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Western Boundary Currents modeled in a rotating platform*

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- An overview of Western Boundary Currents

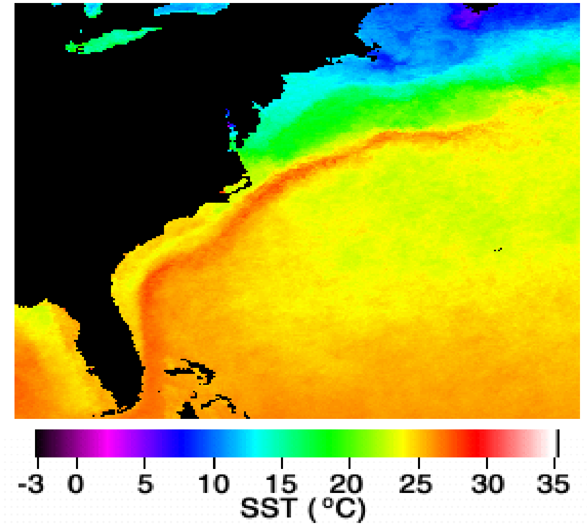
- Modelling WBCs in a rotating tank

- Setup used at SINTEF to study WBCs

- Experimental results

The most relevant example of Western Boundary Current: the *Gulf Stream*

This image is part of the Poupard version of the Franklin-Folger Gulf Stream Chart printed *Maritime Observations* (1786). The Gulf Stream is the black/grey region along what is now the U.S. East coast.



This is a sea surface temperature image from the AVHRR showing an average of all of the data for the year of 1996. The red-orange streak of 28 °C to 30 °C water shows the Gulf Stream.

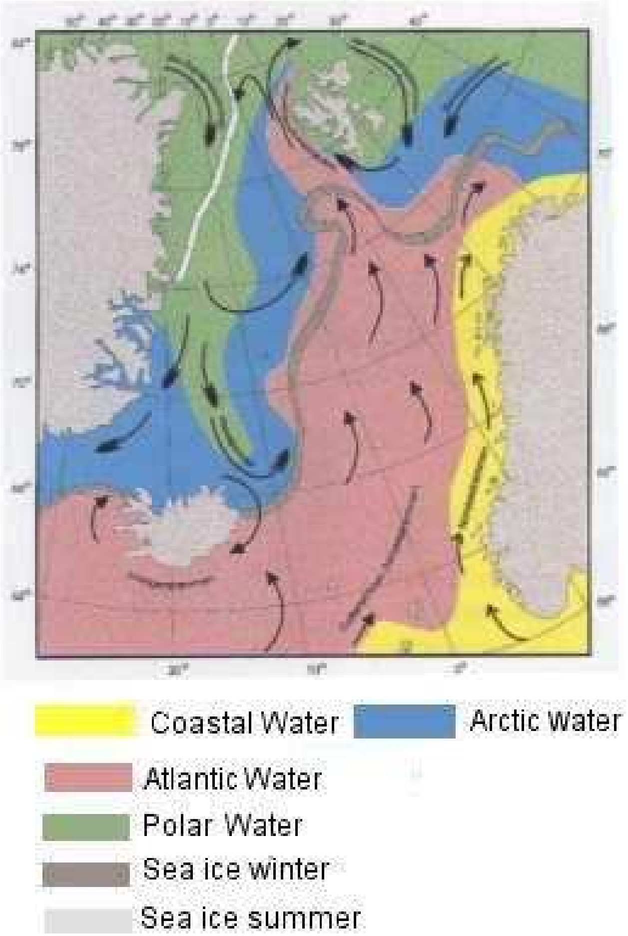
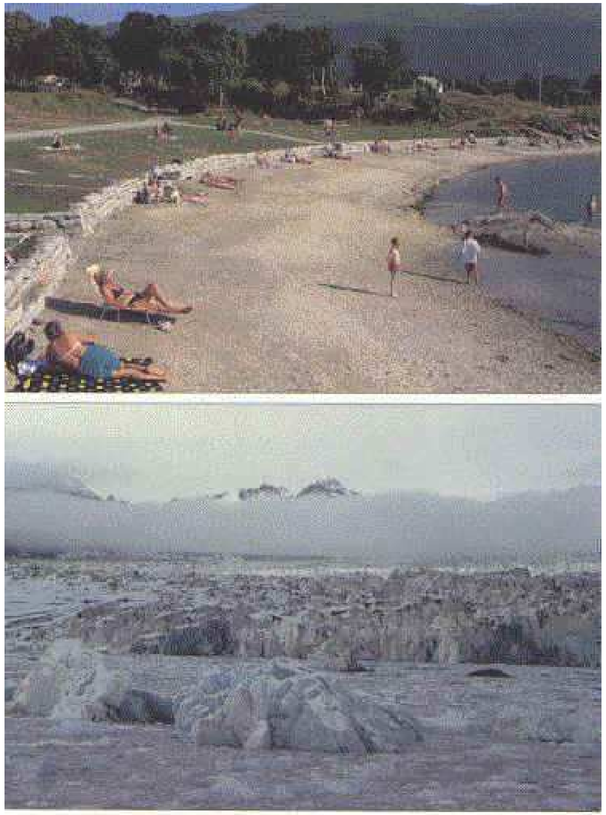


Figure 1. Surface currents in the Norwegian Sea and adjoining oceans

(from an article in the popular science periodical Ottar, 4/99)



(above) A summer's day at "Telegrafbukta" in Tromsø. (below) A summer's day at Nansenfjord, in south-east Greenland. Both pictures are taken at a latitude of 70 degrees north. The difference in the climate is due to the sea currents. Tromsø enjoys a warmer climate due to the warming effect of the Gulf Stream, while the eastern coast of Greenland is cooled by the East-Greenland current.

Physical principles

$$= \frac{d}{dt}(\zeta + f) \quad (f = f_0 + \beta y)$$

In a subtropical gyre the dynamics can be diagnostically analyzed through the evolution equation for the potential vorticity in the quasigeostrophic approximation ($\varepsilon \ll 1$) for a homogeneous incompressible fluid (Pedlosky, 1979):

$$\nabla^2\psi_t + J(\psi, \nabla^2\psi) + \beta\psi_x = \frac{curl_z\tau}{\rho D} + A_H \nabla^4\psi$$

$$J(\psi, \nabla^2\psi) + \beta\psi_x = A_H \nabla^4\psi$$

Along the western boundary the gain of planetary vorticity for poleward moving water columns intensifies the flow. A steady flow can be established if such gain is eventually balanced by dissipative effects. Also inertial effects play a major role in shaping the western boundary currents.

