

Themes 2019

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Gap-leaping and intruding western boundary currents investigated with the large Coriolis-LEGI rotating platform*

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Henk Dijkstra ⁽³⁾, Joël Sommeria ⁽²⁾

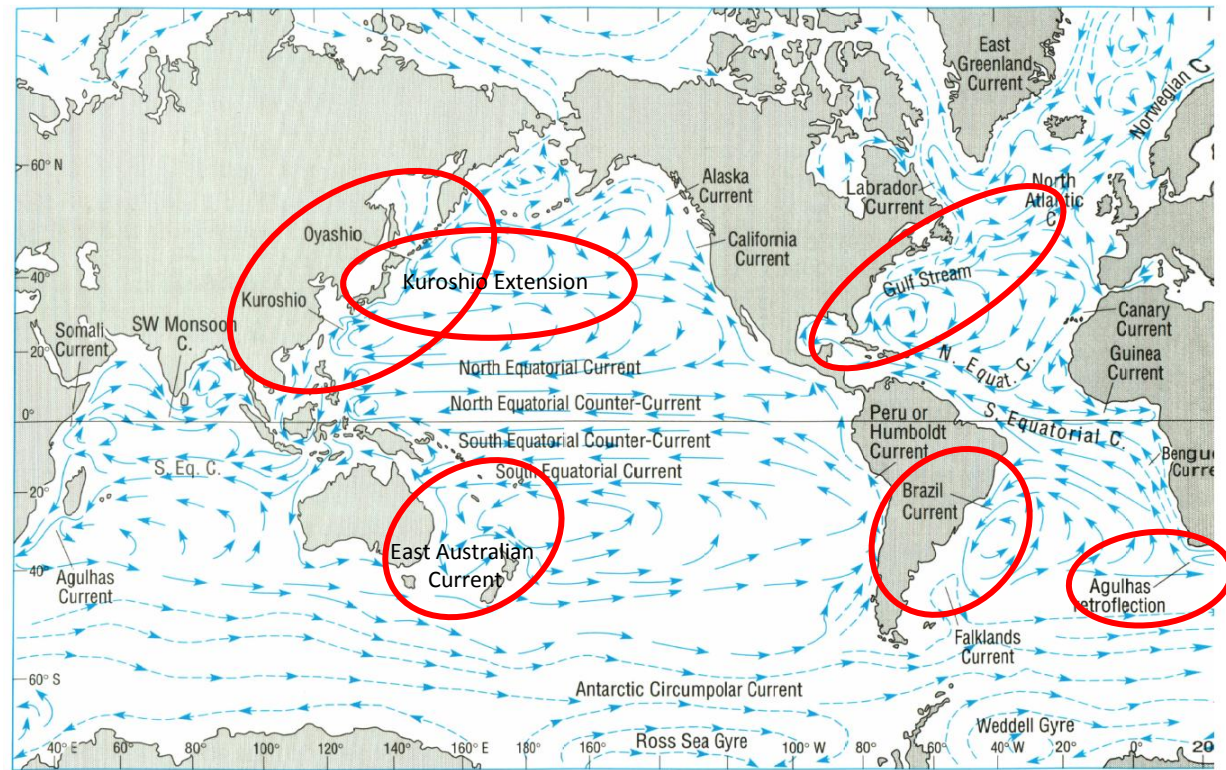
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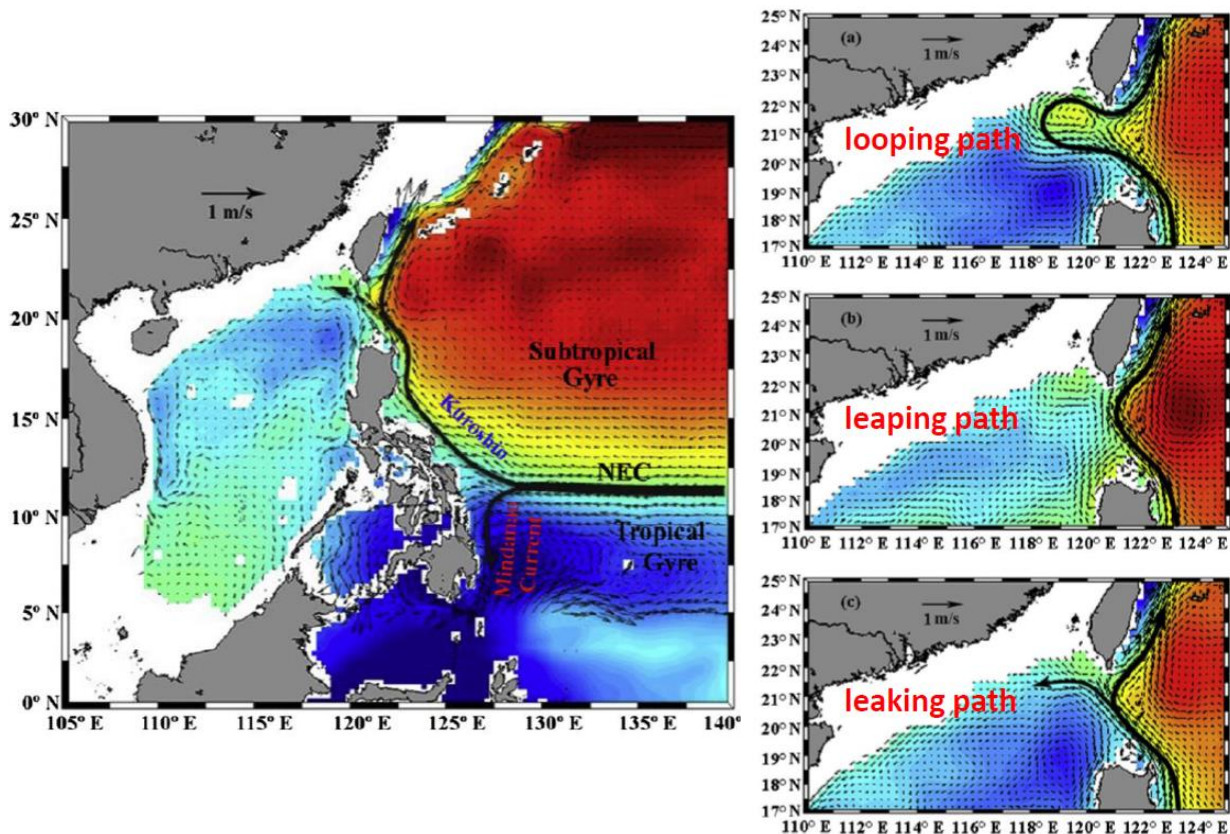
* The project **19GAPWEBS** has been carried out in June-July 2019 and has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 654110-**HYDRALAB+**

Western boundary currents (WBCs), such as, for example, the **Kuroshio** and the **Gulf Stream**, are very intense currents flowing along the western boundaries of the oceans. WBCs -and their respective extensions- have an important effect on climate because of their huge heat transports, the corresponding air-sea interactions and the role they play in sustaining the global conveyor belt.



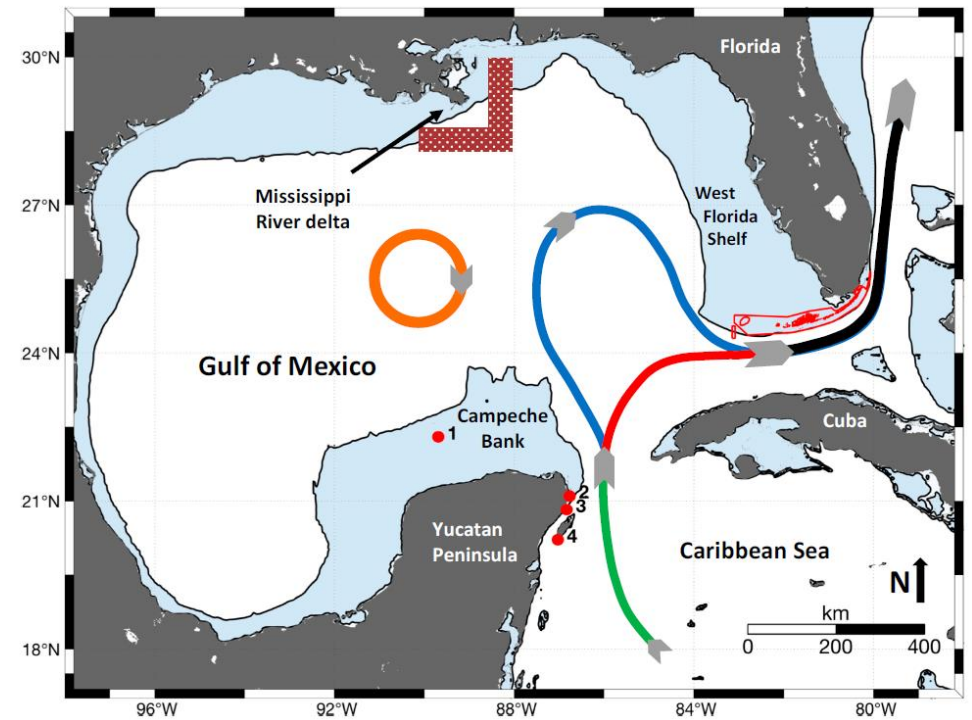
One of the most interesting and intriguing WBC phenomena is the **interaction of the jet with a lateral gap**

The **Kuroshio** carrying the northwestern Pacific water intrudes partially into the SCS through the Luzon Strait, significantly affecting the hydrology, circulation and mixing in the SCS



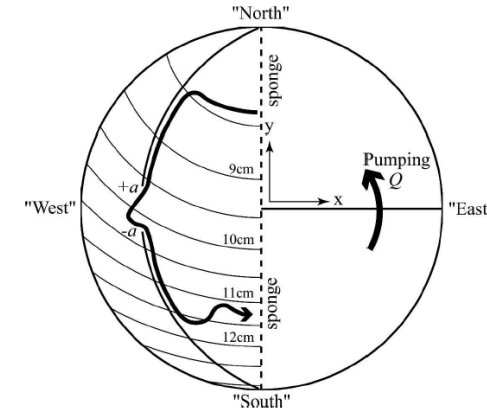
Nan et al. (2011; 2015)

The **Gulf of Mexico Loop Current** enters the Gulf of Mexico as the Yucatan Current (green) and exits through the Florida Straits (black). The Loop Current can assume two different states: a retracted state (red) and an extended state (blue)

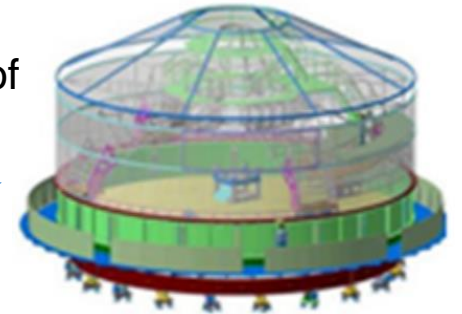


Otis et al. (2019)

Laboratory experiments aimed at investigating WBCs leaping across gaps were performed in a cylindrical tank on a 1-meter rotating table by Sheremet & Kuehl (2007)

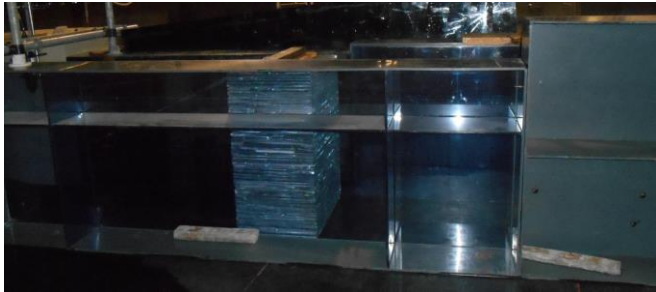
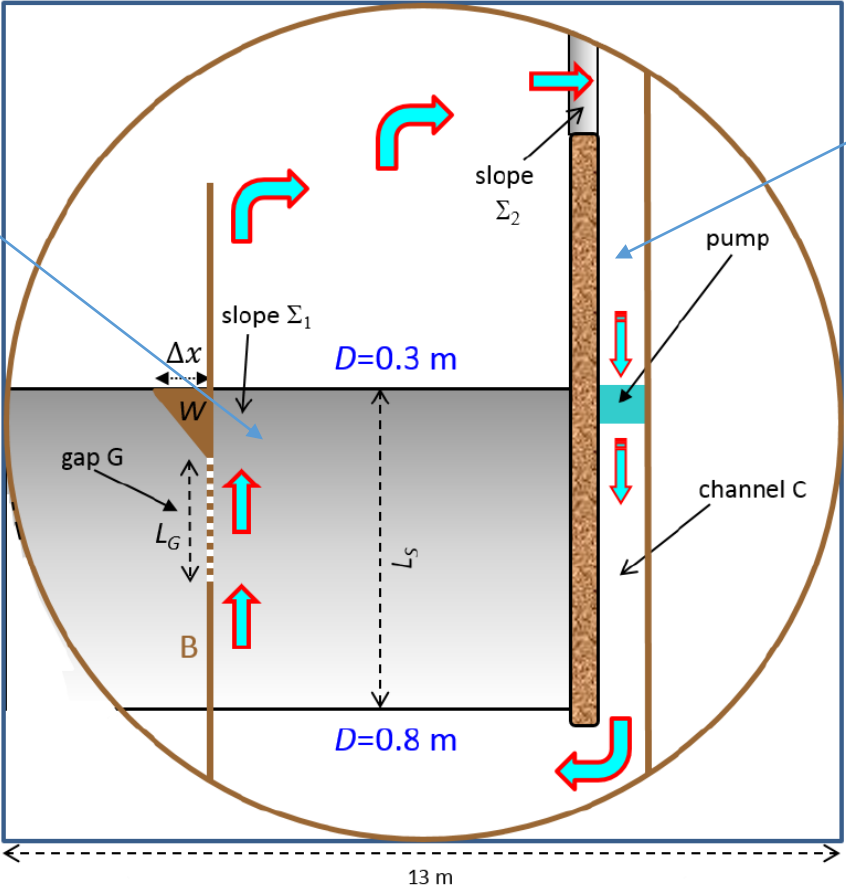
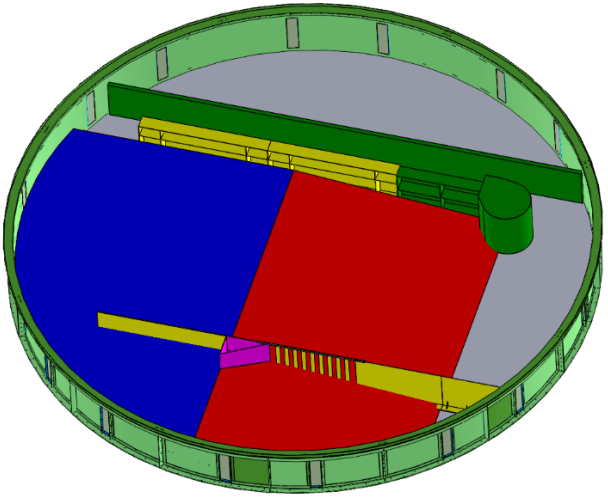
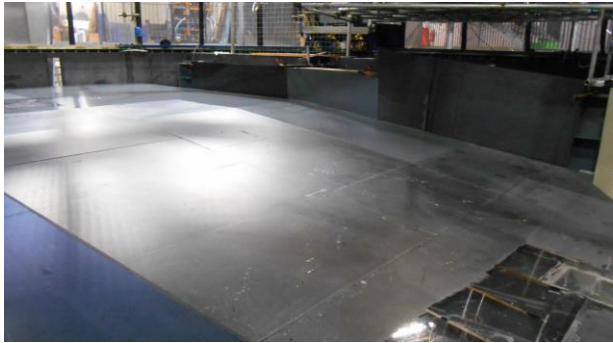


