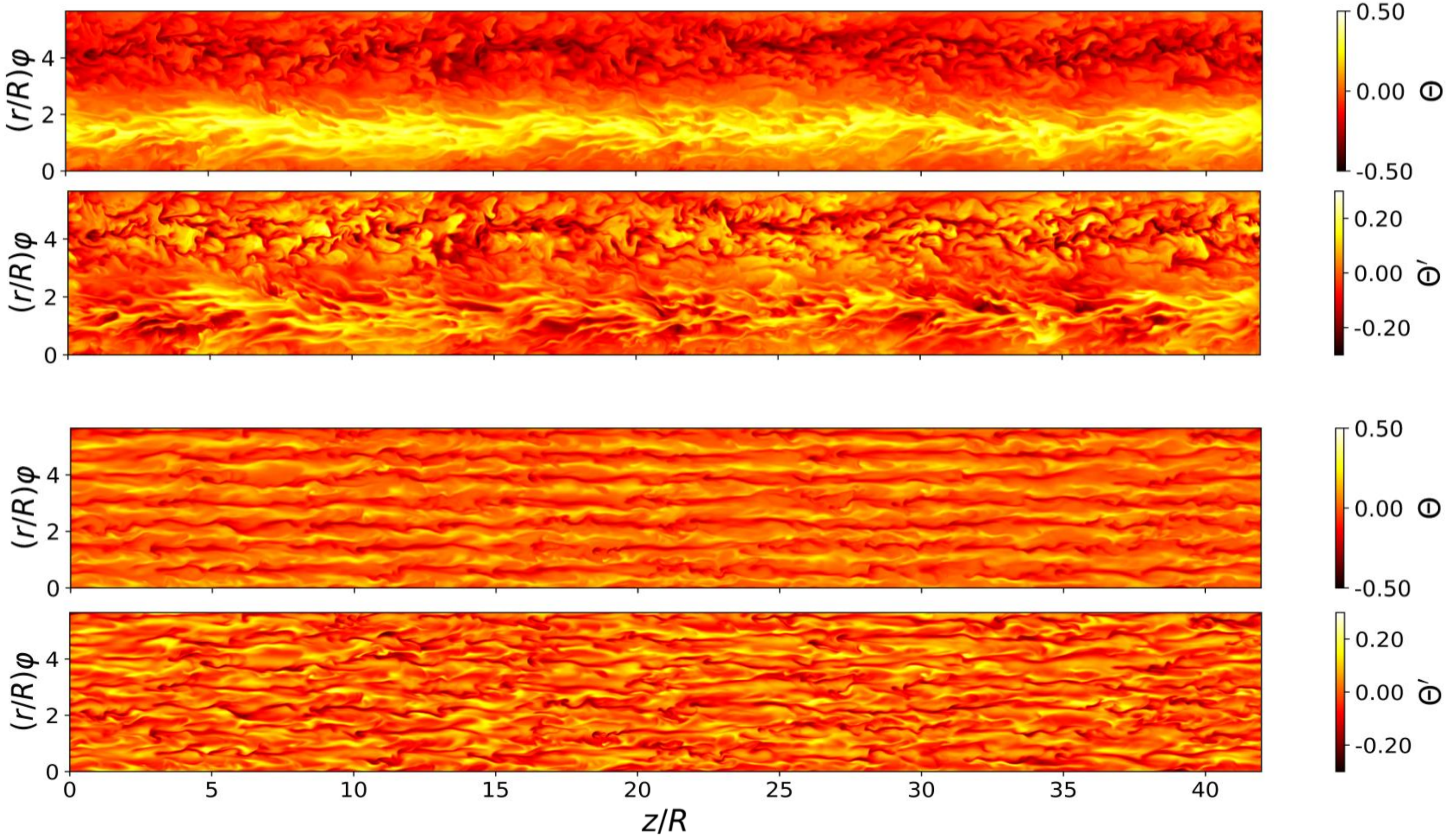


- Smaller thermal boundary layer and restriction of buoyancy force to the near-wall region.
- Streamwise turbulent heat flux is concentrated in the layer $5 < y^+ < 20$.
- Areas of radial turbulent heat flux only extend to the area in front of the colder and hotter wall sections.
- The turbulent heat flux is the smallest, where the velocity in streamwise direction is the biggest.