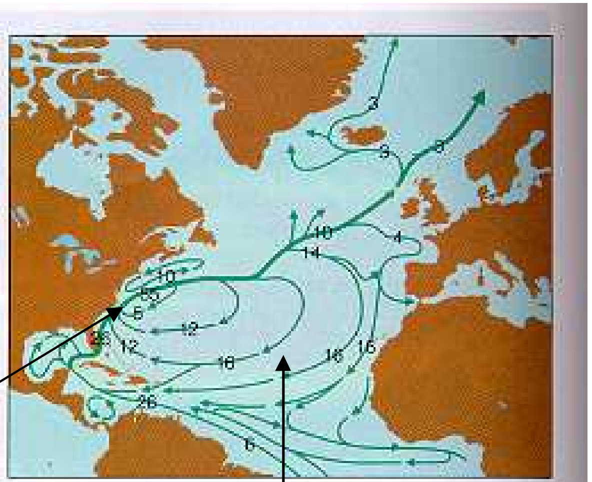


Figure 9.9 The general surface circulation of the North Atlantic. The numbers indicate flow rates in sverdrups (1 sv = 1 million cubic meters of water per second).

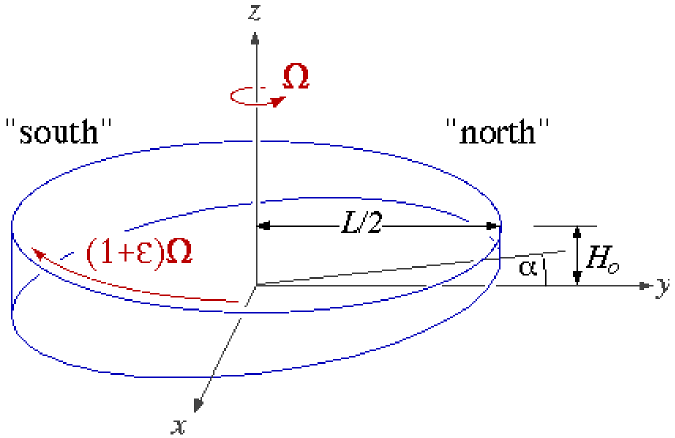
$$\beta\psi_x = \frac{curl_z\tau}{\rho D}$$

In the oceanic interior
the Sverdrup balance holds

Modelling WBCs in a rotating tank

The planetary beta effect can be represented in a rotating tank by an equivalent topographic beta effect:

$$\beta^{*} = \frac{f_0}{D}\left|\nabla d\right|$$

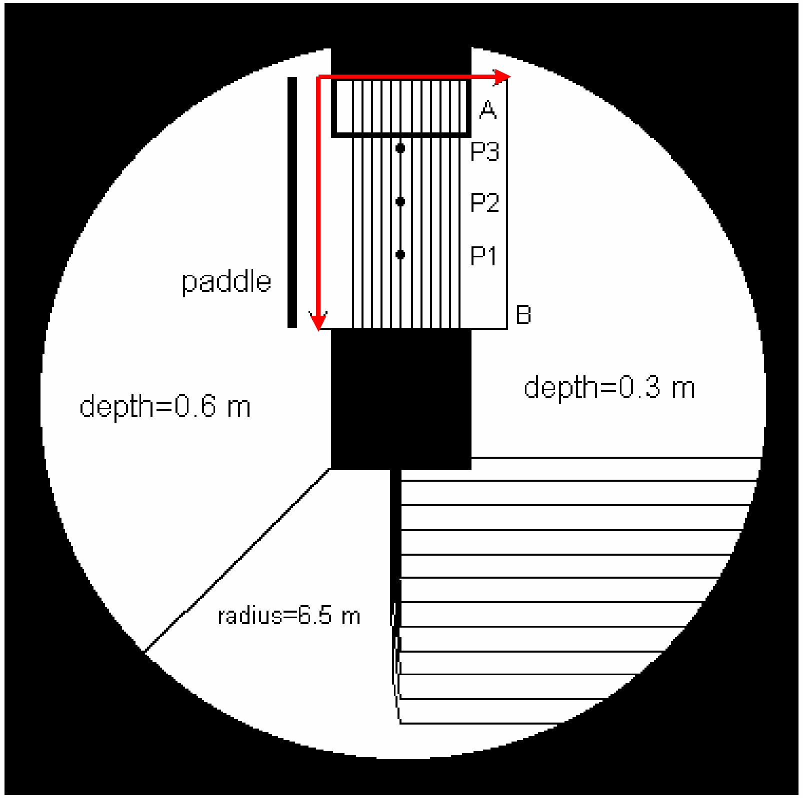


The "*sliced cylinder/cone*" model (Pedlosky and Greenspan, 1967; Beardsley, 1969, 1975; Griffiths and Veronis, 1997, Kiss, 2001) was used to perform studies on the *subtropical gyre system*.

However, a laboratory study specifically aimed at analysing the cross-shore structure of *western boundary currents* appeared not to have been carried out yet.

