From fractal-generated turbulence to gravity currents: an overview of the versatility of Incompact3d

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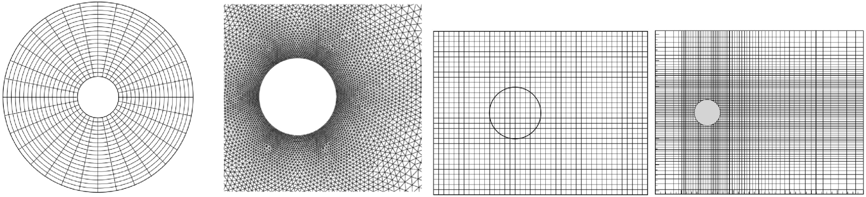
Thank you

- Eric Lamballais (Poitiers)
- Christos Vassilicos (London)
- Ning Li (NAG)
- Sylvain Lardeau, Rémi Gauthier, Thibault Dairay, Cédric Flageul, Philippe Parnaudeau, Véronique Fortuné, Jorge Silvestrini, Léandro Pinto, Luis Felipe

Cartesian grid: Pros and Cons



Pros

- Easy to generate
- Simplicity
- Cost
- Efficiency

Cons

- Cost
- Versatility
- Solid body ?

Solutions for Cons: Incompact3d

- High Performance Computing (by Ning Li)
- Numerical Dissipation (by Eric Lamballais)
- Customized Immersed Boundary Method

Applications

- Turbulent jet impinging on a heated plate (by Thibault Dairay)
- Fractal Generated Turbulence
- Fluidic Control of turbulent jet
- Gravity Currents

Overview

Customized Immersed Boundary Method

Incompressible Navier-Stokes equations

$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla p - \frac{1}{2}[\nabla(\mathbf{u} \otimes \mathbf{u}) + (\mathbf{u}.\nabla)\mathbf{u}] + \nu \Delta u$$

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

where $\mathbf{u}(\mathbf{x}, t)$ is the velocity, $p(\mathbf{x}, t)$ the pressure and ν the kinematic viscosity.

$$\mathbf{N}(\mathbf{u}) = \frac{1}{2}[\nabla.(\mathbf{u} \otimes \mathbf{u}) + (\mathbf{u}.\nabla)\mathbf{u}]$$

for the non-linear terms

$$\mathbf{L}(\mathbf{u}) = \nu \Delta u$$

for the viscous terms

$$\tilde{p}^{k+1} = \frac{1}{\Delta t} \int_{t^k}^{t^{k+1}} p \; dt$$

for the average pressure field

Customized Immersed Boundary Method

Fractional Step Method

$$
\begin{aligned}
\frac{\mathbf{u}^* - \mathbf{u}^k}{\Delta t} &= \frac{23}{12}\left[\mathbf{L}(\mathbf{u}^k) - \mathbf{N}(\mathbf{u}^k)\right] - \frac{16}{12}\left[\mathbf{L}(\mathbf{u}^{k-1}) - \mathbf{N}(\mathbf{u}^{k-1})\right] + \\
&\quad \frac{5}{12}\left[\mathbf{L}(\mathbf{u}^{k-2}) - \mathbf{N}(\mathbf{u}^{k-2})\right] - \nabla \tilde{p}^k \\
\frac{\mathbf{u}^* - \mathbf{u}^{**}}{\Delta t} &= \nabla \tilde{p}^k \\
\frac{\mathbf{u}^{k+1} - \mathbf{u}^{**}}{\Delta t} &= -\nabla \tilde{p}^{k+1}
\end{aligned}
$$

Customized Immersed Boundary Method

Imposition of boundary conditions on $\mathbf{u}^*$

Impossible to impose on $\mathbf{u}^{k+1}$ because of incompressibility

Solution:

Example with a channel flow

$$\mathbf{u}^*_{wall} = 0$$

$$\mathbf{u}^{k+1}_{wall} = \mathbf{u}^*_{wall} - \nabla \tilde{p}^{k+1}$$

$$\mathbf{u}^{k+1}_{wall} = -\nabla \tilde{p}^{k+1} \neq 0$$

$$\mathbf{u}^*_{wall} = \nabla \tilde{p}^{k}$$

$$\mathbf{u}^{k+1}_{wall} = \mathbf{u}^*_{wall} - \nabla \tilde{p}^{k+1}$$

$$\mathbf{u}^{k+1}_{wall} = \nabla \tilde{p}^{k} - \nabla \tilde{p}^{k+1} \approx 0$$