Instantanious Temperature Fields for Wall-Parallel Plane

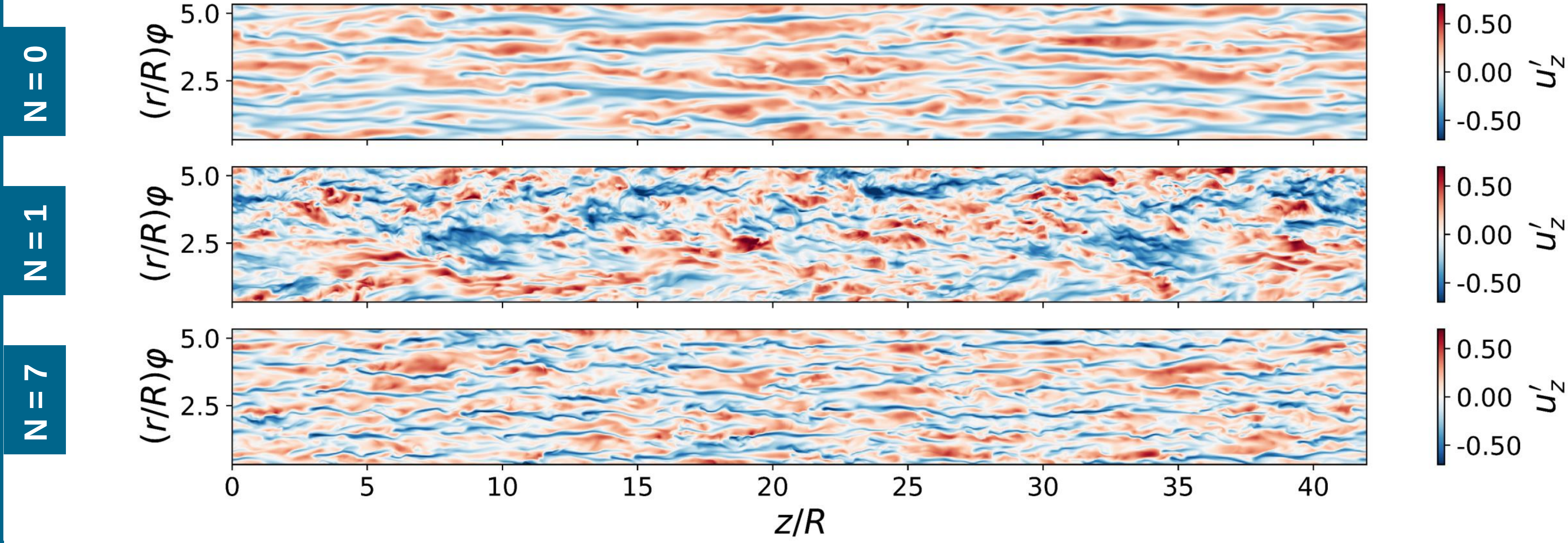
N = 1

N = 7



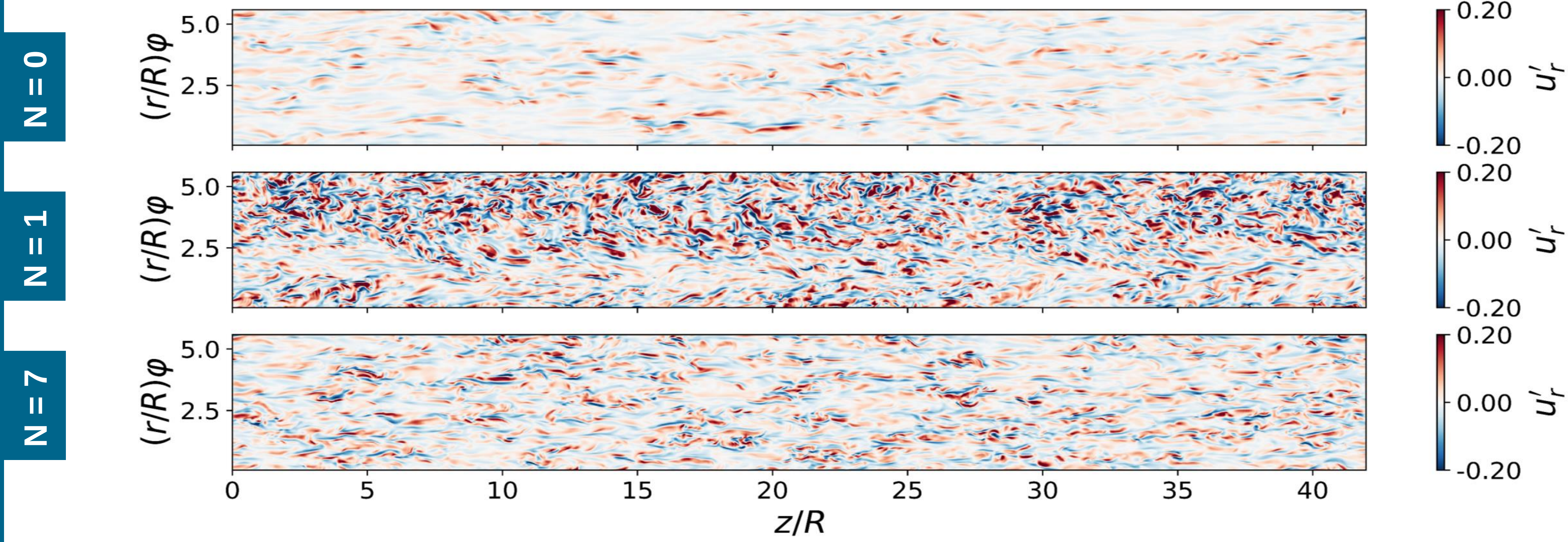
- Footprint of wall heating visible even at $y^+ = 15$, but smaller maximum temperatures for $N = 7$.
- For $N = 1$ the structure of the temperature fluctuations different in warmer and colder region.
- For $N = 7$ the temperature fluctuations are more ordered and elongated in flow direction.