The great relevance of the problem calls for **larger scale simulations** and the investigation of **inertial regimes that characterize ocean dynamics, with little influence of viscosity**. This requires the use of the **13-m diameter Coriolis-LEGI rotating platform**

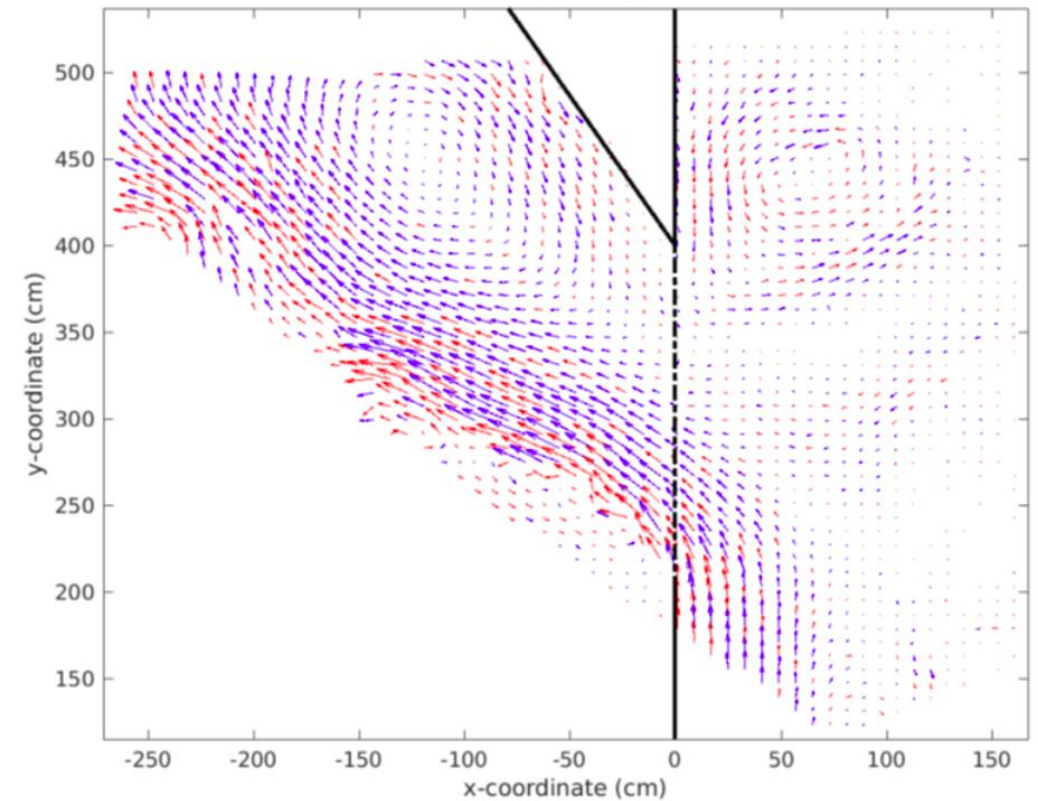
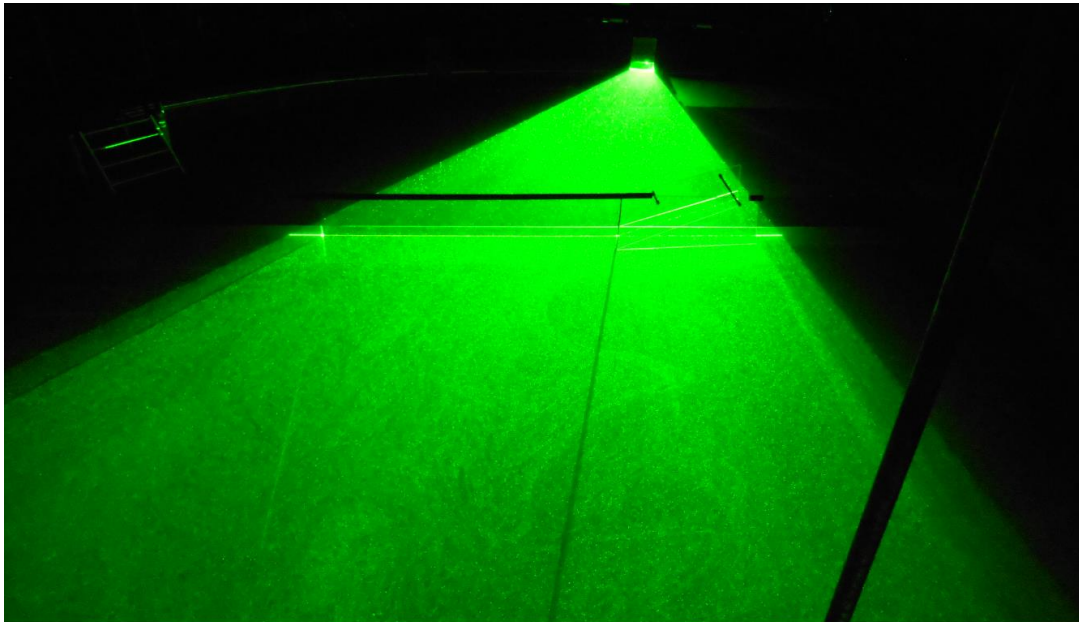


This has motivated the **Hydralab+ GAPWEBS** project, which is based on a substantial extension of previous experiments performed with the old 13-m diameter rotating platform in Grenoble (Pierini et al. 2002) and with the 5-m diameter rotating platform in Trondheim (Pierini et al. 2008; 2011)

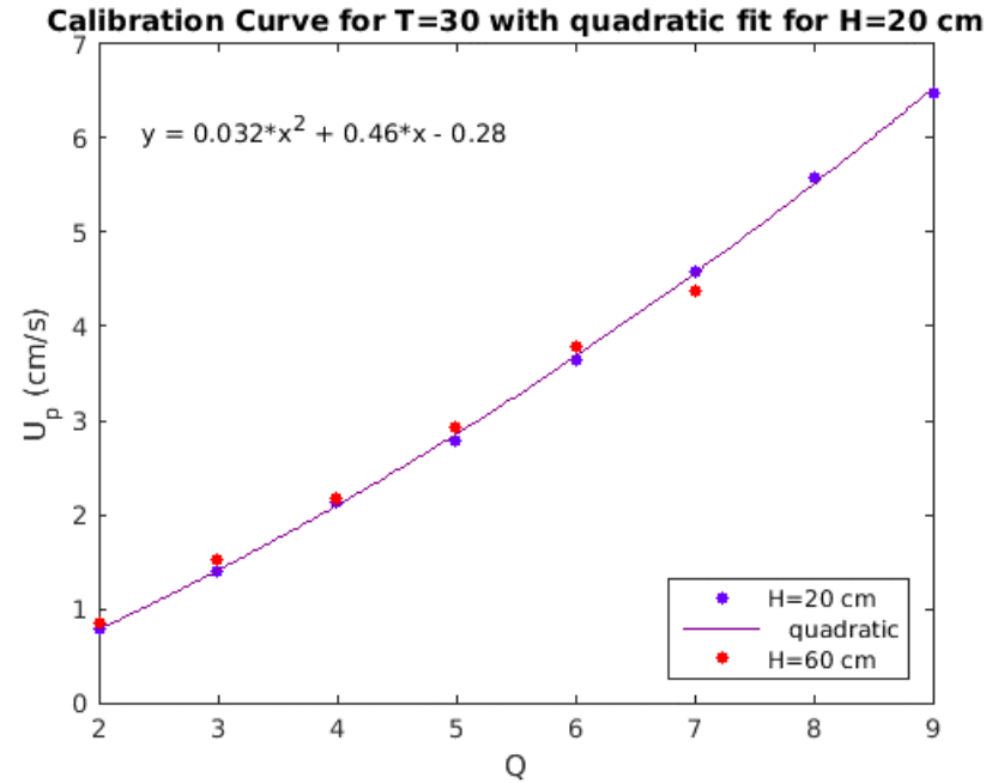
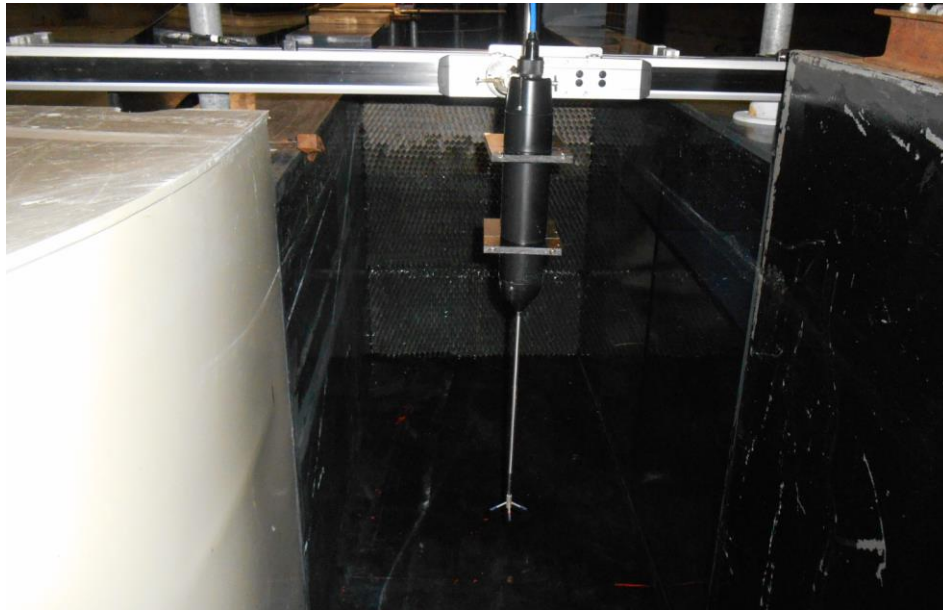
A pumping system located in a channel produces a current that, following the lateral boundaries, generates a virtually **unsheared flow at the entrance of a bottom slope**. This provides the **topographic beta-effect** necessary for the intensification.



Particle Imaging Velocimetry (PIV) is used for flow visualization, where tracer particles are embedded in the fluid allowing for instantaneous velocity measurements of the fluid. Depending on the setup of the experiment, 1-4 of the cameras are used to capture images in different locations in the 13 mm rotating tank.



An **Acoustic Doppler Velocimetry probe** located in the end of the channel, mounted on a traverse, measures the velocity of the current at different points across the width of the channel during each experiments.



Scaling:

$$u\nabla^2 v - v\nabla^2 u + \beta v \cong (A_H \nabla^2 - r)(v_x - u_y)$$

$$\varepsilon(u'v'_{x'x'} - v'u'_{x'x'}) + v' \cong E v'_{x'x'x'} - B v'_{x'}$$

The dimensionless parameters ε , E , and B measuring the importance of nonlinearities and lateral and bottom friction are given by

$$\varepsilon = \frac{U}{\beta l^2} = \left(\frac{\delta_I}{l}\right)^2; \quad E = \frac{A_H}{\beta l^3} = \left(\frac{\delta_M}{l}\right)^3; \quad B = \frac{r}{\beta l} = \frac{\delta_S}{l},$$

$$\delta_I = \left(\frac{U}{\beta}\right)^{1/2}; \quad \delta_M = \left(\frac{A_H}{\beta}\right)^{1/3}; \quad \delta_S = \frac{\delta_E f_0}{2D\beta}; \quad \delta_E = \left(\frac{2A_v}{f_0}\right)^{1/2}$$