Customized Immersed Boundary Method

Three different strategies

$\mathbf{u}^* = 0$

- Easy to implement
- Discontinuities on the velocity field
- Boundaries of solid regions are mesh dependant

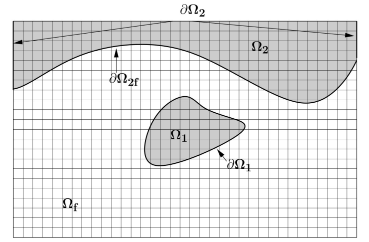
Mirror flow

- Easy to implement with basic geometries (although...)
- Almost impossible with complex geometries
- More accurate boundaries for solid regions
- Not compatible with 2D domain decomposition

Alternating direction forcing strategy

- Based on Lagrangian Polynomial as an extension of solution in solid regions
- Easy to implement with complex geometries
- Compatible with 2D domain decomposition

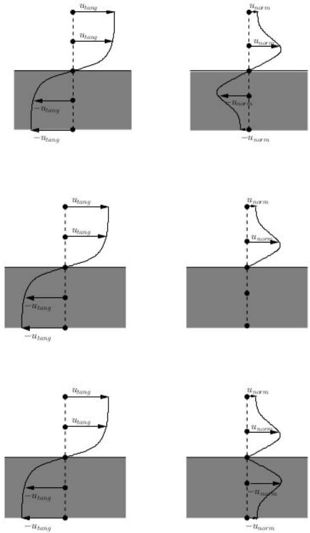
Direct forcing



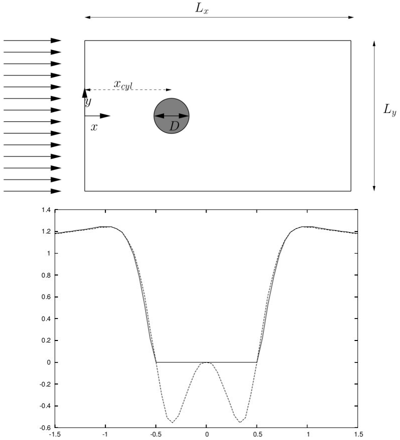
- Forcing on $\mathbf{u}^*$
- use of ε with:
  $\varepsilon = 1$ in solid regions
  $\varepsilon = 0$ in fluid regions

$$\nabla \cdot \nabla \tilde{p}^{k+1} = \frac{\nabla \cdot (1-\varepsilon)\mathbf{u}^*}{\Delta t}$$

Mirror Flow

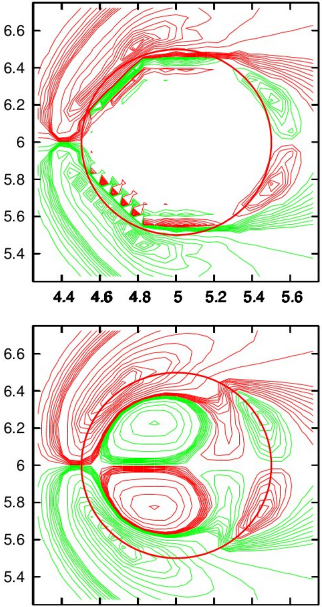


u_{tang}
$-u_{tang}$
u_{norm}
$-u_{norm}$



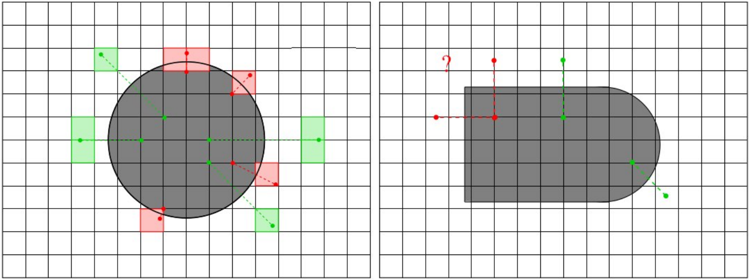
L_x
L_y
x_{cyl}
y
x
D
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-1.5
-1
-0.5
0
0.5
1
1.5