Instantanious Streamwise Velocity Fluctuation Fields



- For $N = 0$ coherent structures of the flow extended and correlated regions can be seen.
- For $N = 1$ the streaks are less ordered and have wider circumferential and shorter streamwise length.
- For $N = 7$ the streamwise and circumferential length of the streaks decreases.
- Low-velocity streaks seem to be more prevalent in the colder regions, and their maximum intensity increases.

Instantanious Radial Velocity Fluctuation Fields



- Correlation of fast fluid moving towards the wall and slow fluid moving away from it is evident.
- For *N = 1* smaller, more intense and chaotic velocity fluctuations and clear difference between warmer and colder region.
- For *N = 7* the intensity of the fluctuations increases and they align with the temperature fluctuations.

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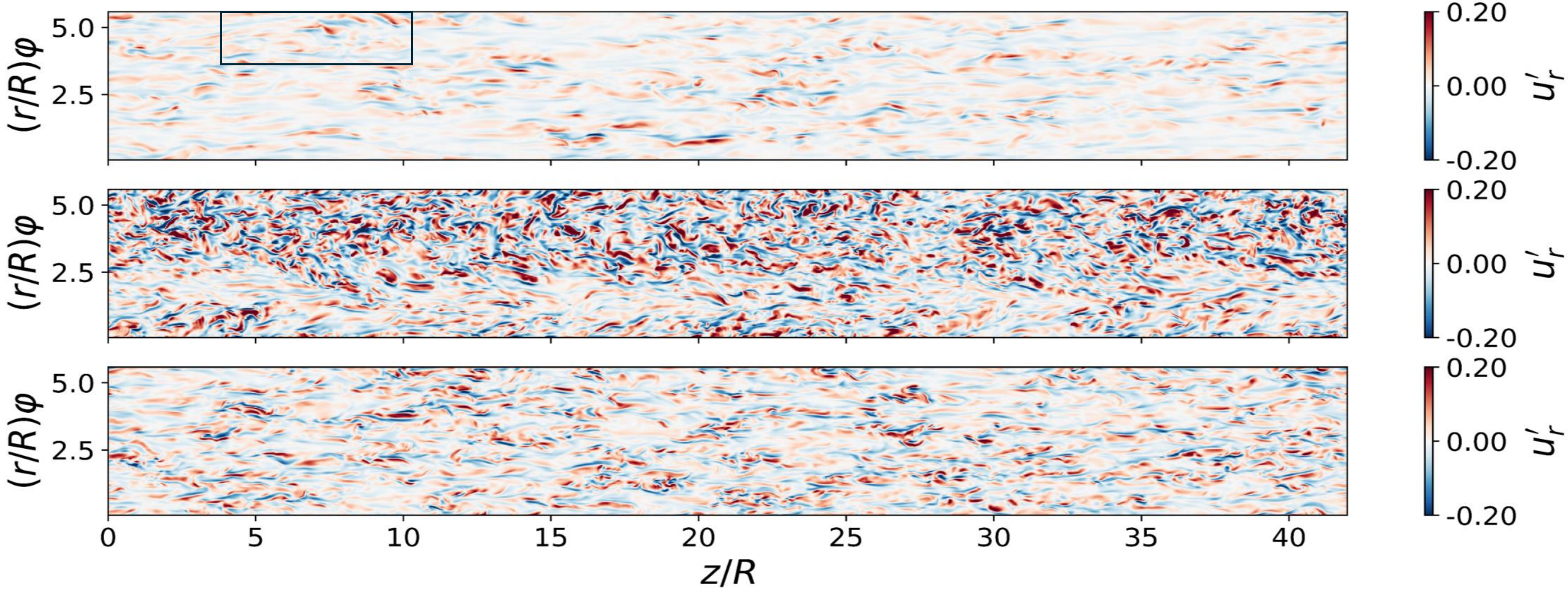

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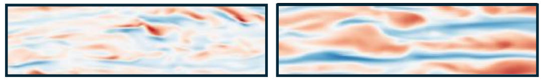