An experiment of this nature was performed at *SINTEF*

Origin of this laboratory study

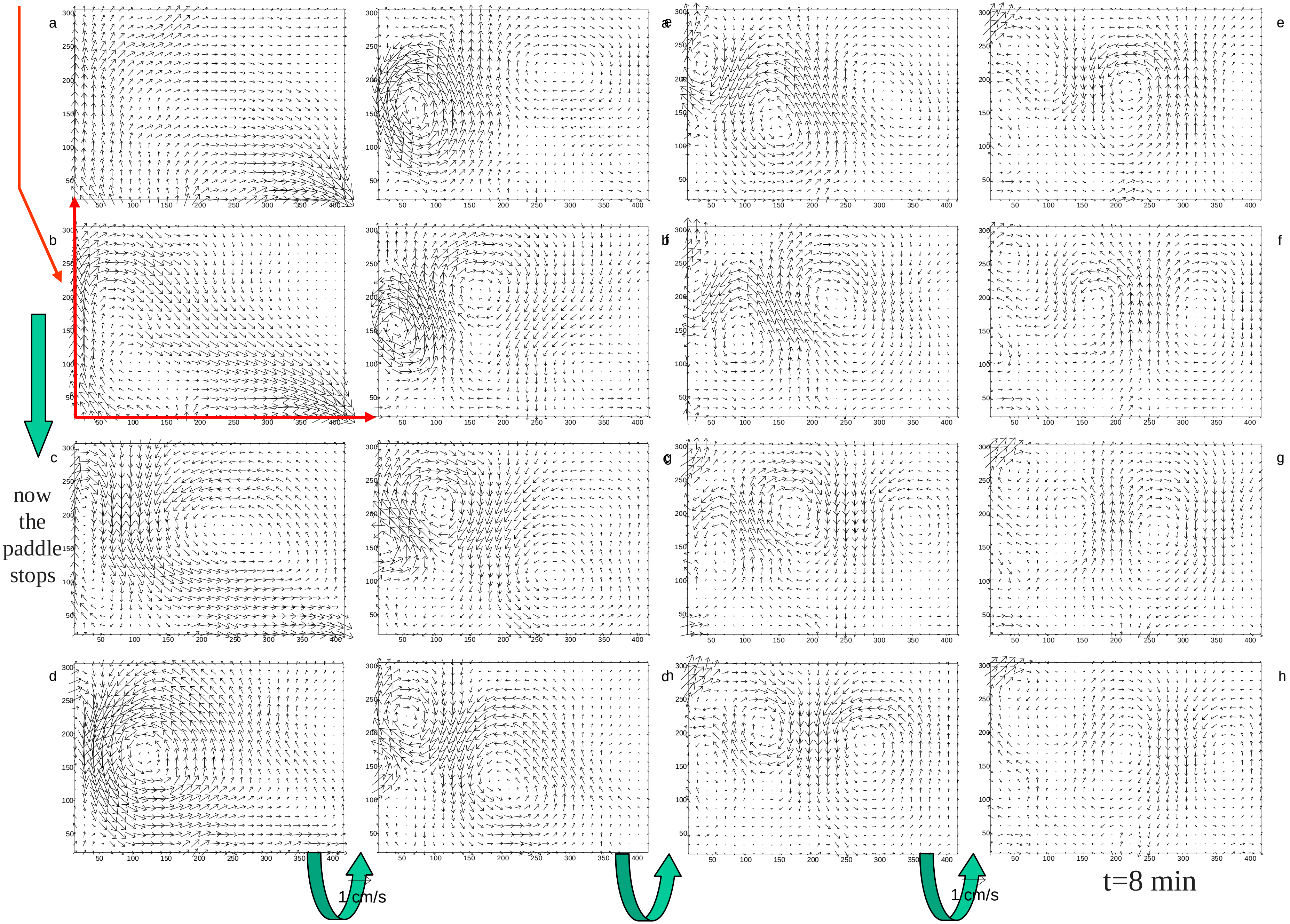


Setup for the study of
topographic Rossby normal modes
in the rotating tank at *LEGI*
in Grenoble
(Pierini, Fincham, Renouard,
D'Ambrosio and Didelle,
Dyn. Atmos. Oceans,
2002, **35**, 205-225)

1^{st} topographic Rossby normal mode (T~2.5 min)