Mirror Flow



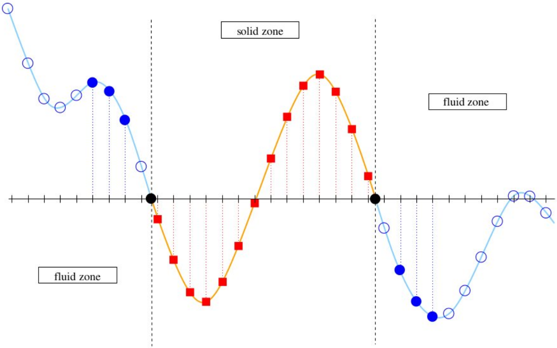
- Reduction of oscillations near the geometry
- Improvement of the solution
- Quantitative and qualitative comparison with reference solution now possible
- Gautier, Biau, Lamballais, 2013, Computers & Fluids
- “exact solution” obtained with spectral code on Cylindrical mesh with accurate BC in far field
- Spectral interpolations so solution is known everywhere

But...

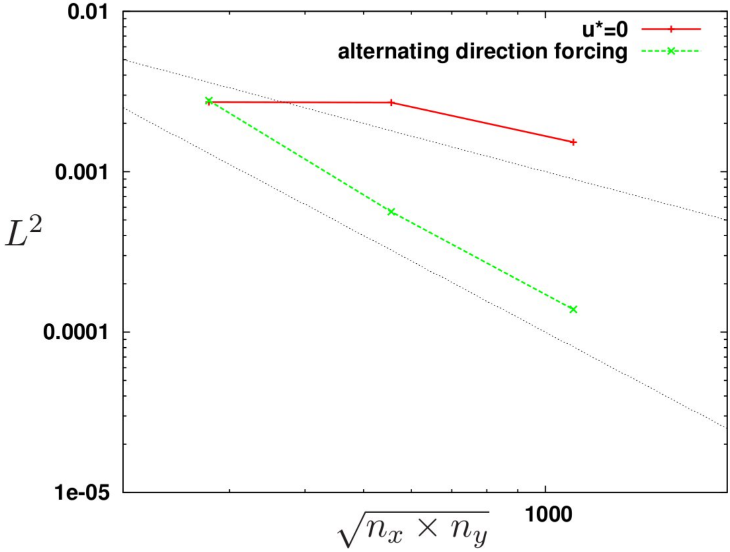


Alternating direction forcing strategy

- Strategy based on a 1D reconstruction using Lagrangian polynomial
- No forcing on velocity, but modification of differenciation operators
- Pre-processing on a very fine mesh to find the geometries
- Compatible with 2D domain decomposition



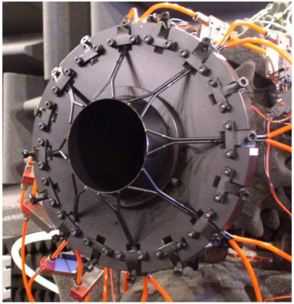
Alternating direction forcing strategy

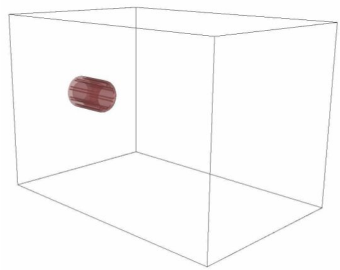


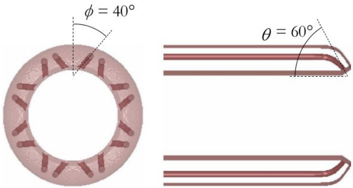
But...

- Solid and fluid regions cannot be too small
- 2^{nd} order convergence for velocity (like everyone else!) BUT 6^{th} order schemes are still worth it
- No control of pressure field $\Rightarrow$ 1^{st} order convergence only
- Mass conservation problem at marginal resolution
- Difference with $\mathbf{u}^* = 0$ forcing at high resolution are negligible (Benchmark with NACA0012 2D simulations for lift and drag)