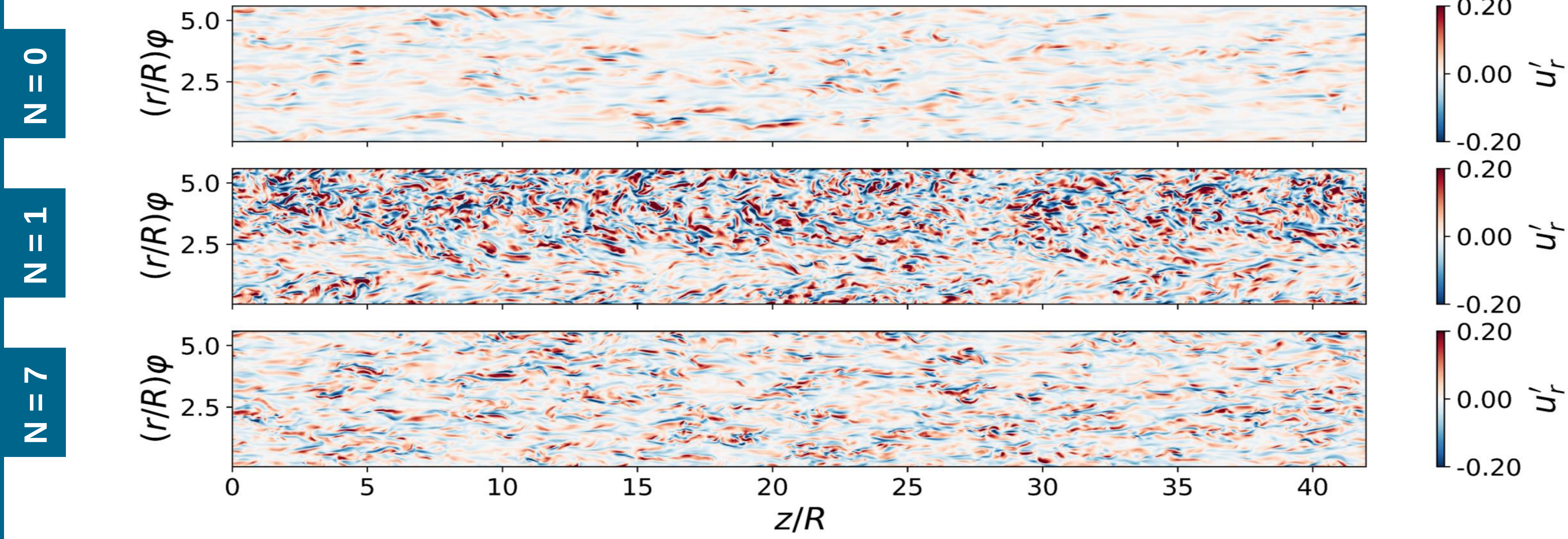

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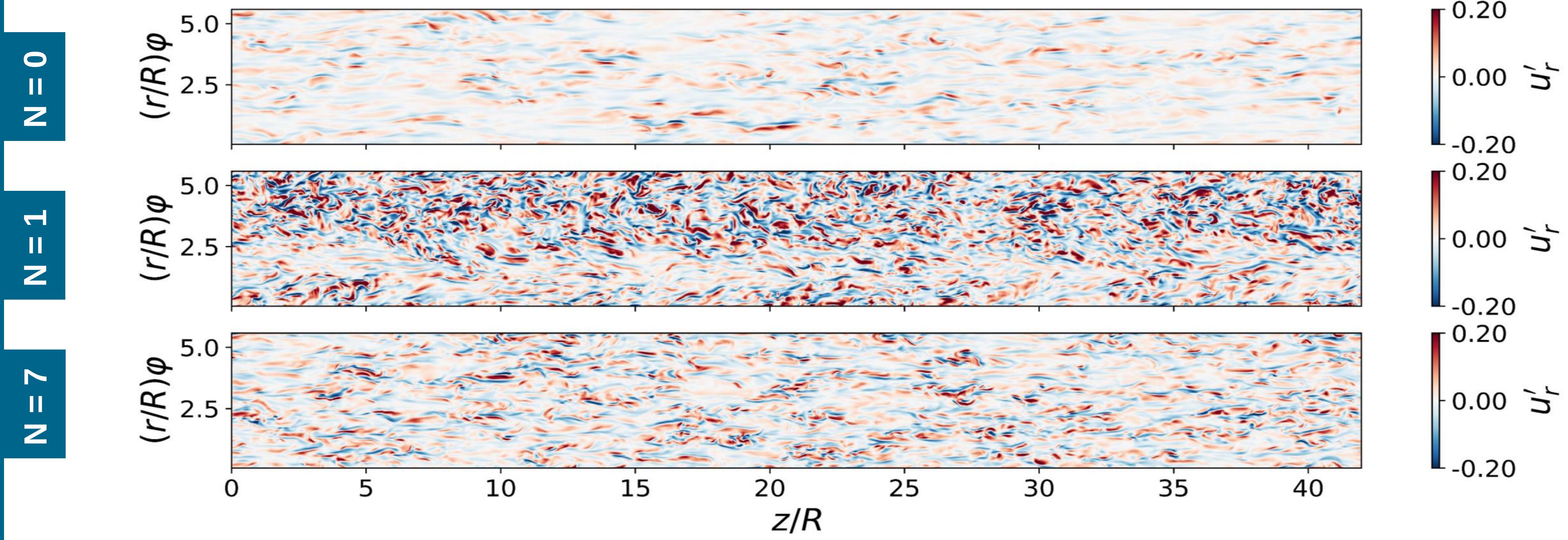