western intensification

t=0.5 min

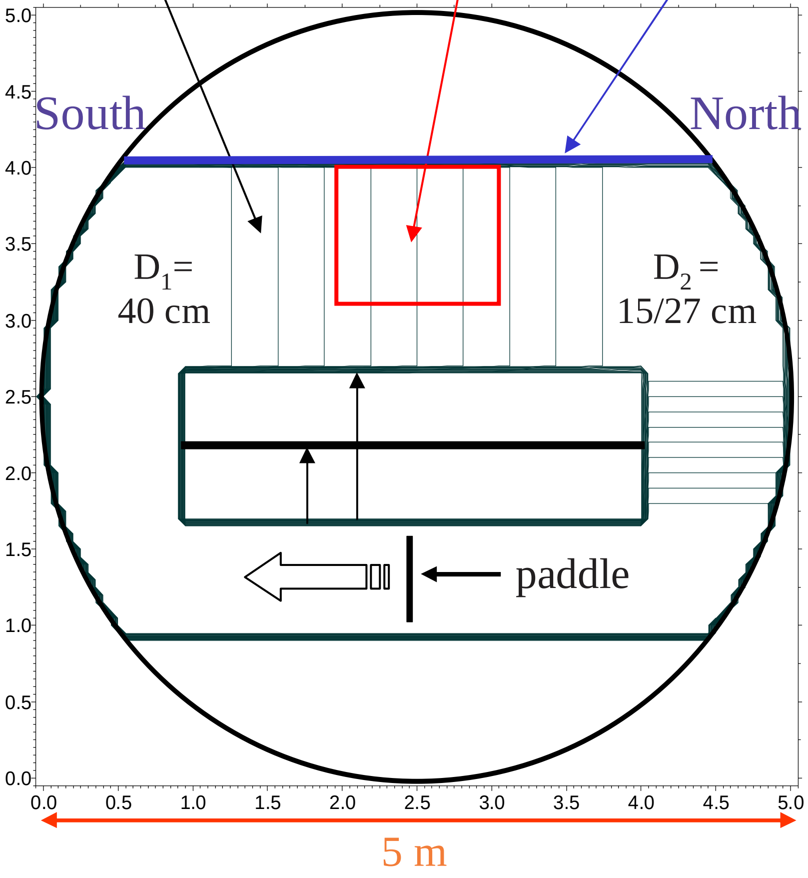


Setup used in this experiment

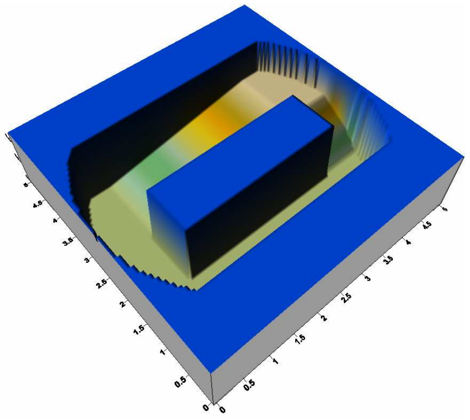
region covered by the photogrammetry

region of topographic beta

“western” boundary

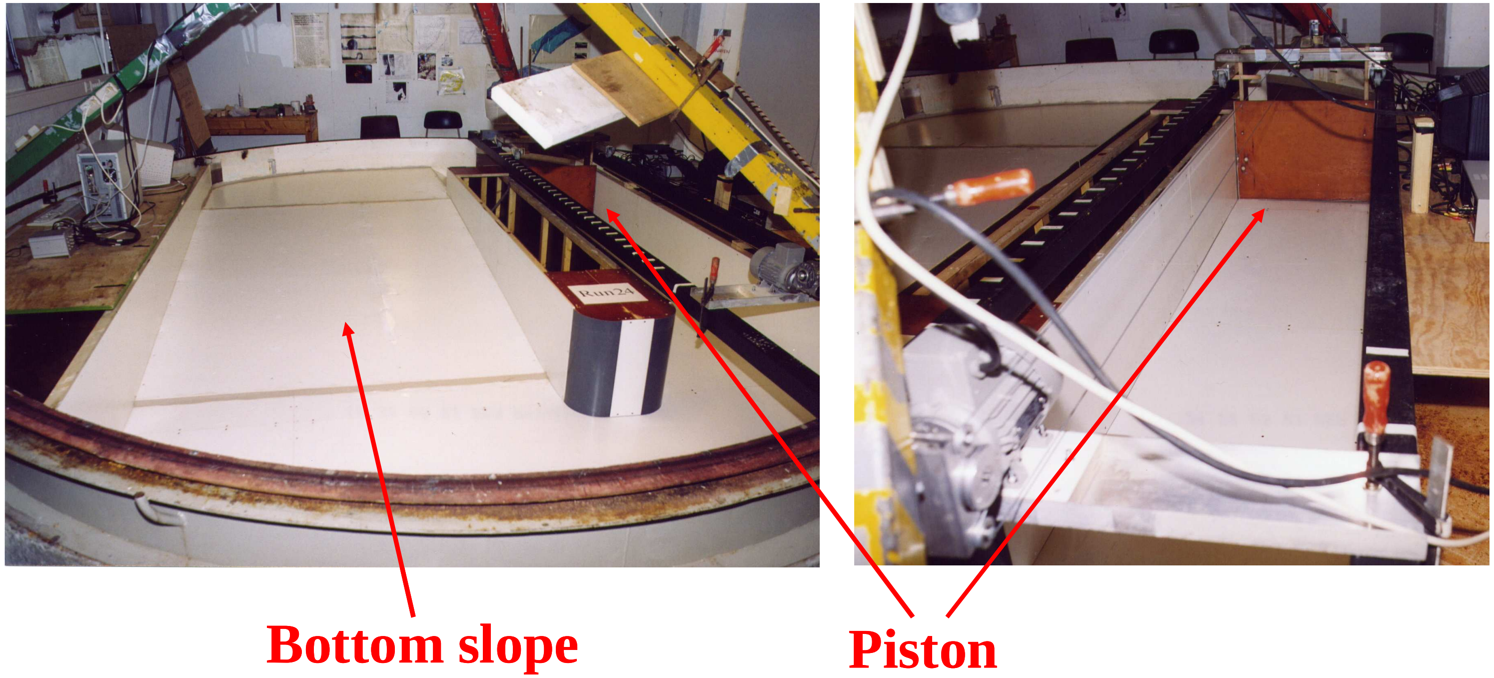


Setup for the study of
western boundary currents
in the rotating tank at *SINTEF*,
in Trondheim



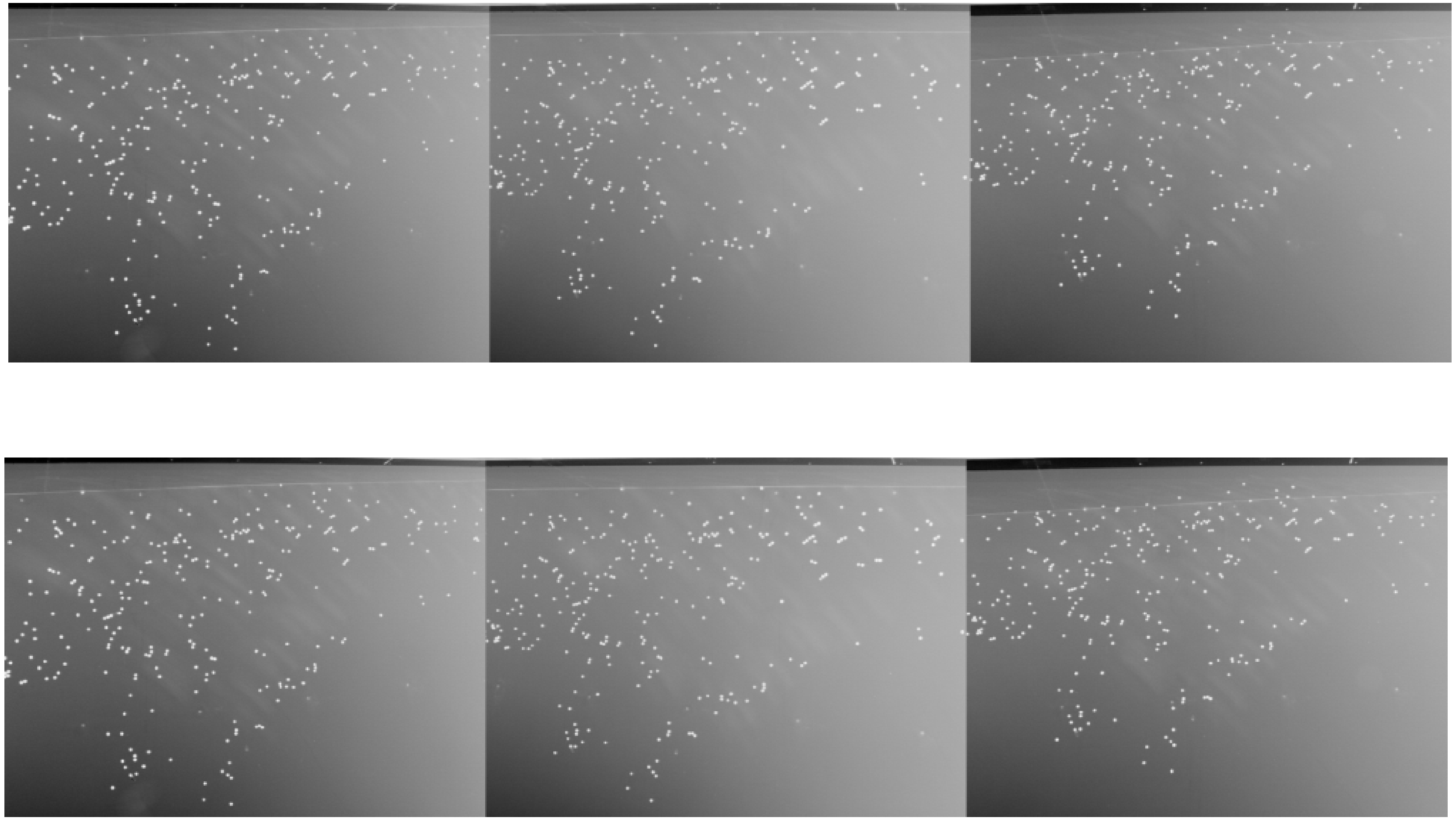
The moving paddle substitutes the wind in providing a “poleward” transport at the entrance of the slope.