Jet control with microjets







Validation with experiments

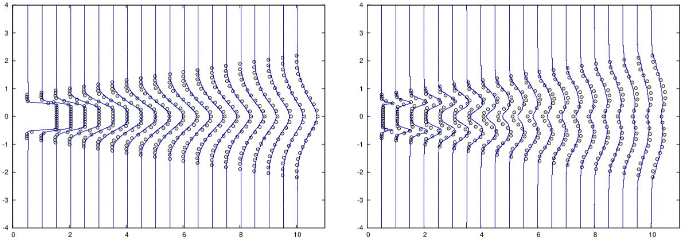
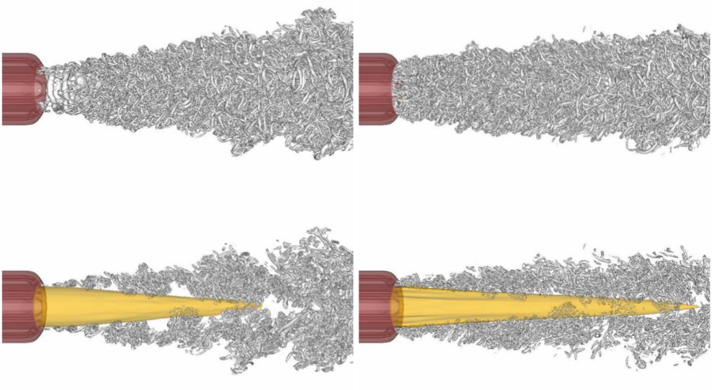
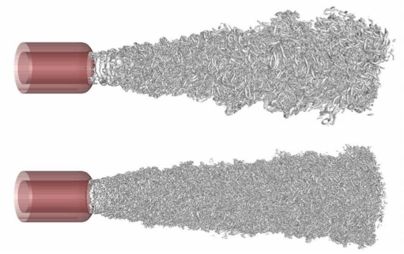


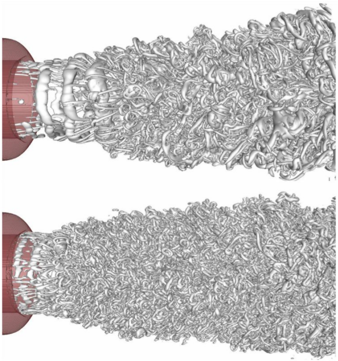
Figure 7. Profiles for the mean streamwise velocity $\langle u \rangle (x_c, y)$ (left) and its associated fluctuating component $\sqrt{\langle u'u' \rangle}(x_c, y)$ (right) for $x_c/D = i/2$ with $i = 1, ..., 20$. Comparison between our DNS (lines) and the experimental data of Maury et al. (2012) (symbols).

Comparison natural/forced cases



Same Reynolds as experiments





Why do we put the control device in the domain?

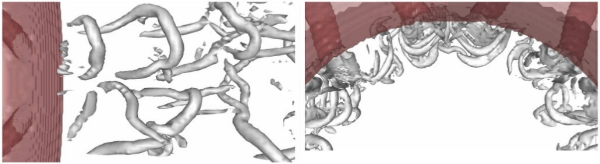


Figure 14. Isosurface for the Q-criterion where the more intense horseshoe structures (with the number 1 in figure 15) can be seen. The left visualisation is enlarge near a pair of converging microjets and the right one is a vue from the inside of the main jet.

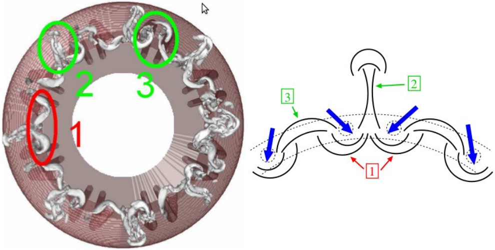
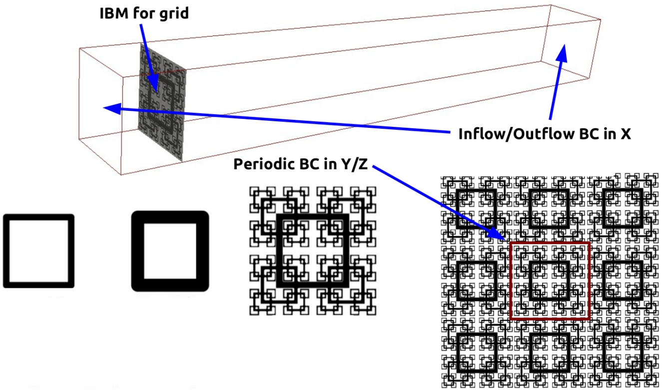


Figure 15. Identification of the three coherent structures in the near-nozzle region for $0 < x/D < 0.5$ with a Q-criterion visualisation (left) and a schematic sketch behind 4 microjets (right).