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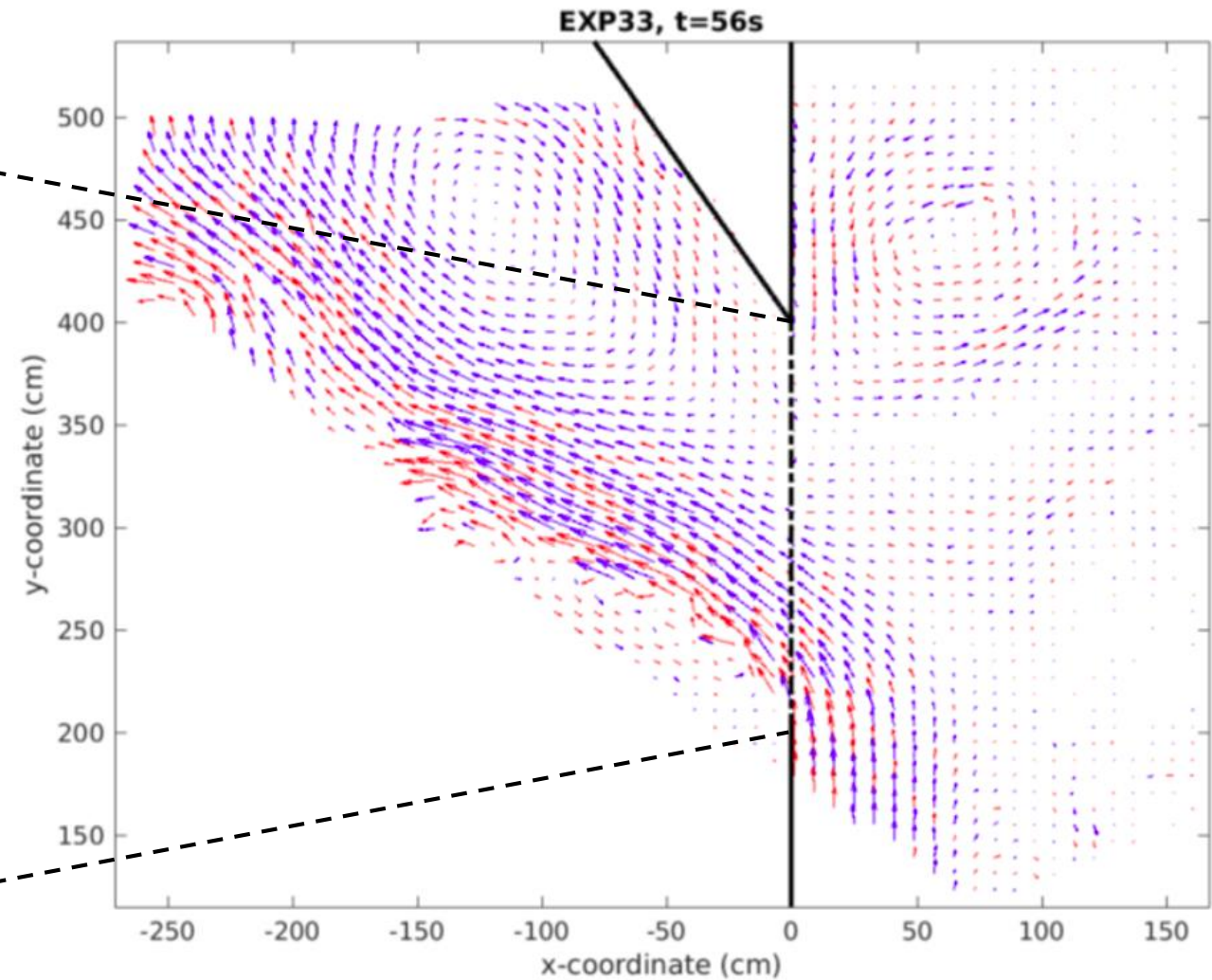
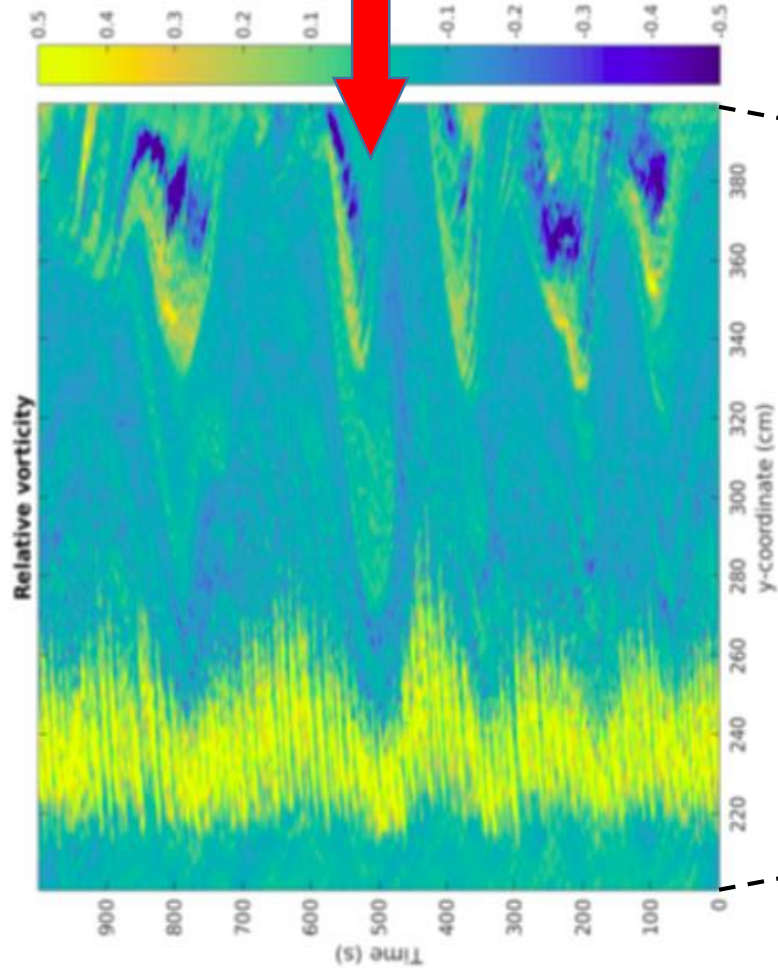
Many (92) experiments have been carried out by varying: **rotation period**, **pump intensity**, **gap width** and **geometry** (experiments with an island in the gap and with a wedge-shaped continent have also been performed)

Notation	Definition	Unit	Values	Remarks
T	rotation period	s	30,60	
Q	power pump		1 - 8	This is the intensity as appearing in the pump power variator.
L_G	gap width	m	0 - 2	
x_0	gap position	m	0 - 0.7	x_0 is the distance (positive southward) between the northernmost limit of the gap and the beginning of the triangle
I_n	number of islands	cm	0 - 5	
I_w	island width	m	0.1-0.5	Each elementary island has a width $I_w=0.1$ m; wider islands have been obtained by using more elementary islands

Several dynamical regimes have been identified for each geometry, corresponding to **partial leaping**, **leaking** or **deep looping** inside the gap. In all cases, nonlinear **intrinsic chaotic fluctuations** emerge under our steady forcing

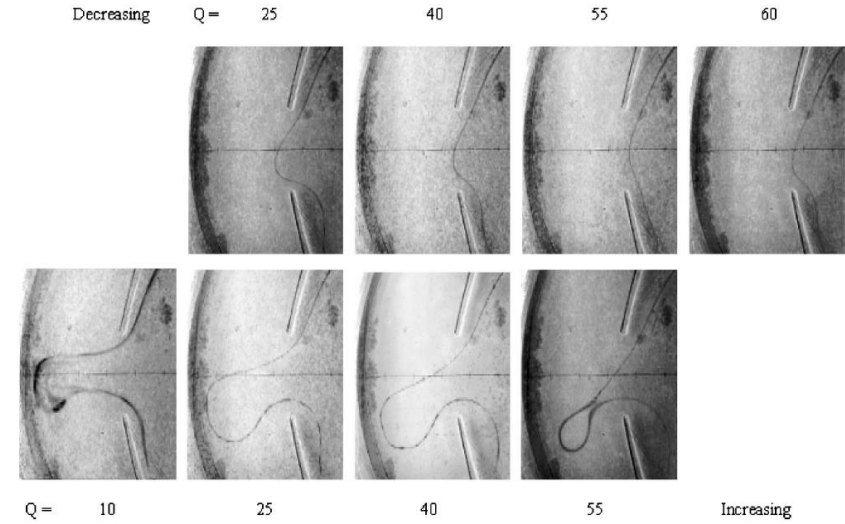
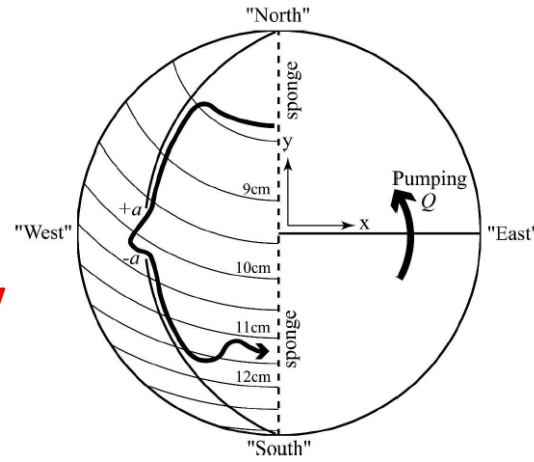
These are
**intrinsic chaotic
self-sustained oscillations**

2 m-gap / no islands
 $T = 60 \text{ s}; Q = 6 \text{ (Exp. 33), } 8 \text{ (Exp. 34); } L_G = 2 \text{ m}$



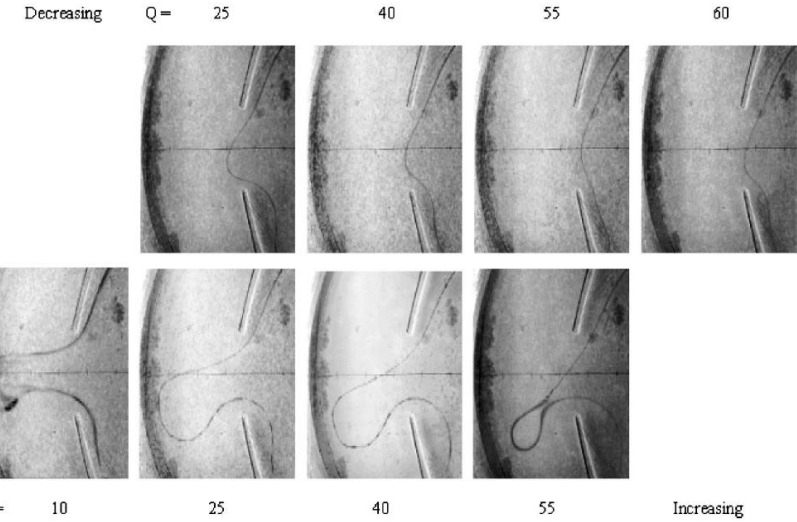
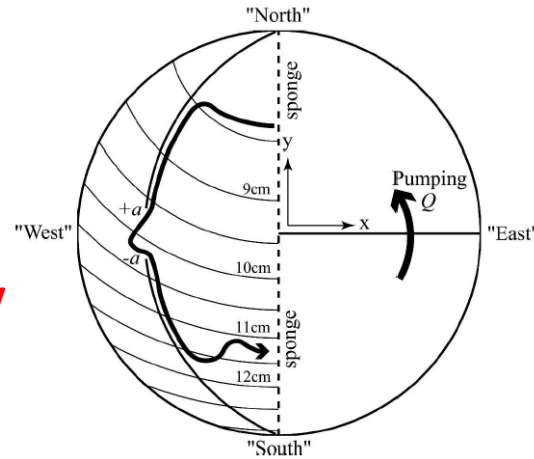
In the 1-m rotating tank of Sheremet and Kuehl (2007), multiple flow patterns and hysteresis are found:

Note that all the flow patterns are **steady** under steady forcing, except during the transient phase



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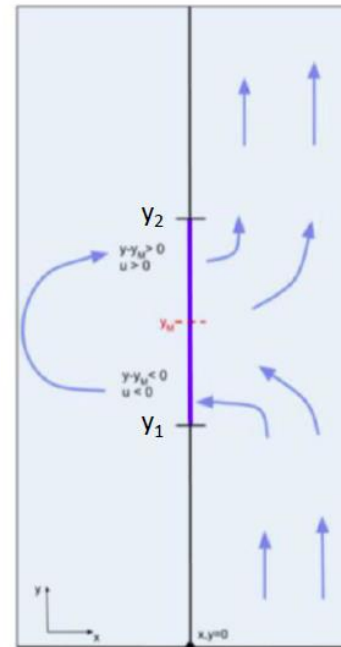


Also in our large-scale experiments the forcing is steady, but lateral and bottom **friction effects are so weak compared with nonlinear inertial effects** that the system is well beyond the first Hopf bifurcation; in fact, it is always in a chaotic regime