(the *local* effect of the wind in a WBC is of secondary importance)


Run24
Bottom slope
Piston

Example of digital pictures
(taken at two successive instants of time)
used for the photogrammetry

Run 22, frames 200/201 (2 fps)

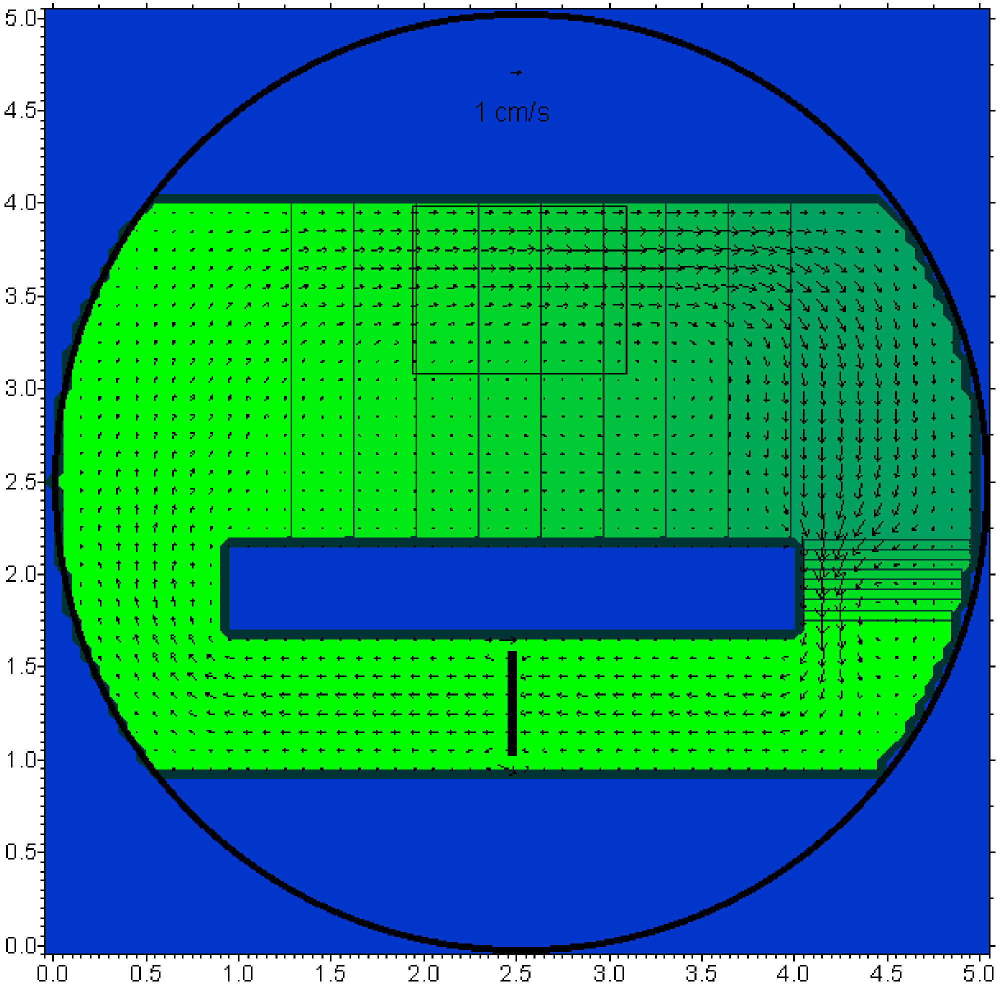


Application of a numerical model

The application of a numerical circulation model based on the shallow water equations has helped (in both the experiment in Grenoble and in this one) in defining an optimal experimental setup.

The same model was used throughout the experimental activity in order to provide a preliminary interpretation of the results.

For instance, running the linearized version of the model allowed us to obtain a clear information on the role played by the nonlinearities in shaping the flow.



Scaling

$$\varepsilon = \frac{U}{fL}; \quad \beta^{*} = \frac{f}{D} d_{y}; \quad \delta_{I} = \left(\frac{U}{\beta}\right)^{\frac{1}{2}}; \quad \delta_{M} = \left(\frac{\nu}{\beta}\right)^{\frac{1}{3}}; \quad \delta_{E} = \left(\frac{2\nu}{f}\right)^{\frac{1}{2}}; \quad \delta_{S} = \frac{\delta_{E} f}{2D\beta}$$

parameters for the Gulf Stream:

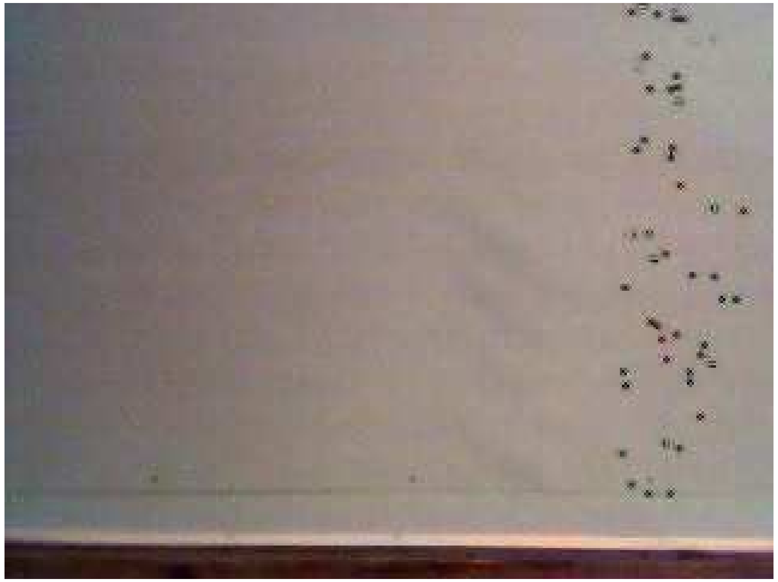
U~1 m/s, L ~100 km, f ~10^{-4} rad s^{-1}, β~$2x10^{-11}$ rad m^{-1} s^{-1}, ν~100-1000 m^{2} s^{-1}

parameters for Coriolis (Run50):

U~2.5 cm/s, L ~0.5 m, f ~0.42 rad s^{-1}, β~0.14 rad m^{-1} s^{-1}, ν~10^{-6} m^{2} s^{-1}, D~0.3 m

	ε	δ_I	δ_M	δ_E	δ_S	δ_I / δ_M	δ_M / δ_S
Gulf Stream	0.10	223 km	17-36 km	-	-	6-13	-
Coriolis (R.50)	0.12	41 cm	1.9 cm	2.2 mm	1 cm	21	1.8