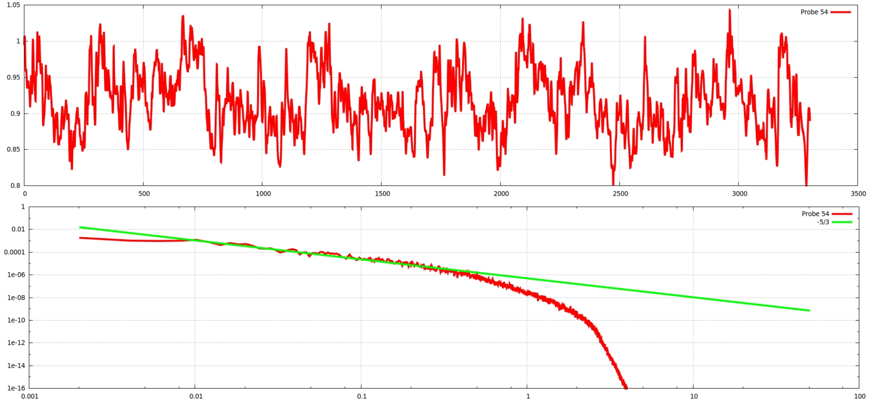
Fractal Generated Turbulence



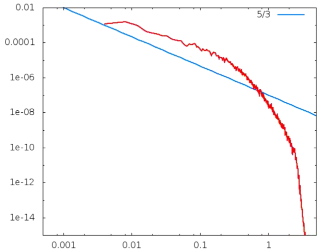
Numerical Wind Tunnel Facility

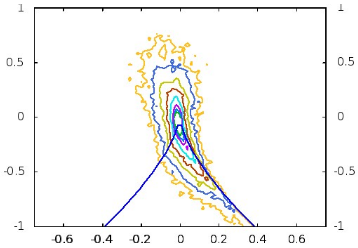
-Virtual probes ⇒ Collection data of in time
-Virtual cameras ⇒ visualizations/animations, collection of data in space
-Virtual microphones ⇒ Acoustic prediction using analogies