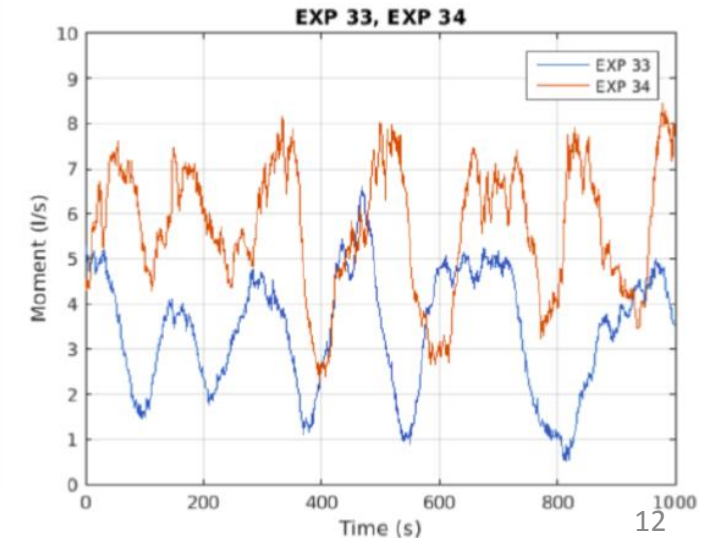
In other terms,

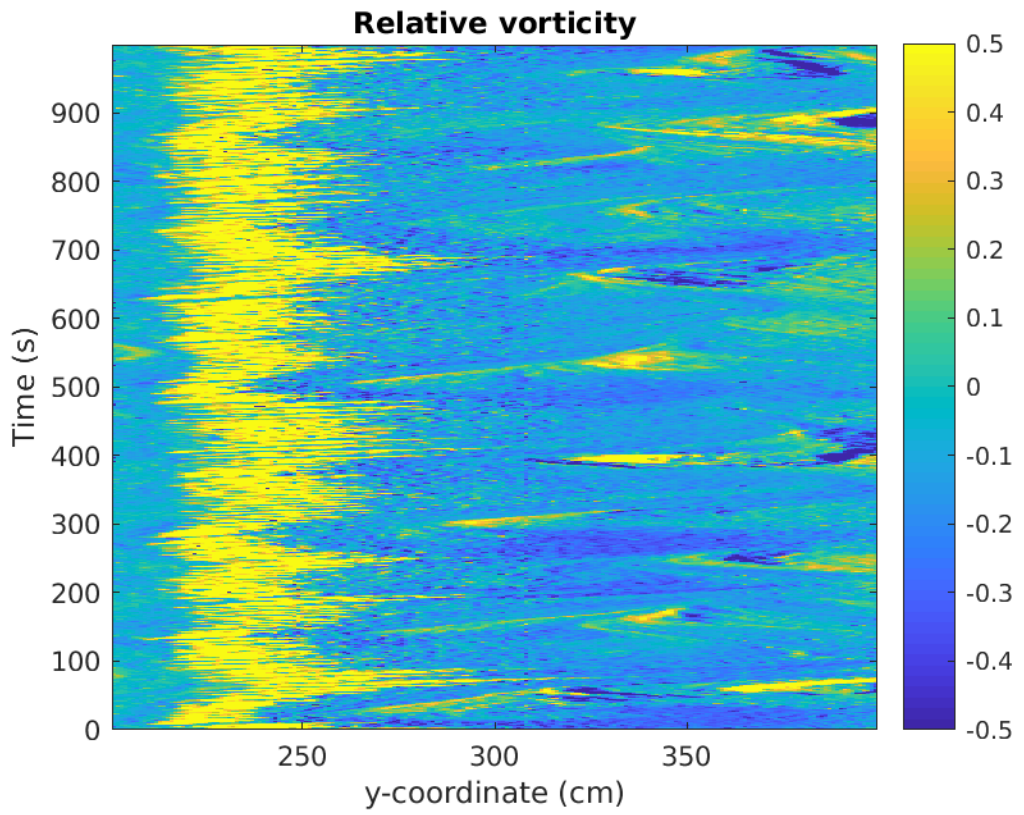
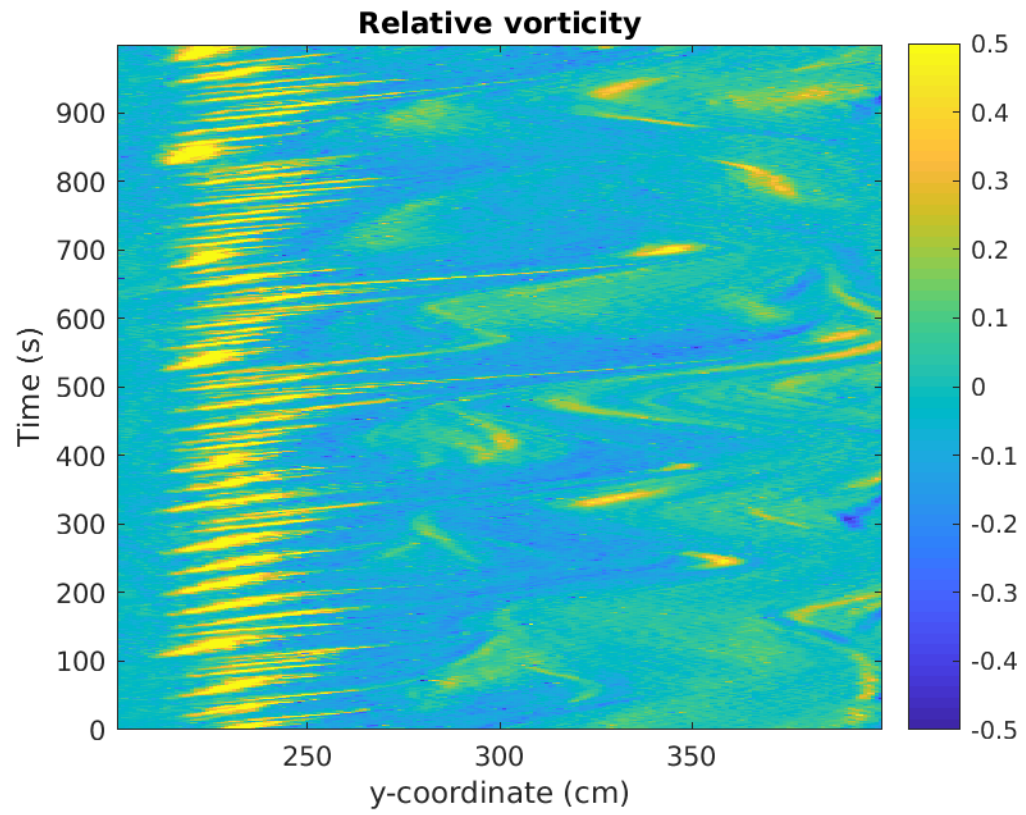
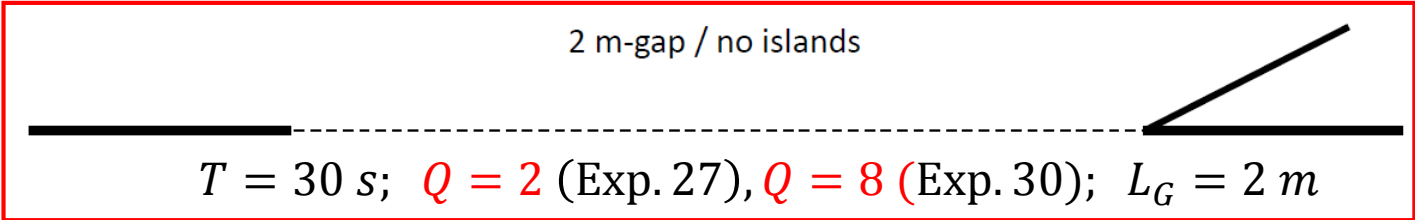
intrinsic chaotic fluctuations are always present

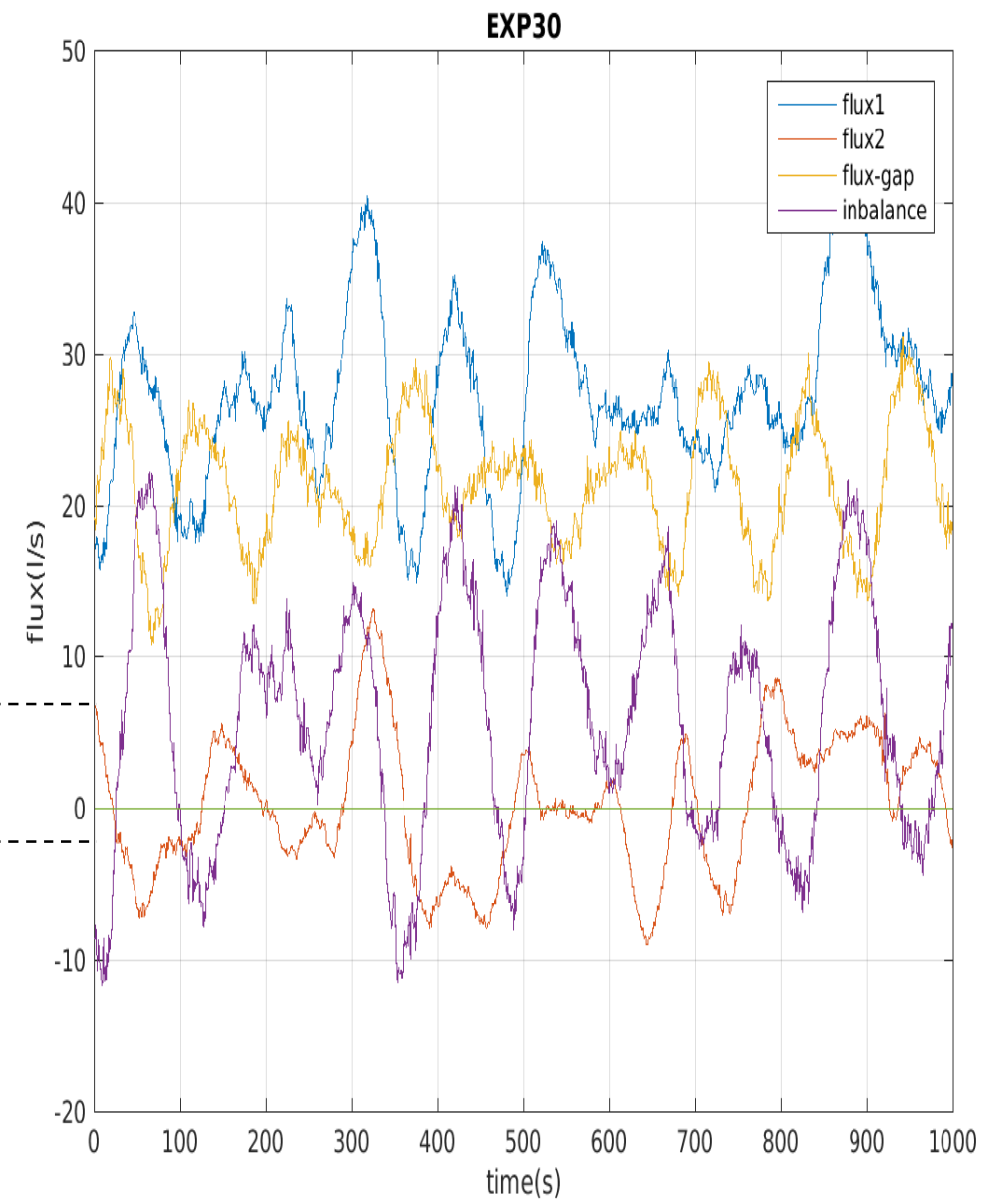
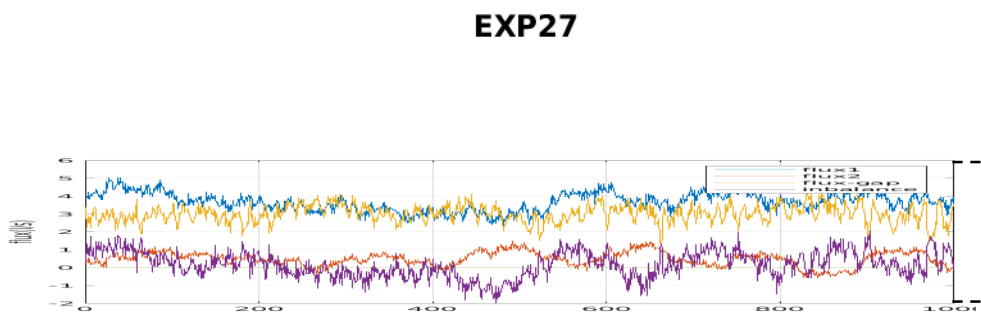
These experiments are therefore closer to the real ocean dynamics

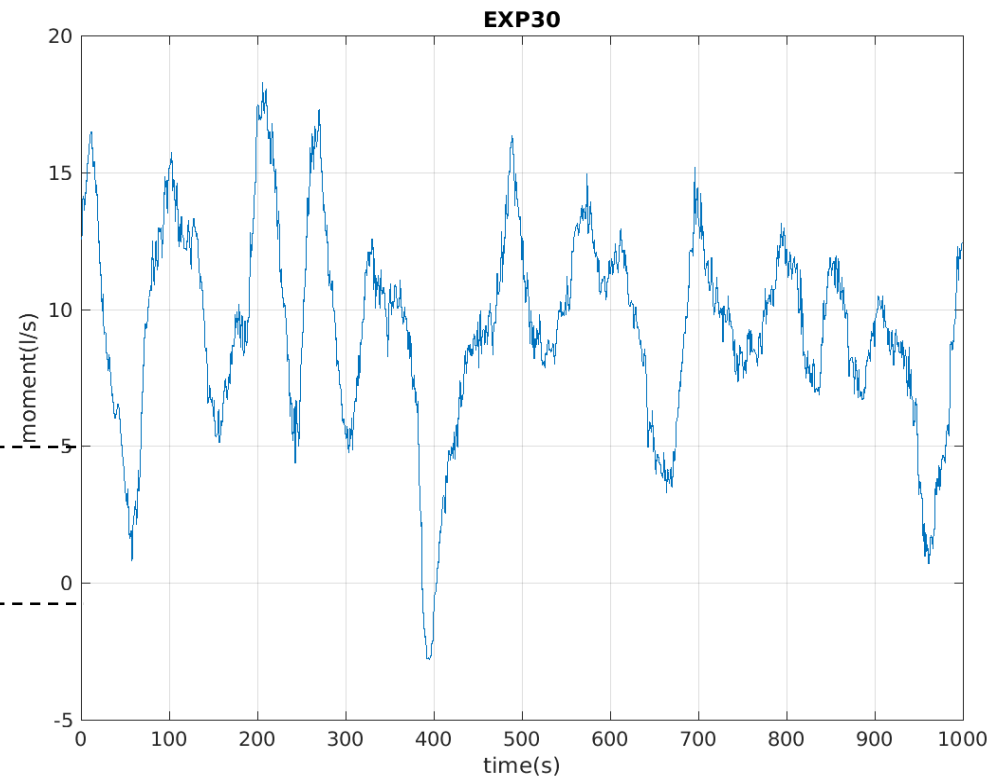
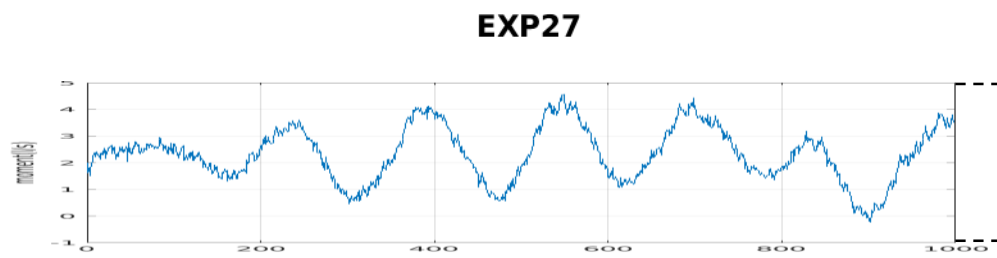