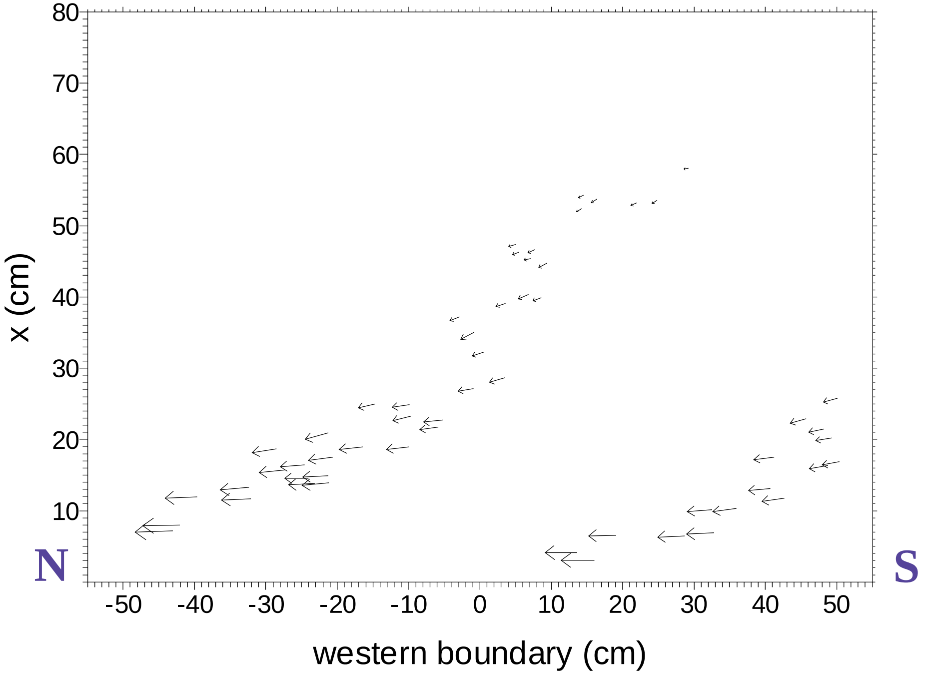
MOVIES



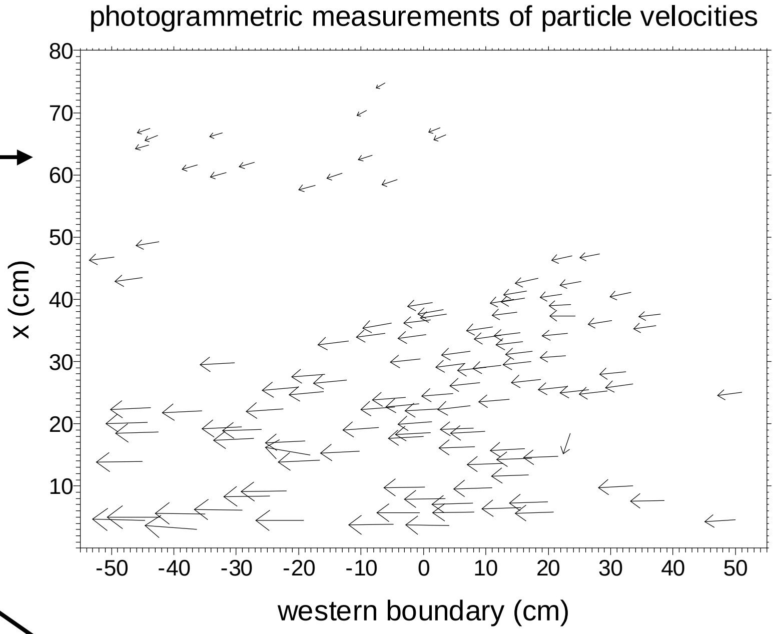
Particle velocities measured at t=60 s for Run2 (D_2=17 cm, thin island, T_{rot}=30 s, u_{paddle}=1 cm/s)

(this is a preliminary experiment in which the particles were not seeded in a proper way; see the next slide for more correct distributions)

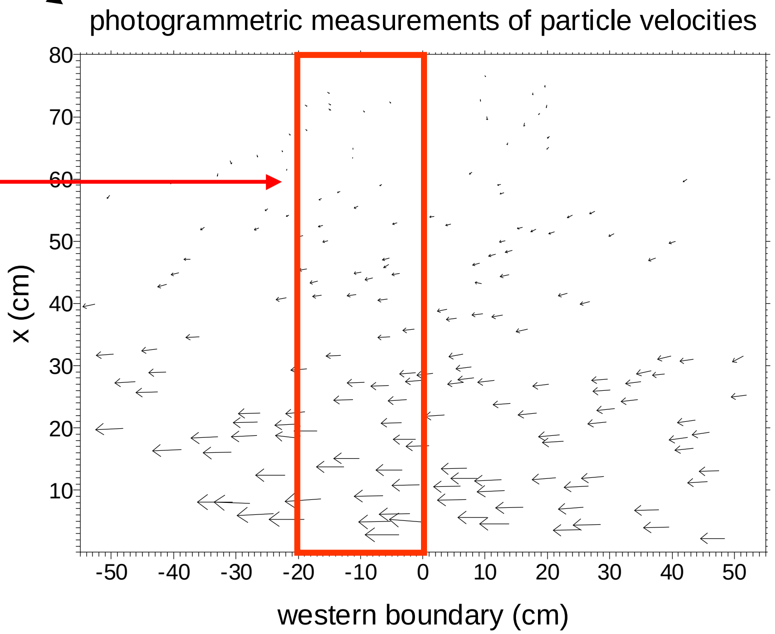
photogrammetric measurements of particle velocities



Particle velocities measured
at t=100 s for Run18
(D_2=17 cm, thin island,
T_{rot}=60 s, u_{paddle}=2 cm/s)

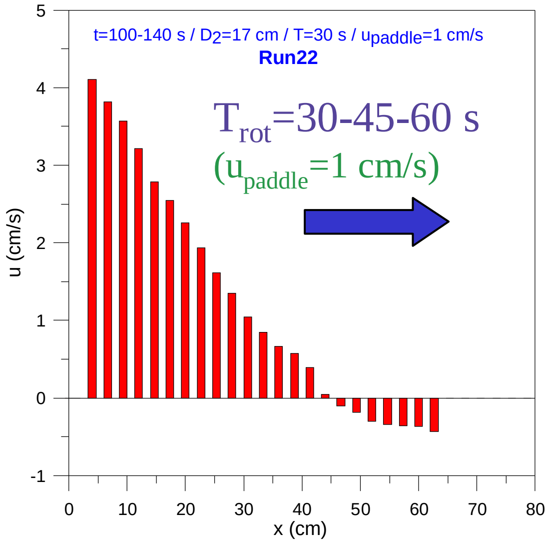


Particle velocities measured
at t=100 s for Run23
(D_2=17 cm, thin island,
T_{rot}=45 s, u_{paddle}=1 cm/s)



In the bar charts shown in the next pages each istogram represents the along-channel velocity averaged over one of the 30 sectors in which the red rectangle on the right is subdivided along x.