Fractal Generated Turbulence

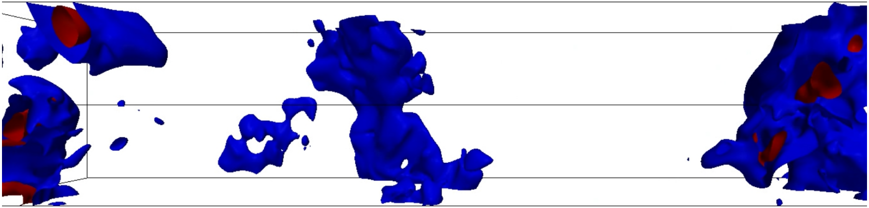


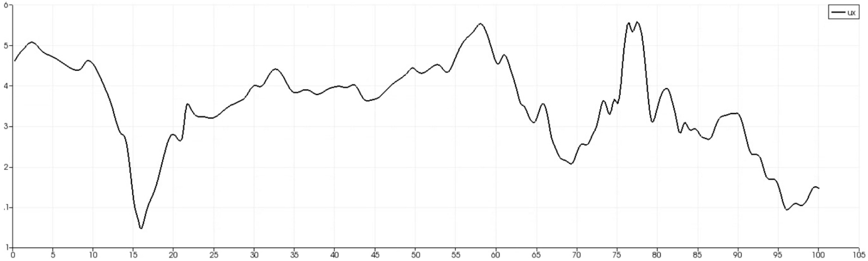
Fractal Generated Turbulence



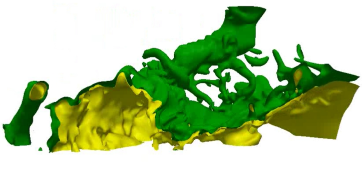


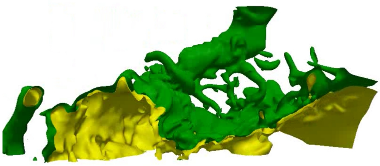
Fractal Generated Turbulence



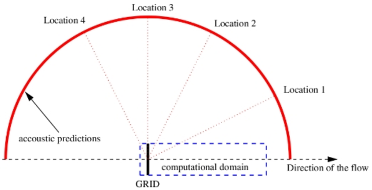


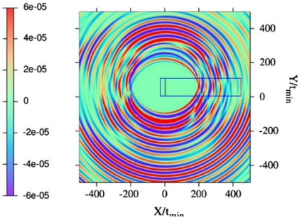
Fractal Generated Turbulence

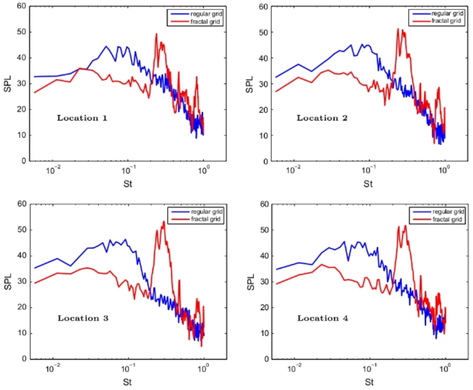




Fractal Generated Turbulence







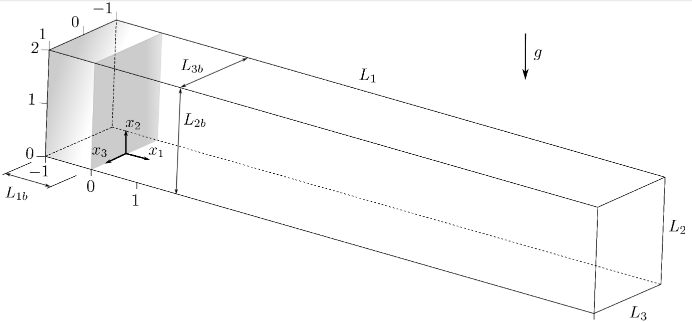
Gravity Currents

Incompressible Navier-Stokes equations + Transport equation

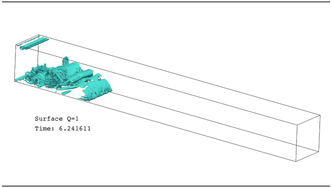
$$\frac{\partial \underline{\mathbf{u}}}{\partial t} + \underline{\mathbf{u}} \cdot \nabla \underline{\mathbf{u}} = \frac{2}{Re} \nabla \cdot \underline{\underline{\mathbf{s}}} - \nabla p + c\, \underline{\mathbf{e}}^g,$$

$$\nabla \cdot \underline{\mathbf{u}} = 0,$$

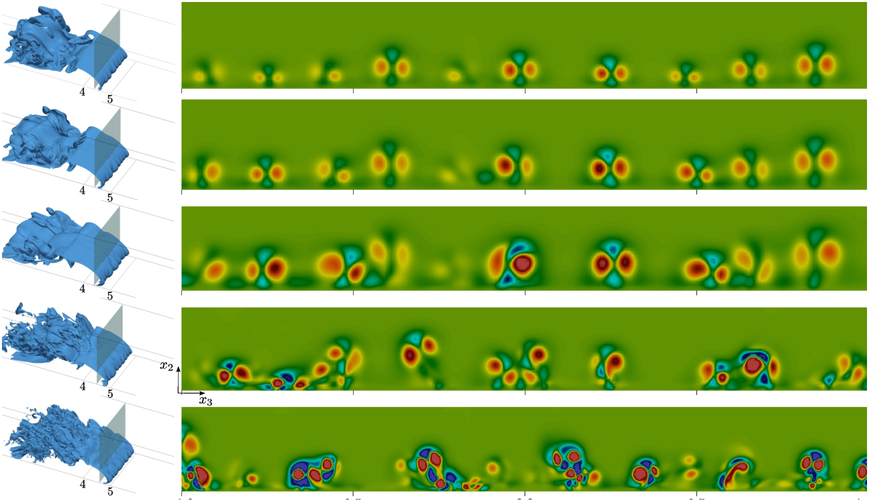
$$\frac{\partial c}{\partial t} + (\underline{\mathbf{u}} + u_s\, \underline{\mathbf{e}}^g) \cdot \nabla c = \frac{1}{ScRe} \nabla^2 c,$$