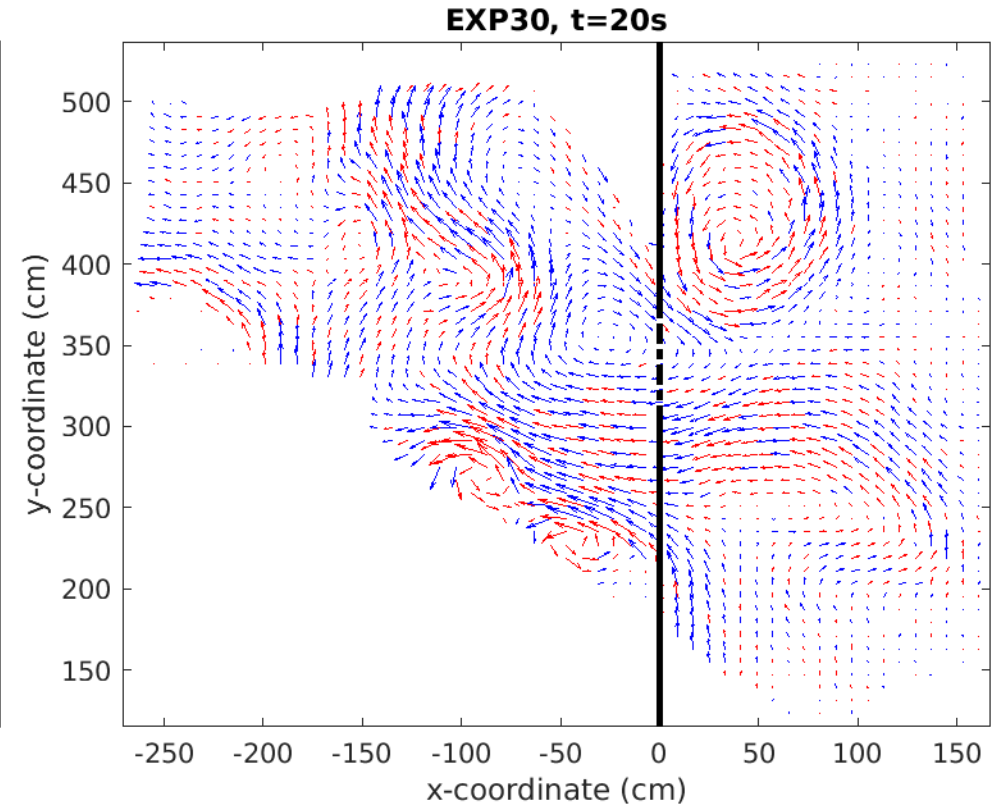
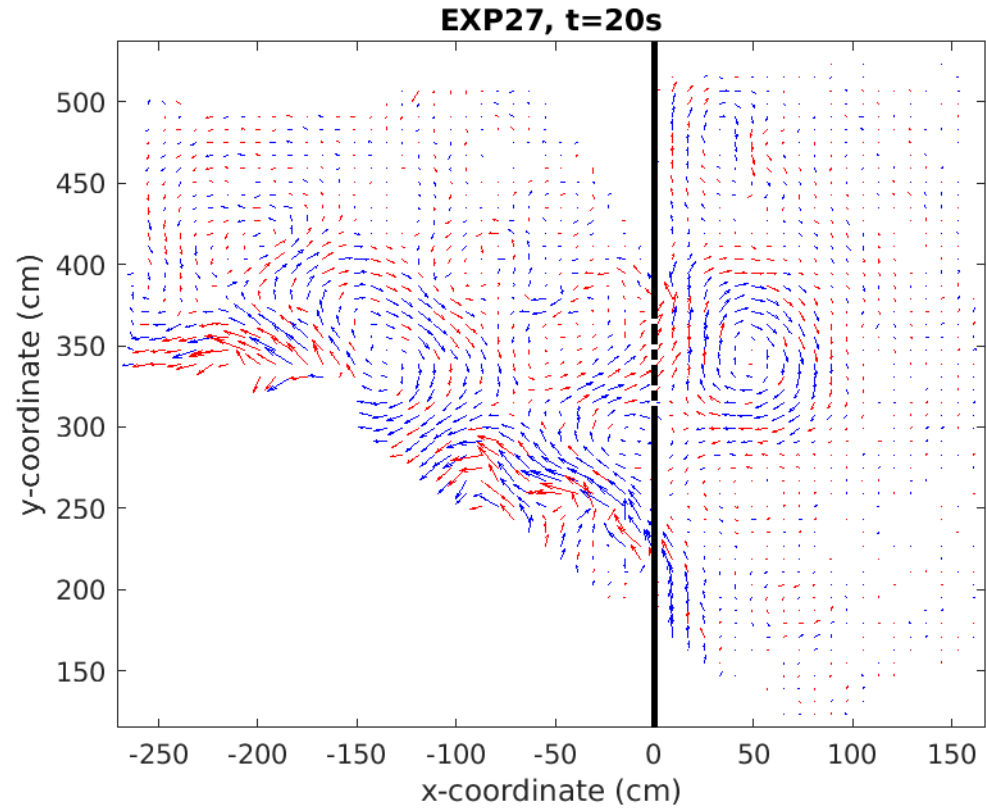
$$M = \int_{y_1}^{y_2} u(y - y_m) dy$$





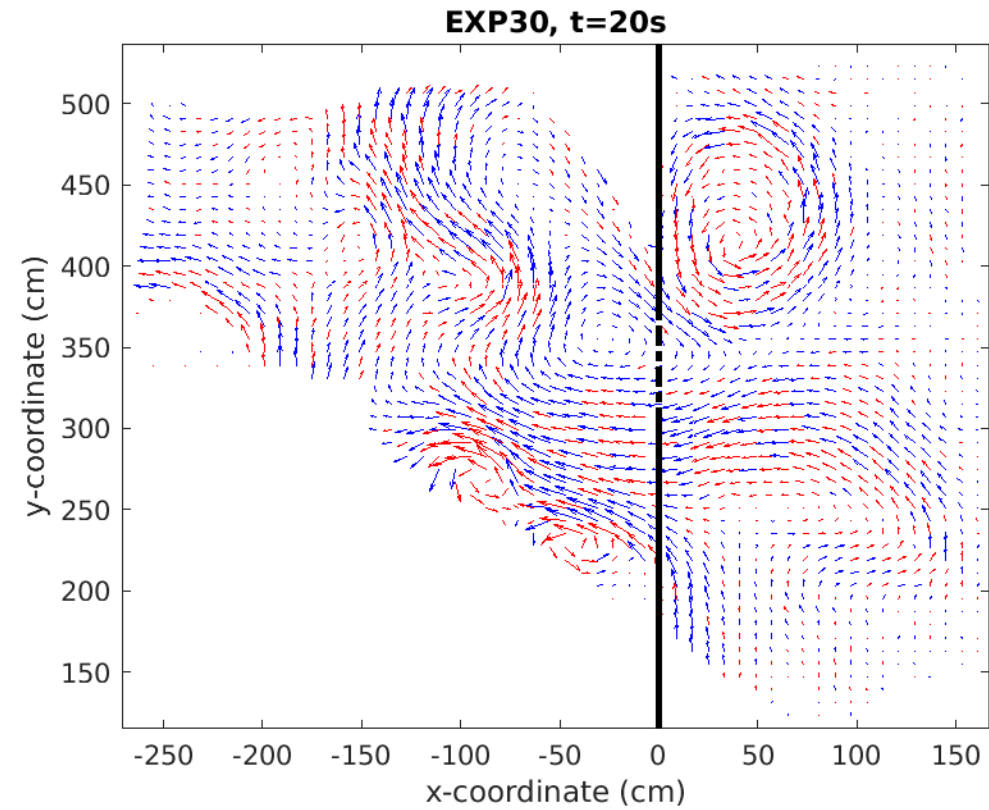






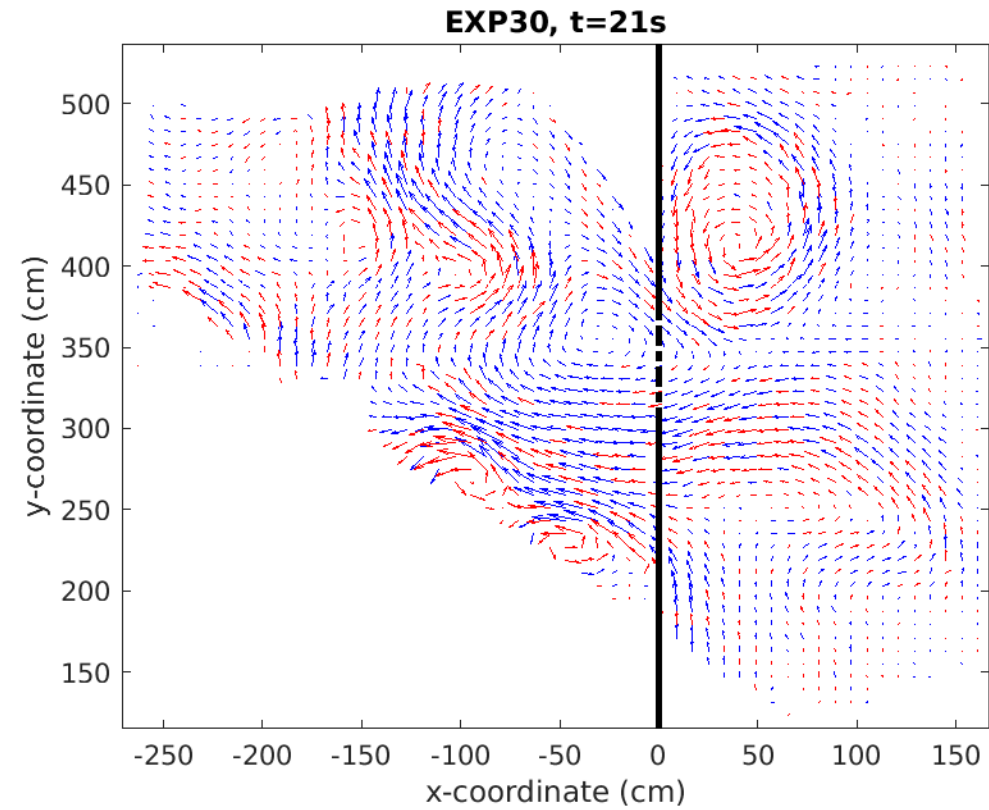
These 10 slides show
the evolution of Exp. 30
during a 10-s interval