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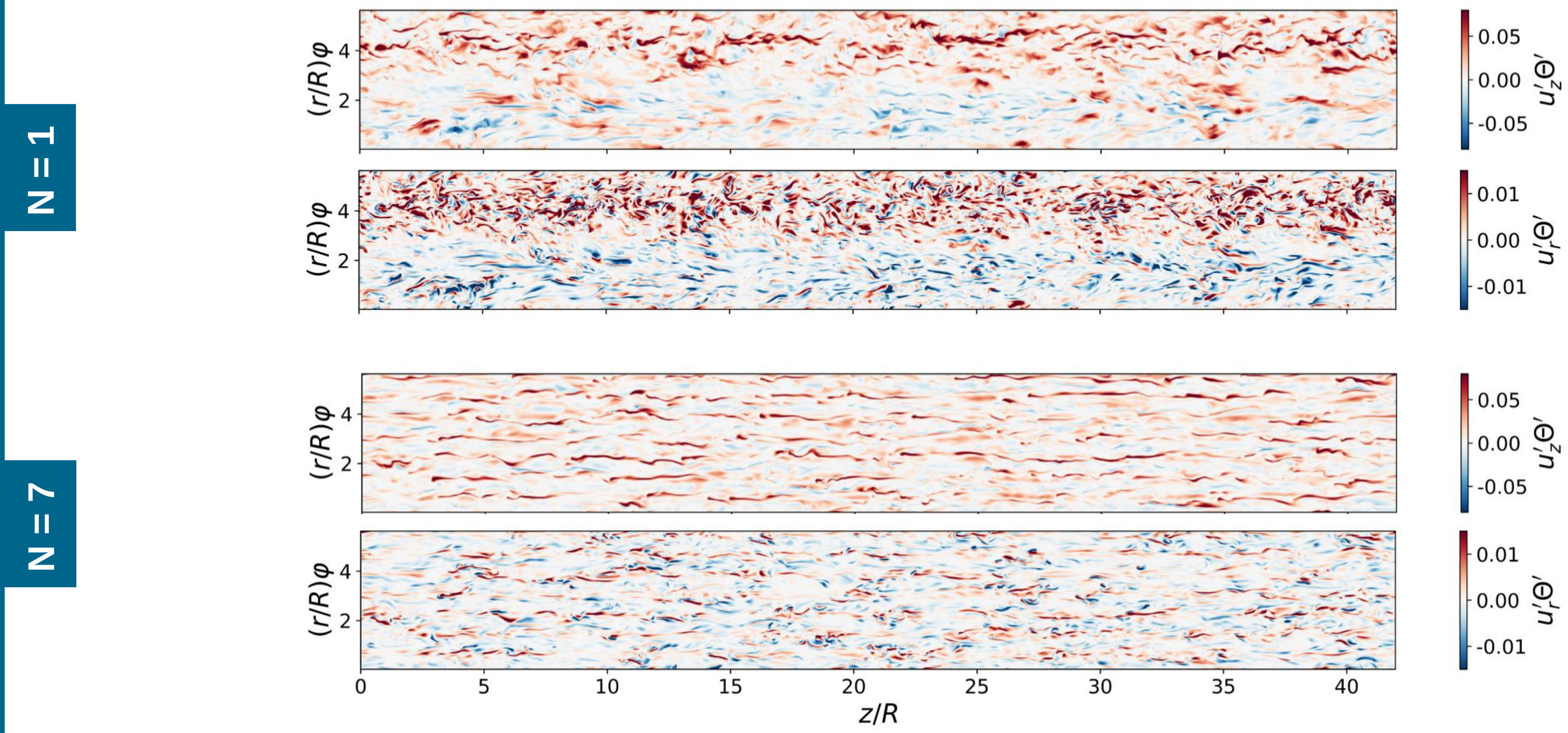
Instantanious Turbulent Heat Fluxes for Wall-Parallel Plane



- Low-velocity streaks are decalerated and high-velocity streaks are accelerated.
- For *N = 1* larger correlation between velocity and temperature fluctuations in colder region.
- For N = 7 the correlation between velocity and temperature is predominantly positive.
- The strongest turbulent heat fluxes occur for low-velocity streaks.