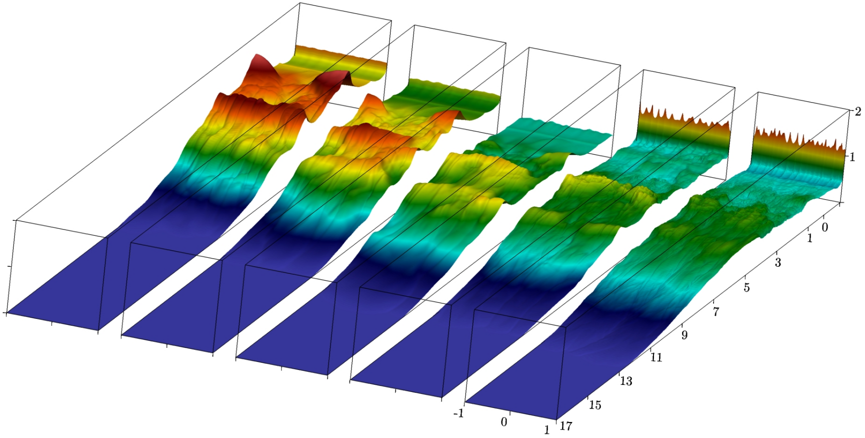
Gravity Currents



Gravity Currents



Gravity Currents



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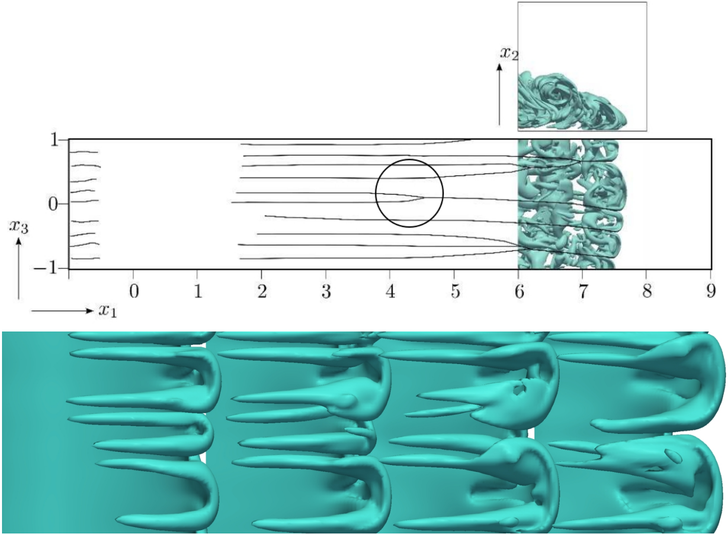

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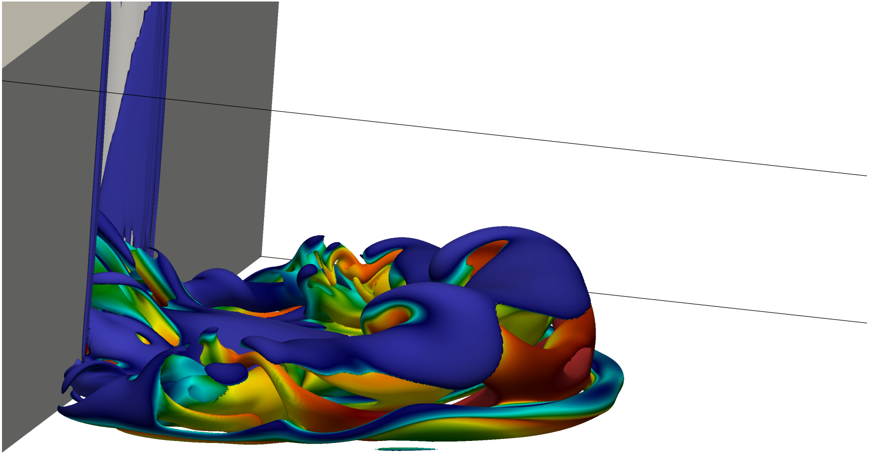

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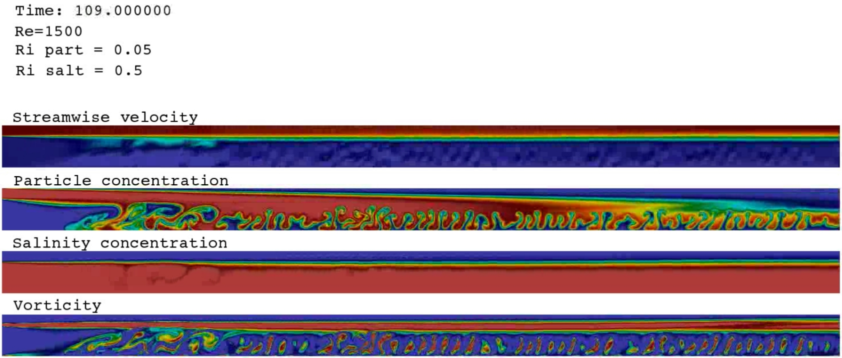

The End