This shows how amazing is
the richness of the dataset
provided by the PIV



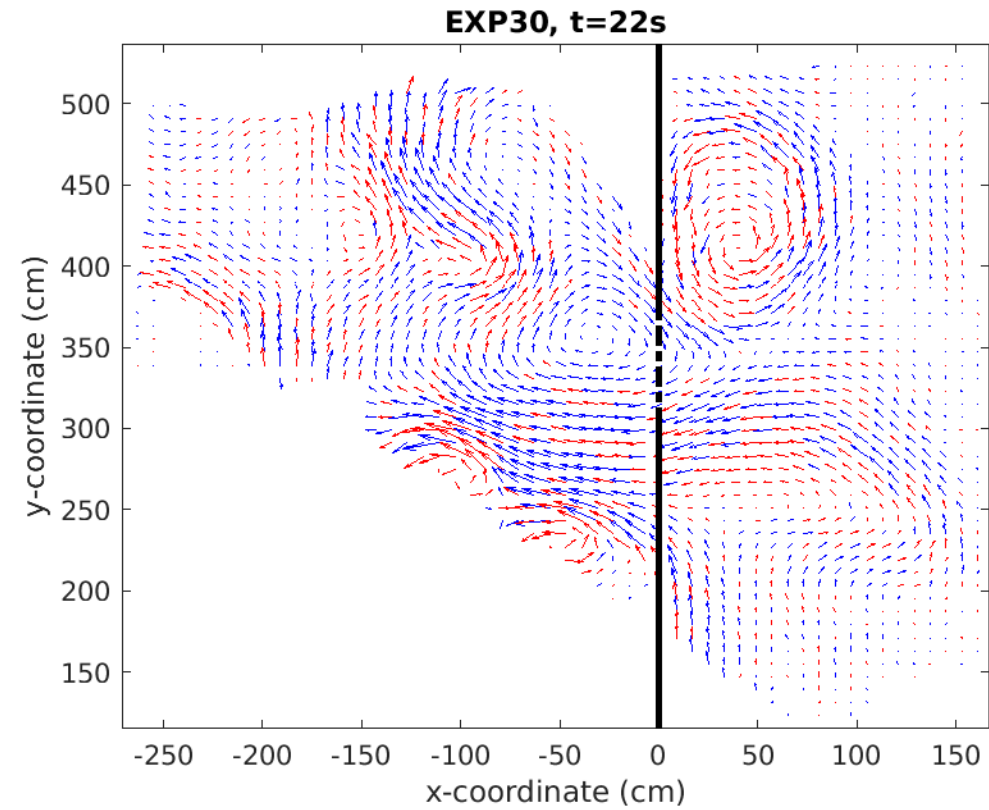
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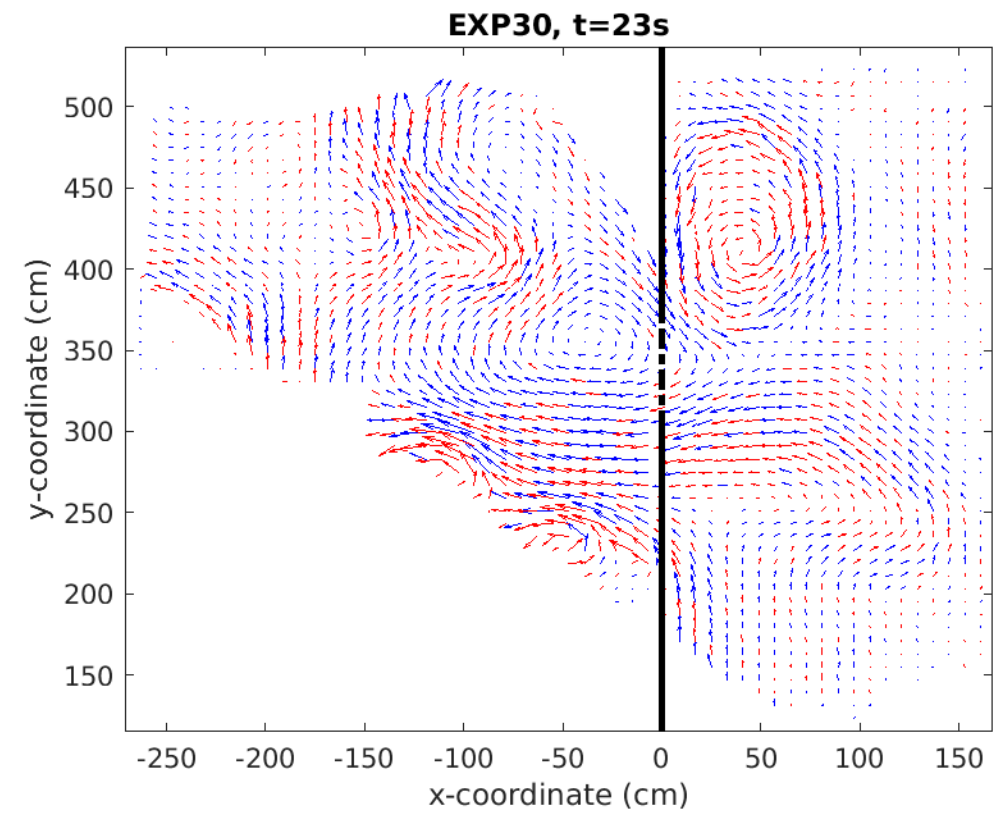
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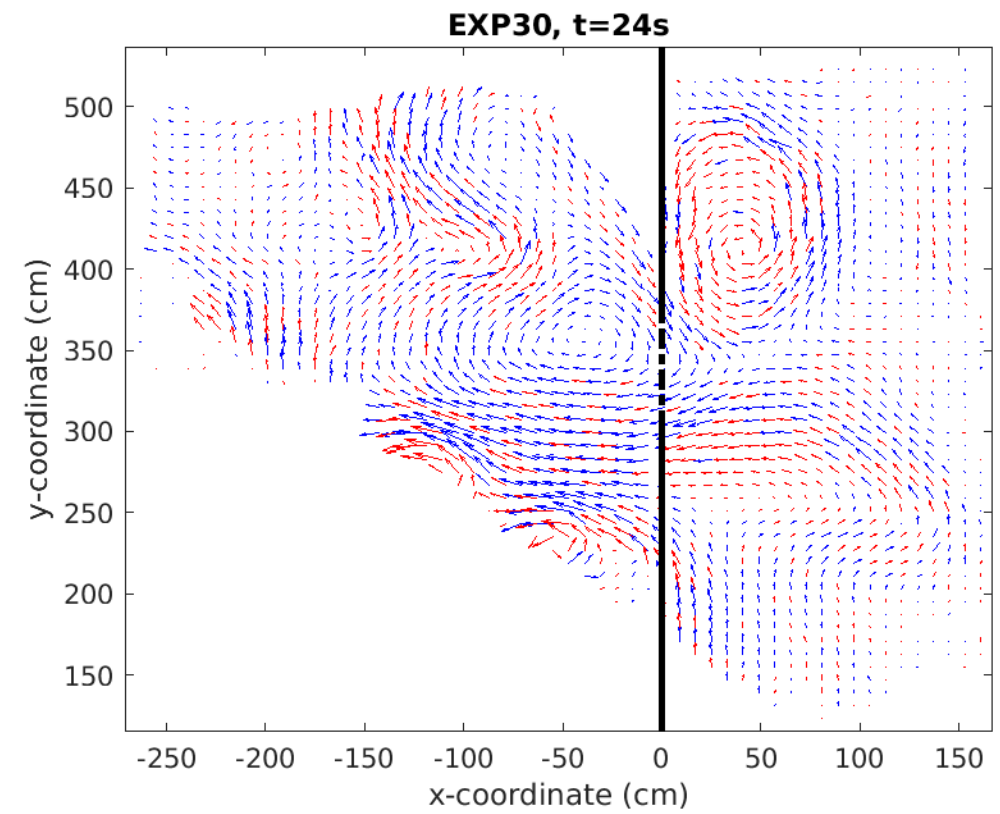
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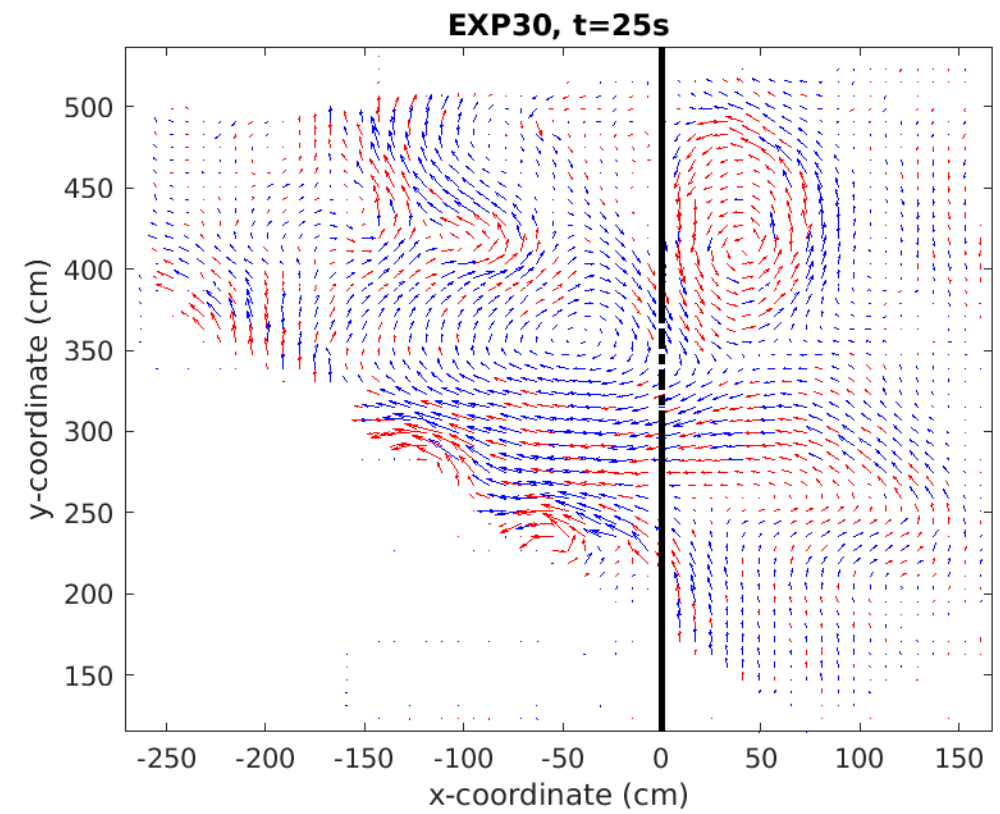
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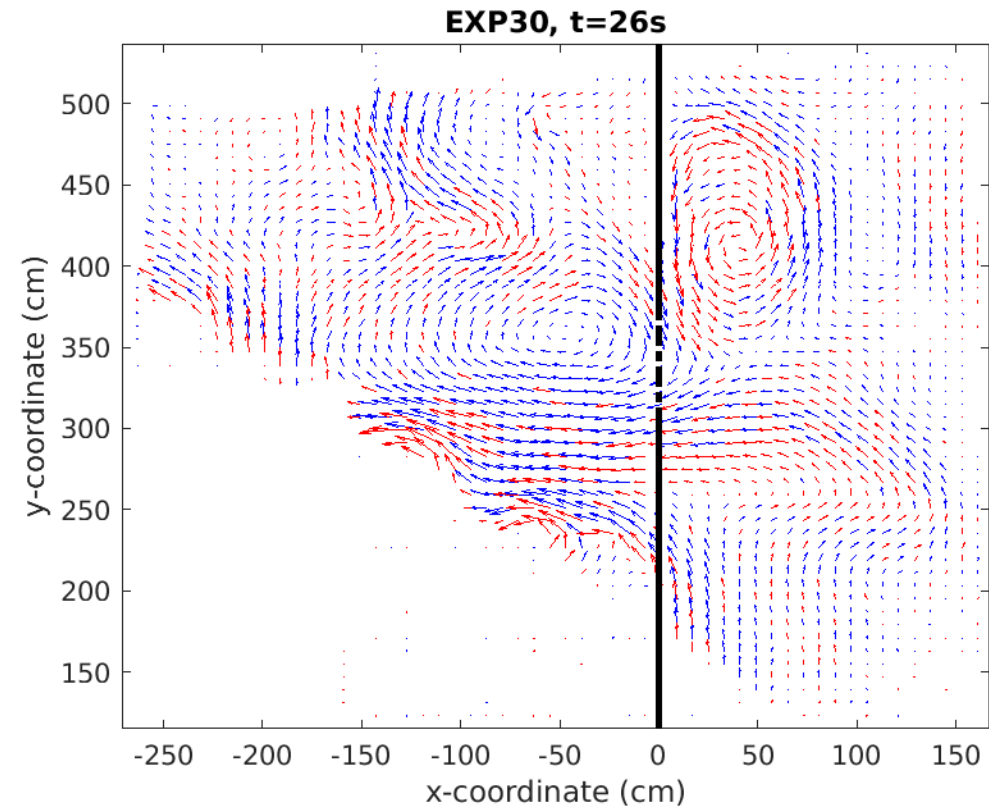
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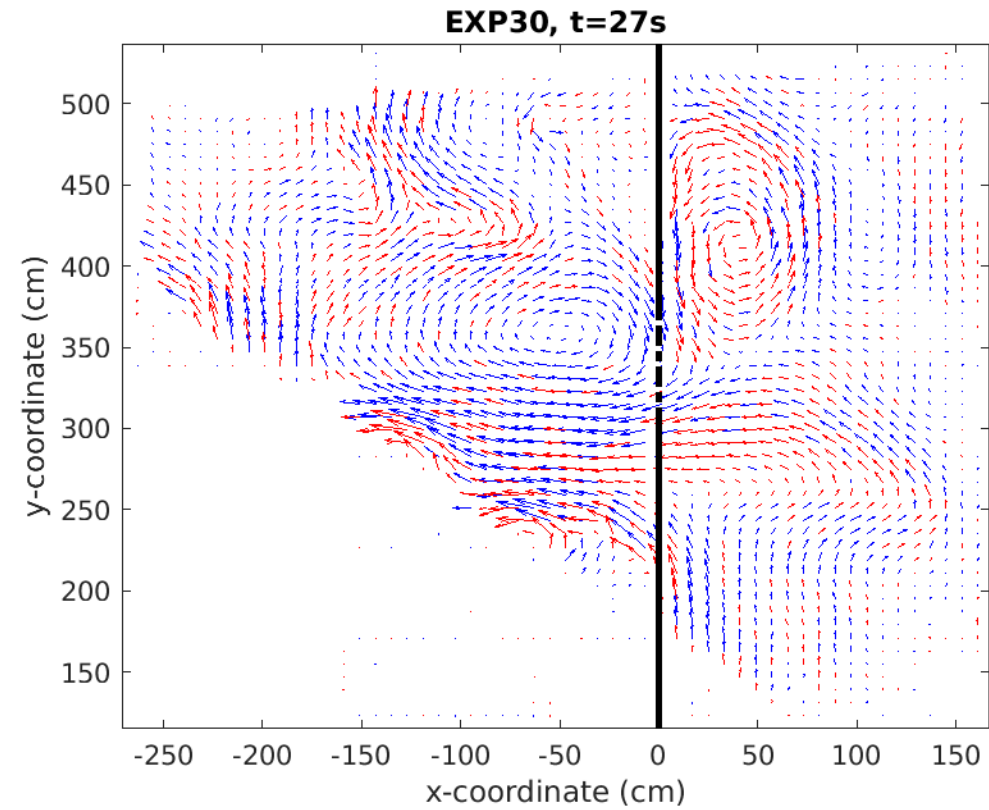
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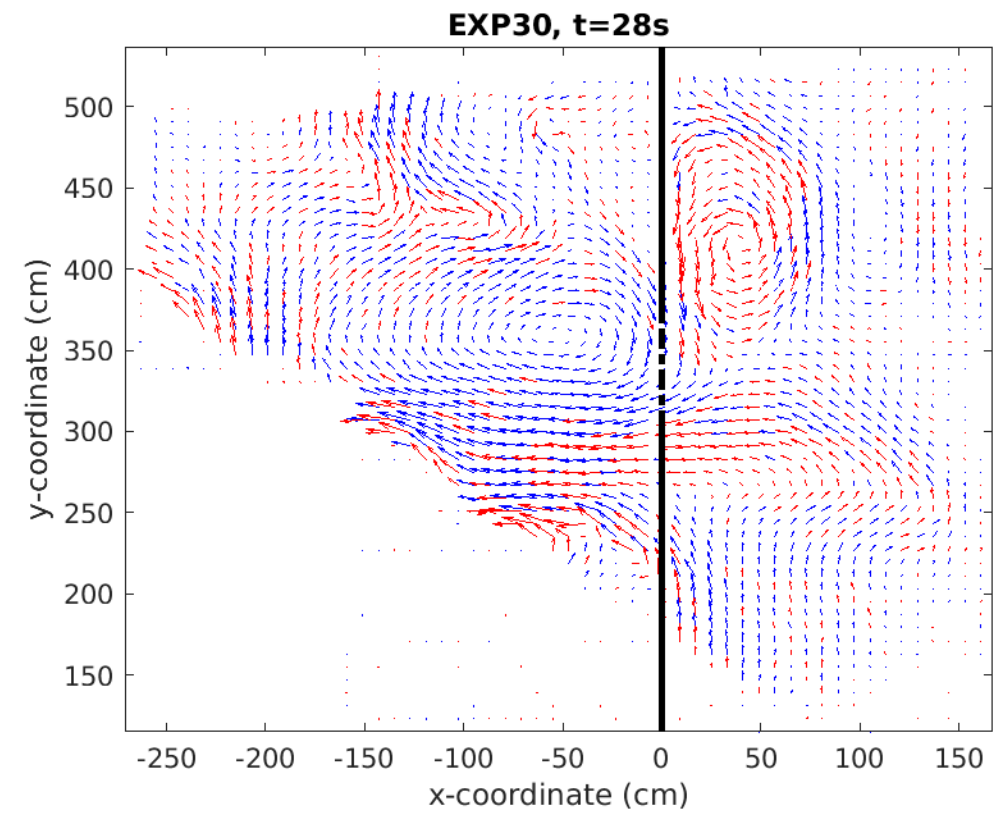
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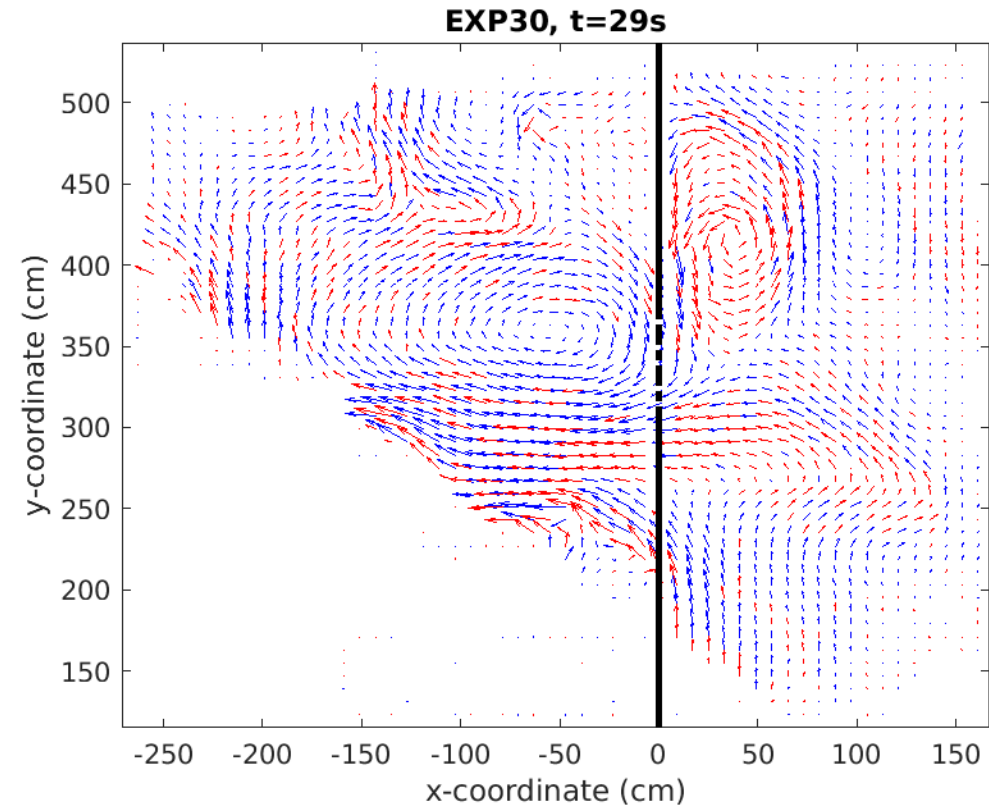
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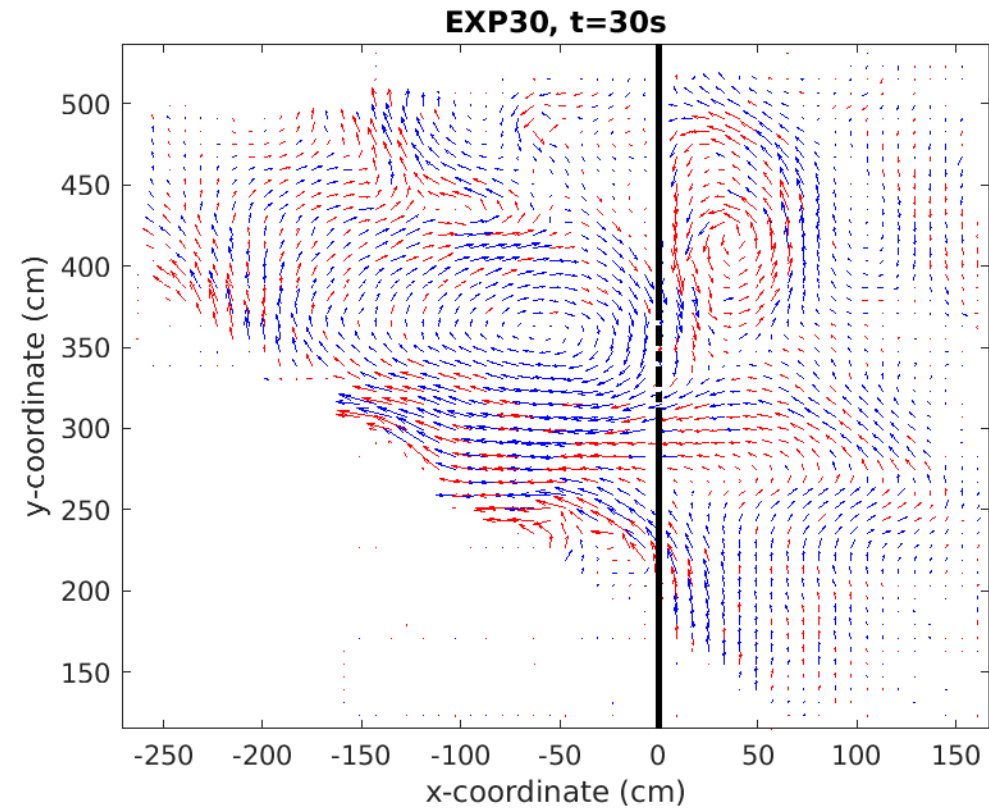
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Conclusions