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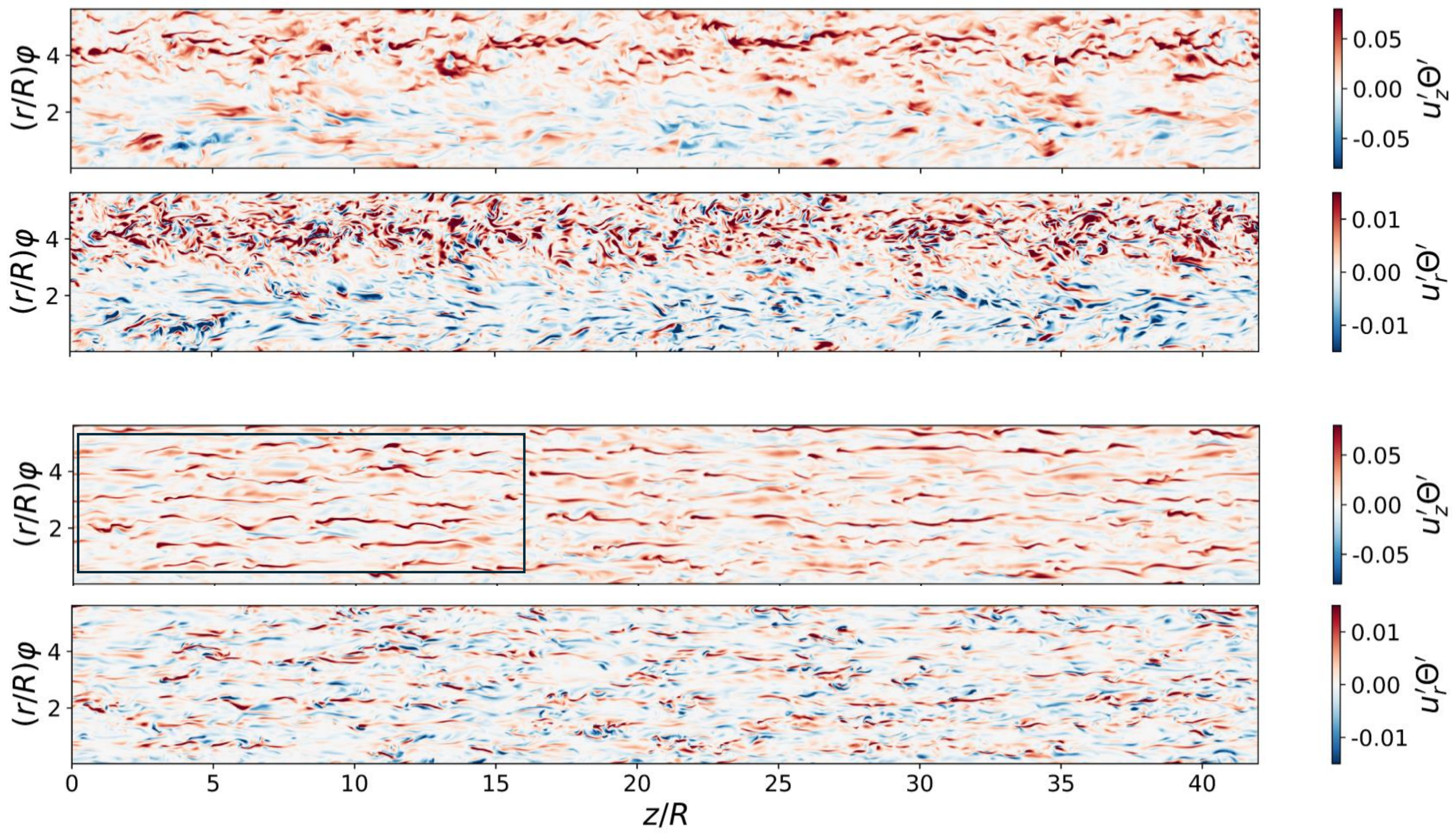