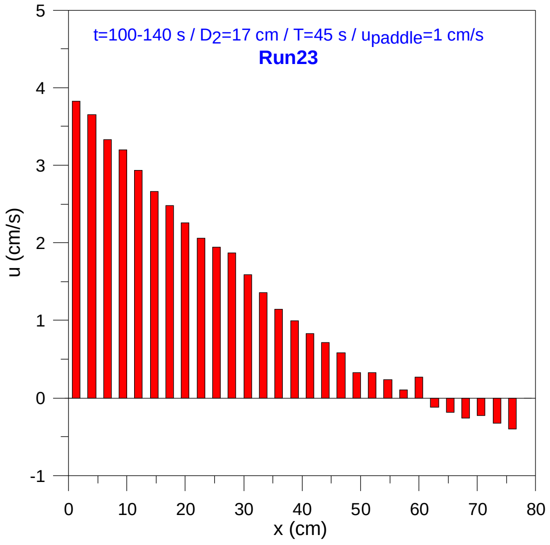
A temporal average is also performed. The time interval (t_1,t_2) (reported in blue in each bar chart) is chosen so that t_1 is just after the spinup is achieved and t_2 is just before the piston stops. During this period the flow is nearly stationary.


t=100-140 s / D_2=17 cm / T=30 s / u_{paddle}=1 cm/s

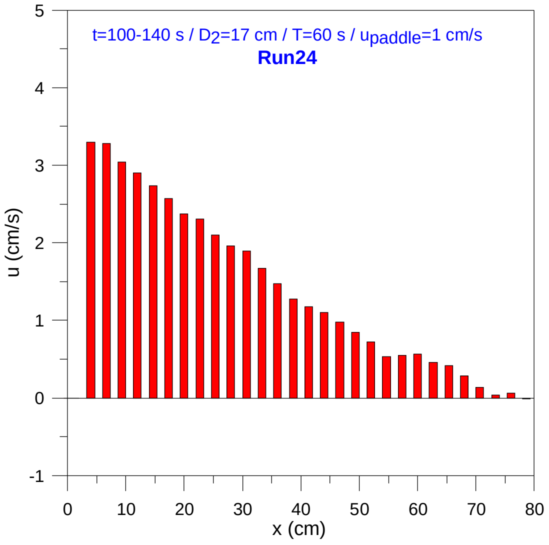
Run22

T_{rot}=30-45-60 s

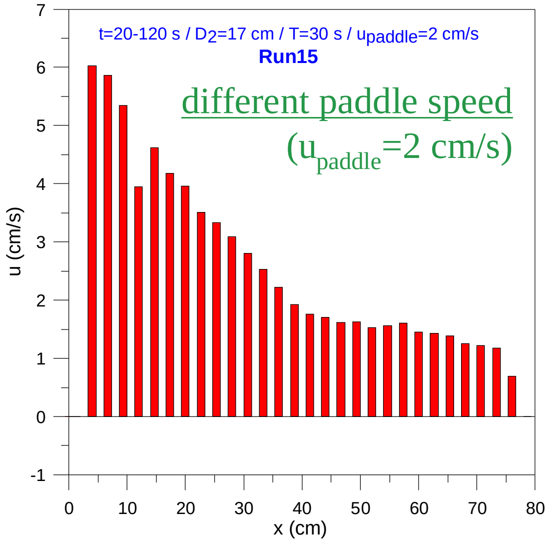
(u_{paddle}=1 cm/s)


t=100-140 s / D_2=17 cm / T=45 s / u_{paddle}=1 cm/s

Run23


t=100-140 s / D_2=17 cm / T=60 s / u_{paddle}=1 cm/s

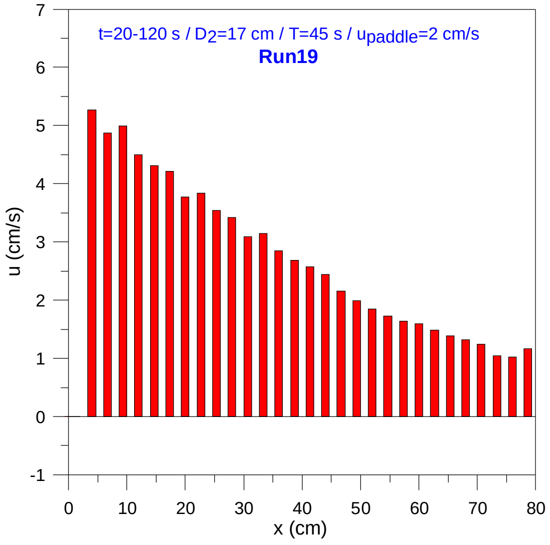
Run24


t=20-120 s / D_2=17 cm / T=30 s / u_{paddle}=2 cm/s

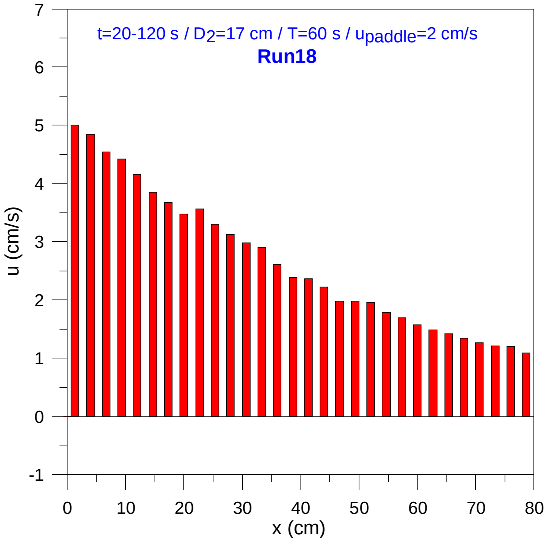
Run15

different paddle speed

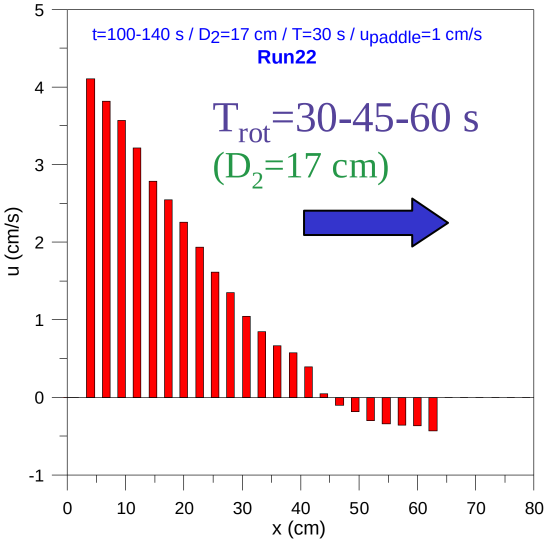
(u_{paddle}=2 cm/s)