The **interaction of a western boundary current with a lateral gap** has been studied experimentally with the 13-m diameter Coriolis rotating platform at LEGI in June-July 2019 in the framework of the **Hydralab+** project. The main oceanographic cases of interest for these experiments are:

- the **Kuroshio Current** looping/leaping/leaking through the Luzon Strait
- the **Gulf of Mexico Loop Current** yielding a retracted and an extended state

A **pumping system** located inside a channel produces a current which, following the lateral boundaries, generates an unshered flow at the entrance of a bottom slope: this provides the **topographic beta-effect** necessary for the intensification. **Particle Imaging Velocimetry** was used for flow visualization, where tracer particles are embedded in the fluid allowing for instantaneous velocity measurements of the fluid. An **Acoustic Doppler Velocimetry probe** located in the end of the channel has allowed for an accurate calibration of the pumping system.

A great advantage of the pumping system compared with a previous forcing system based on a moving paddle is the possibility of performing **experiments with a very long duration**. This is particularly relevant for very strong flows.

Many experiments have been carried out by varying the gap width, the rotation rate and the pump intensity. Experiments with an island in the gap and with a wedge-shaped continent have also been performed.

Several dynamical regimes are identified for each geometry, corresponding to **partial leaping, leaking or deep looping** inside the gap. In all cases, nonlinear **intrinsic chaotic fluctuations** emerge under steady forcing. This important feature makes these experiments more similar to the real ocean dynamics than previous experiments performed with a 1-m diameter facility. This occurs thanks to the large dimension of the tank, which leads to **friction effects that are much weaker than nonlinear inertial effects**.

These results open new perspectives as far as the application of dynamical systems theory to rotating tank experiments is concerned.

thanks for listening



Supplemental material

Numerical modeling

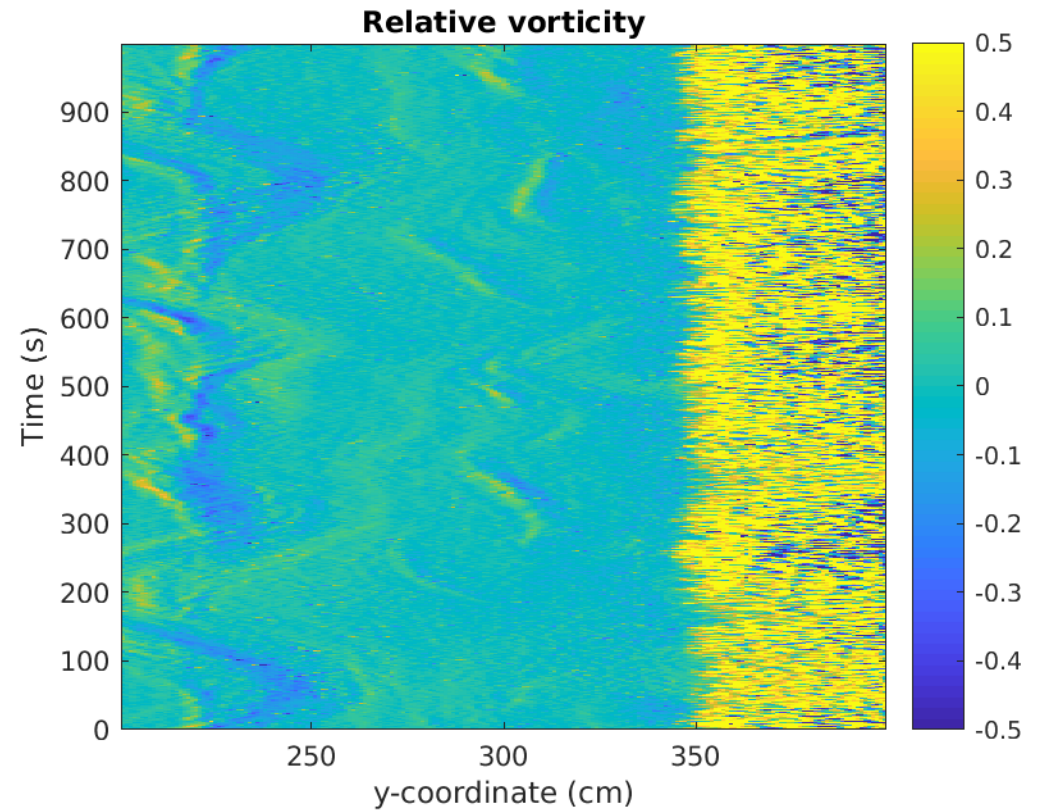
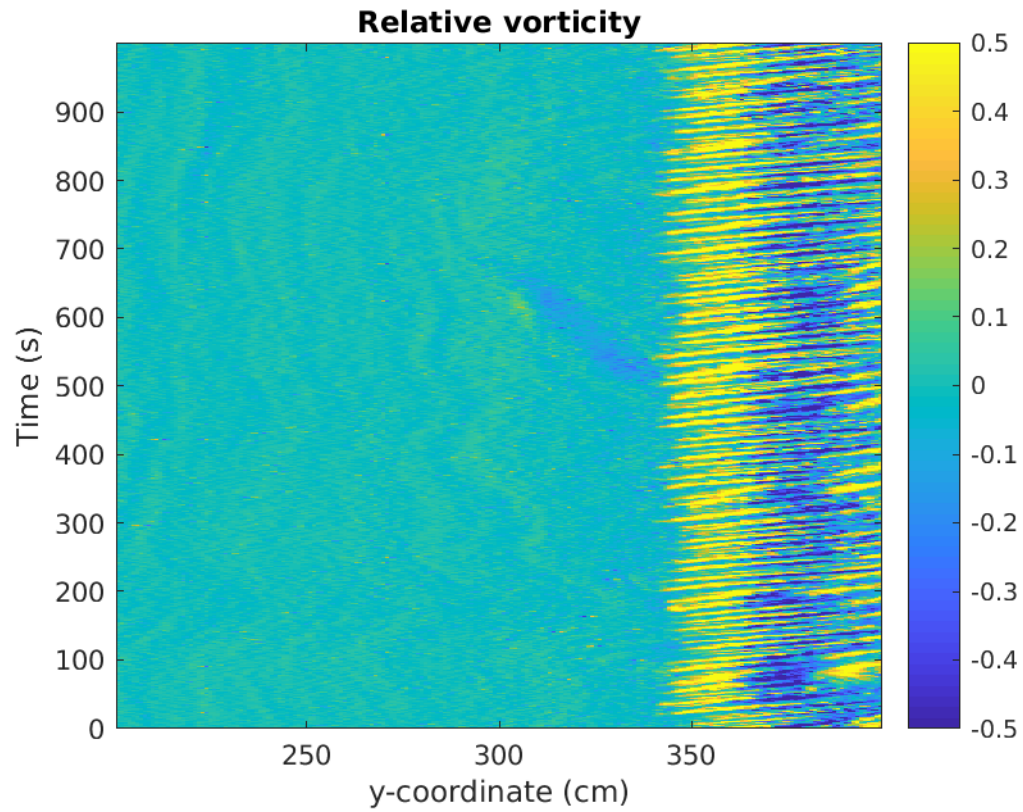
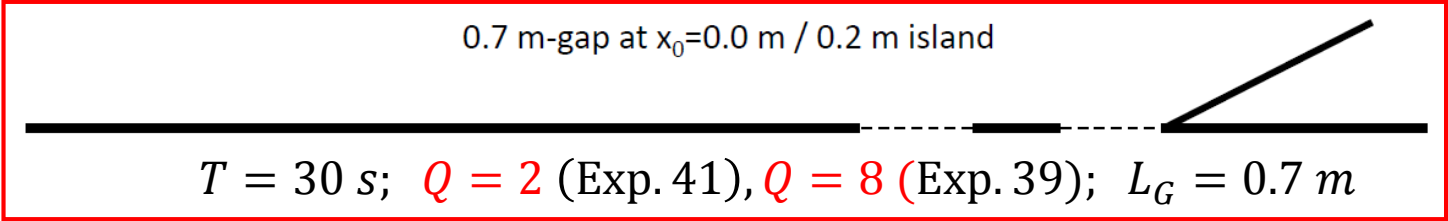
The interplay between experimental research and mathematical/numerical modeling is quite a subtle issue