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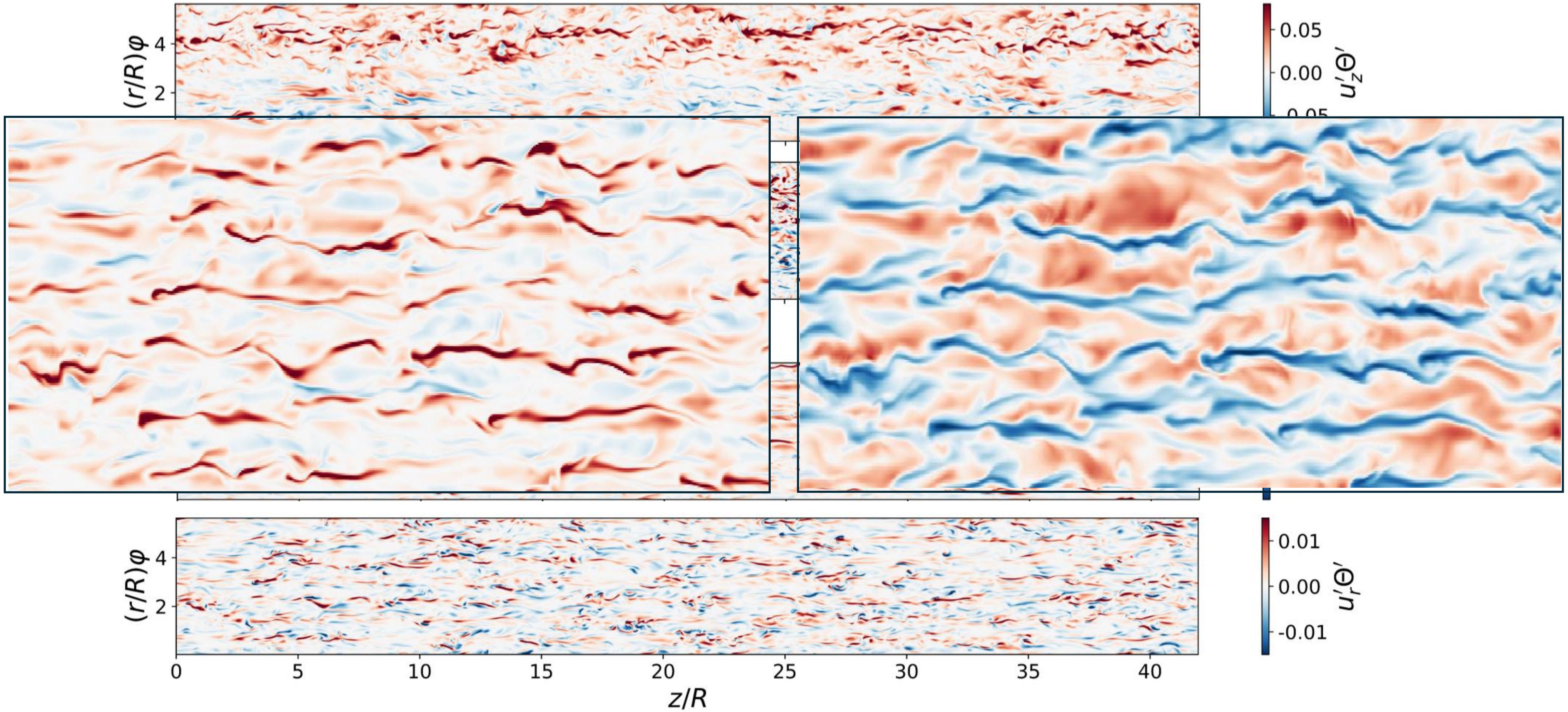

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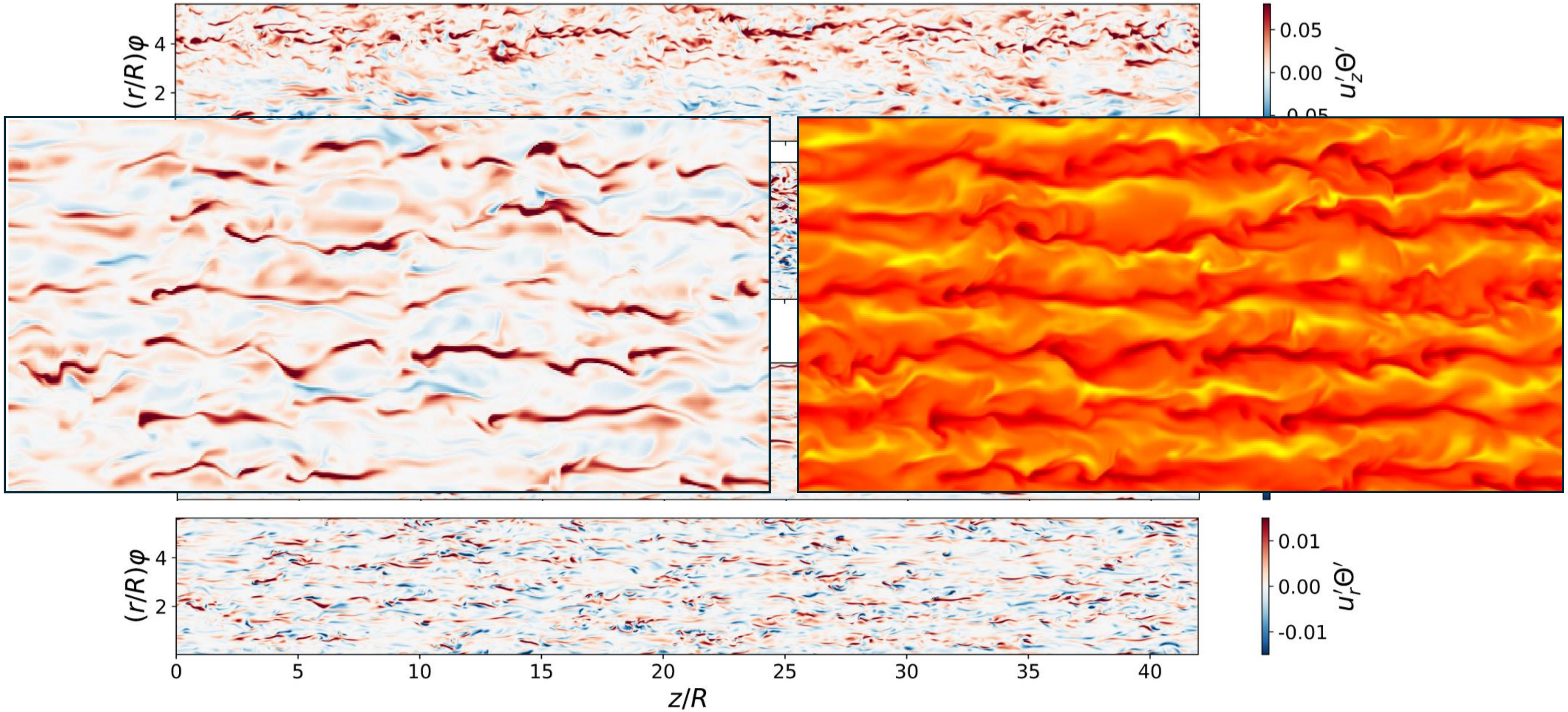

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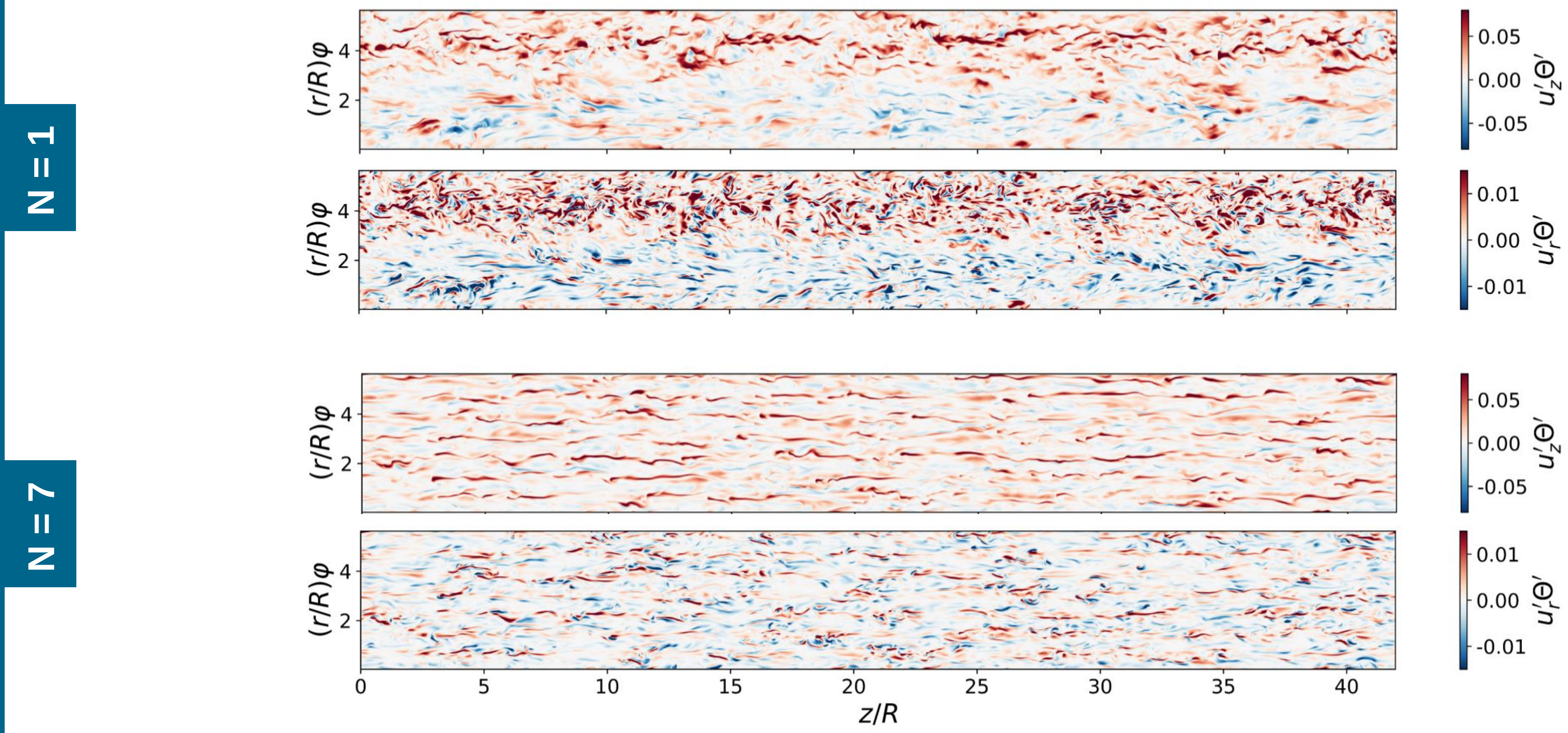

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Conclusions

- The buoyancy leads to a slowing down of the turbulent structures in the colder regions and an amplification of the low-velocity streaks.
- The buoyancy-induced acceleration in the warmer region reduces the radial heat flux.
- Heating with *N = 1* increases the turbulence in the colder and warmer region.
- Heating with *N = 7 results in a decrease in turbulence intensity in the heated region.*
- For *N = 7*, the velocity fluctuations correlate with the temperature fluctuations and the wall temperature.

Questions?

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