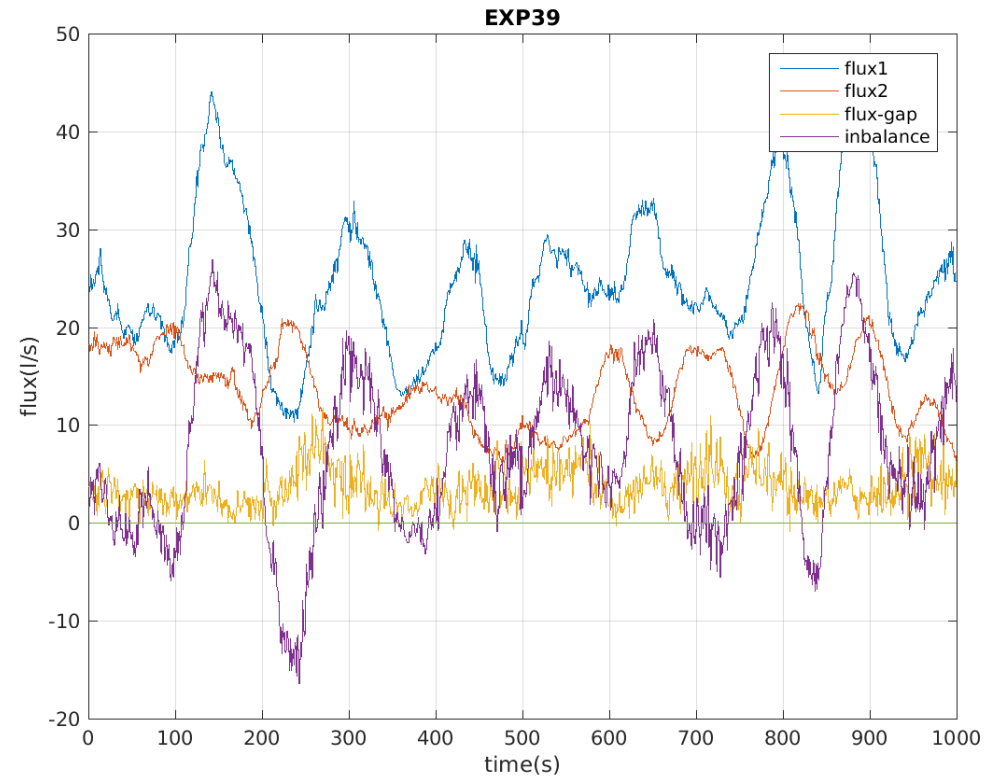
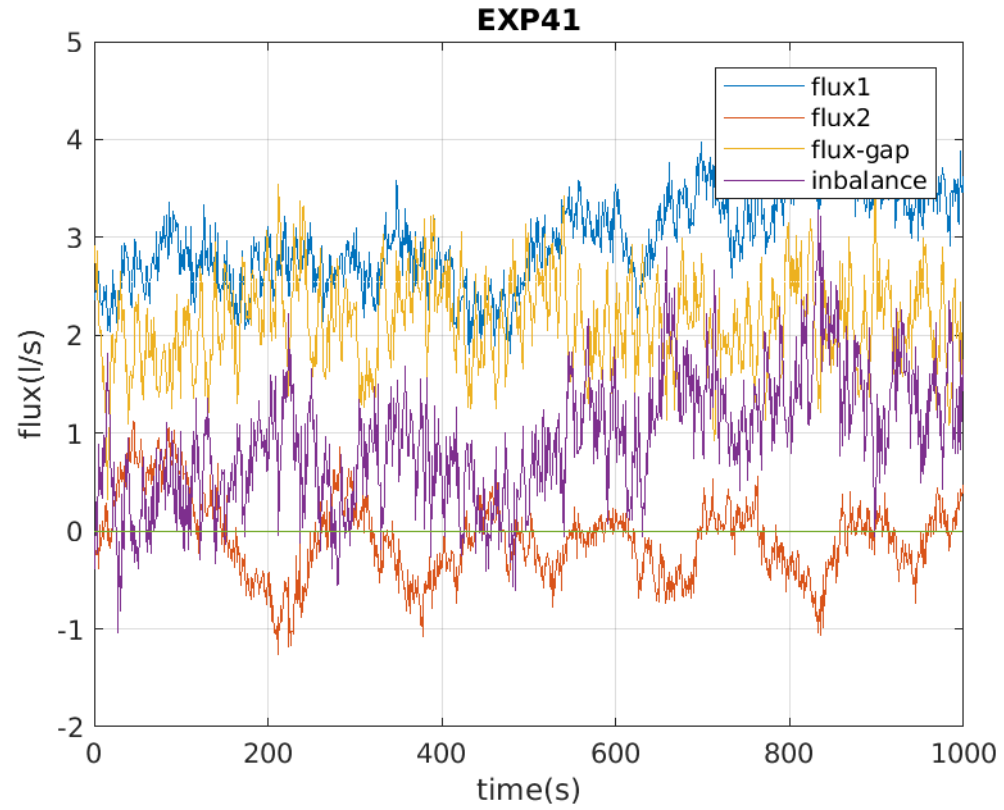
Experimental and numerical hydraulic researches were often seen as competitors; in the '90s experimental research was rather seen as supporting process research for the improvement of mathematical models, but the latter could in turn assist the experimental facility

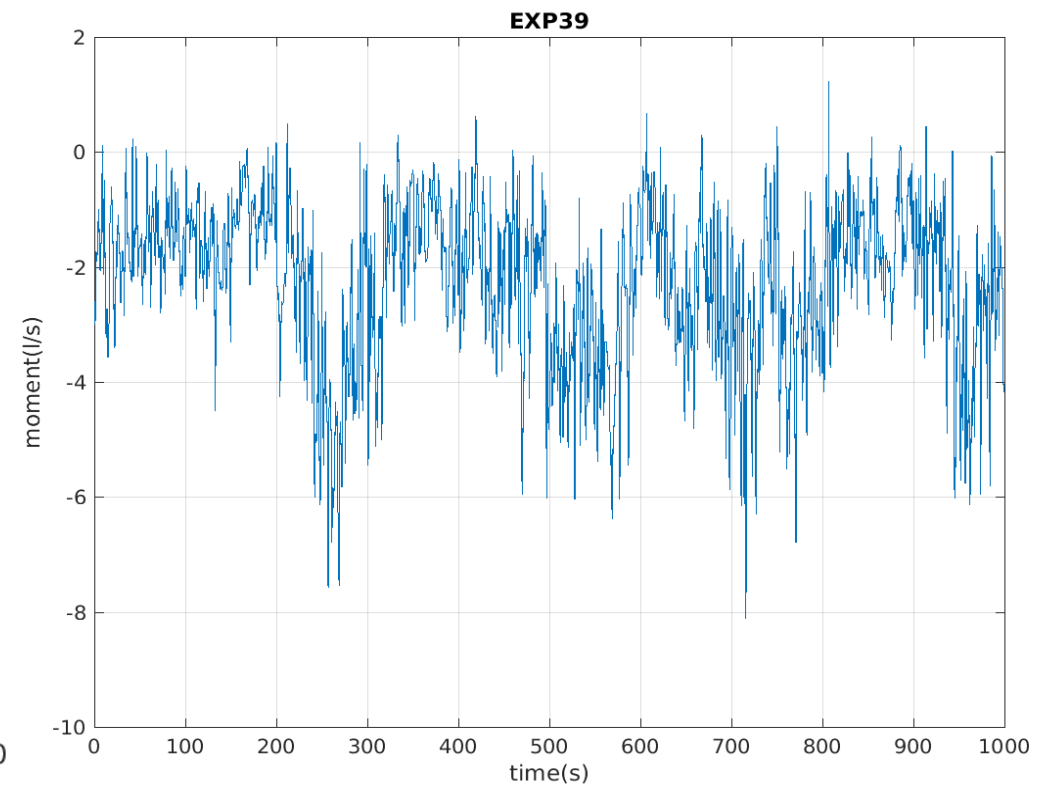
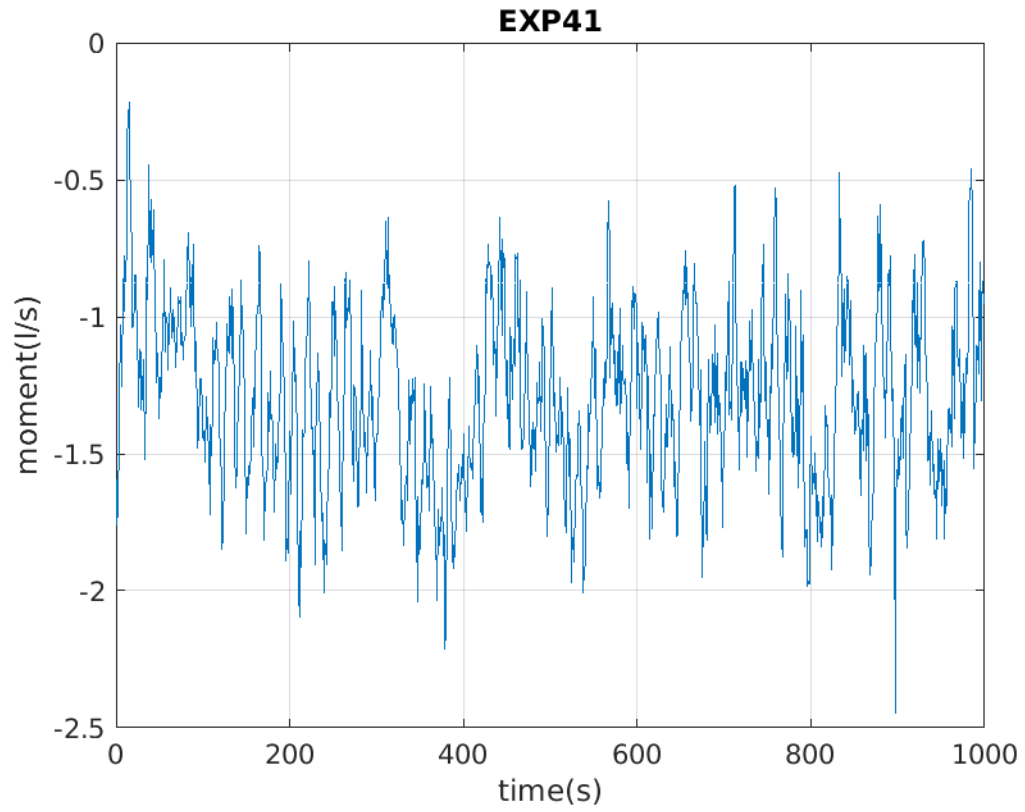
In a more challenging approach, the integrated use of physical models, numerical models, theoretical analysis and field experiments can provide the best advancements in our understanding of the hydraulic processes under investigation

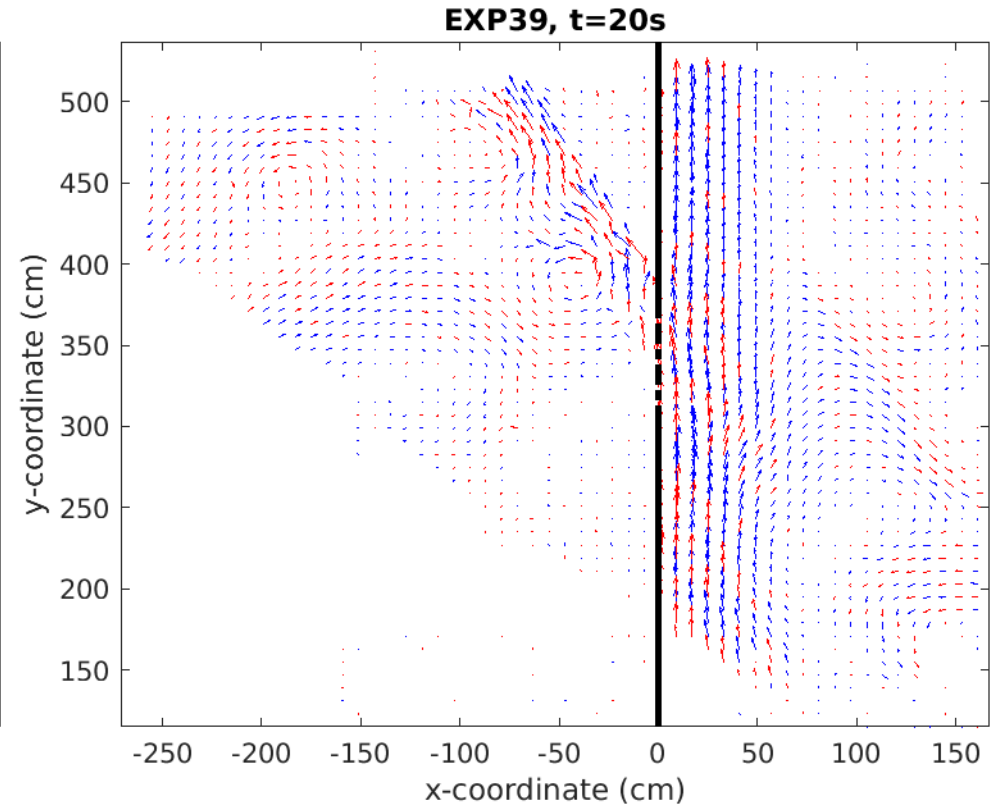
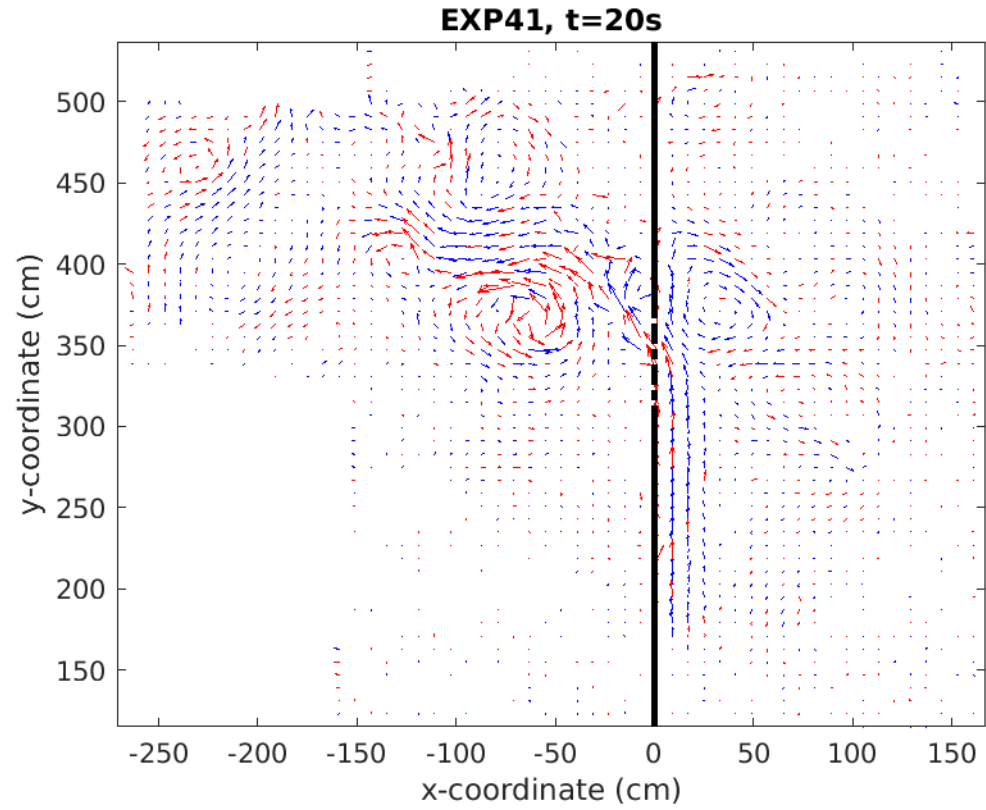
The real challenge is to **achieve a two-way cooperation between experimental research and mathematical modeling so as to migrate from competition to synergy**

According to this view, numerical modeling based on primitive equations/shallow water models will be carried out in synergy with our laboratory experiments









2 m-gap / no islands

$T = 60 \text{ s}$; $Q = 6$ (Exp. 33), $Q = 8$ (Exp. 34); $L_G = 2 \text{ m}$