t=20-120 s / D_2=17 cm / T=45 s / u_{paddle}=2 cm/s

Run19


t=20-120 s / D_2=17 cm / T=60 s / u_{paddle}=2 cm/s

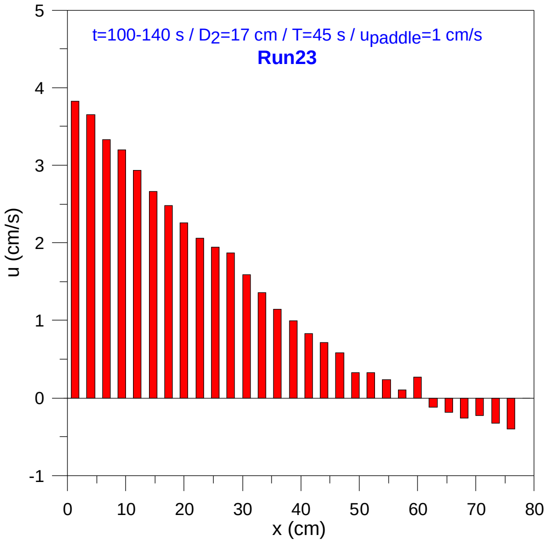
Run18


t=100-140 s / D_2=17 cm / T=30 s / u_{paddle}=1 cm/s

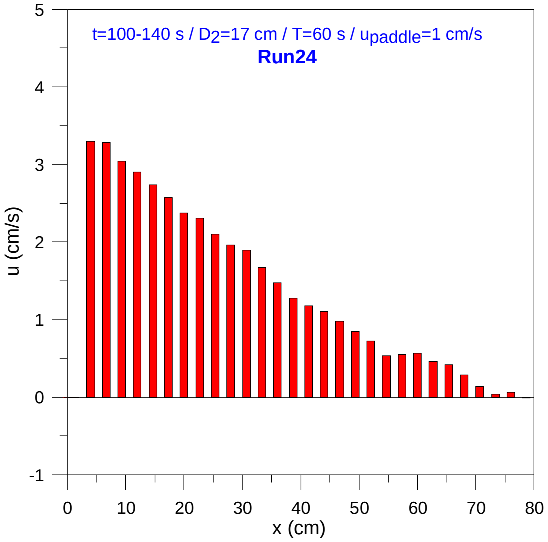
Run22

T_{rot}=30-45-60 s

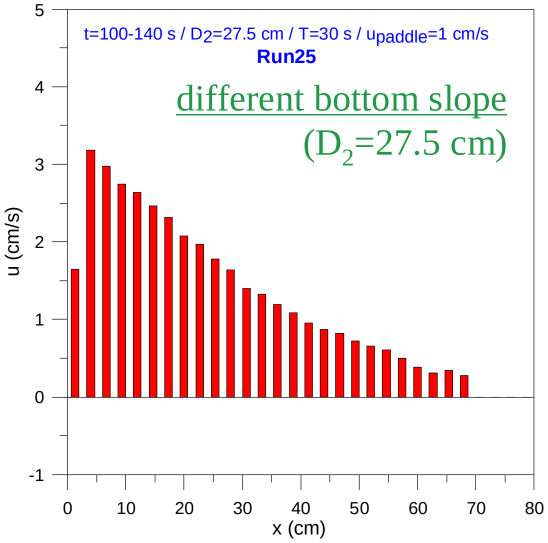
(D_2=17 cm)


t=100-140 s / D_2=17 cm / T=45 s / u_{paddle}=1 cm/s

Run23


t=100-140 s / D_2=17 cm / T=60 s / u_{paddle}=1 cm/s

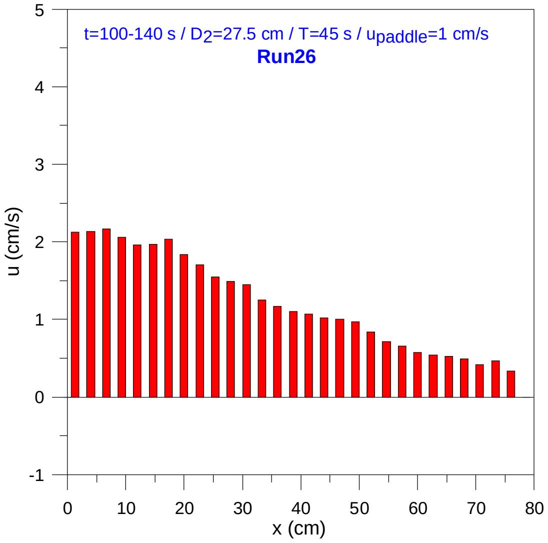
Run24


t=100-140 s / D_2=27.5 cm / T=30 s / u_{paddle}=1 cm/s

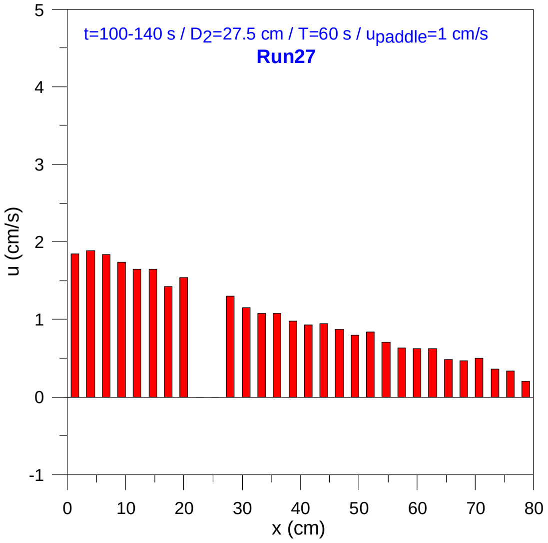
Run25

different bottom slope

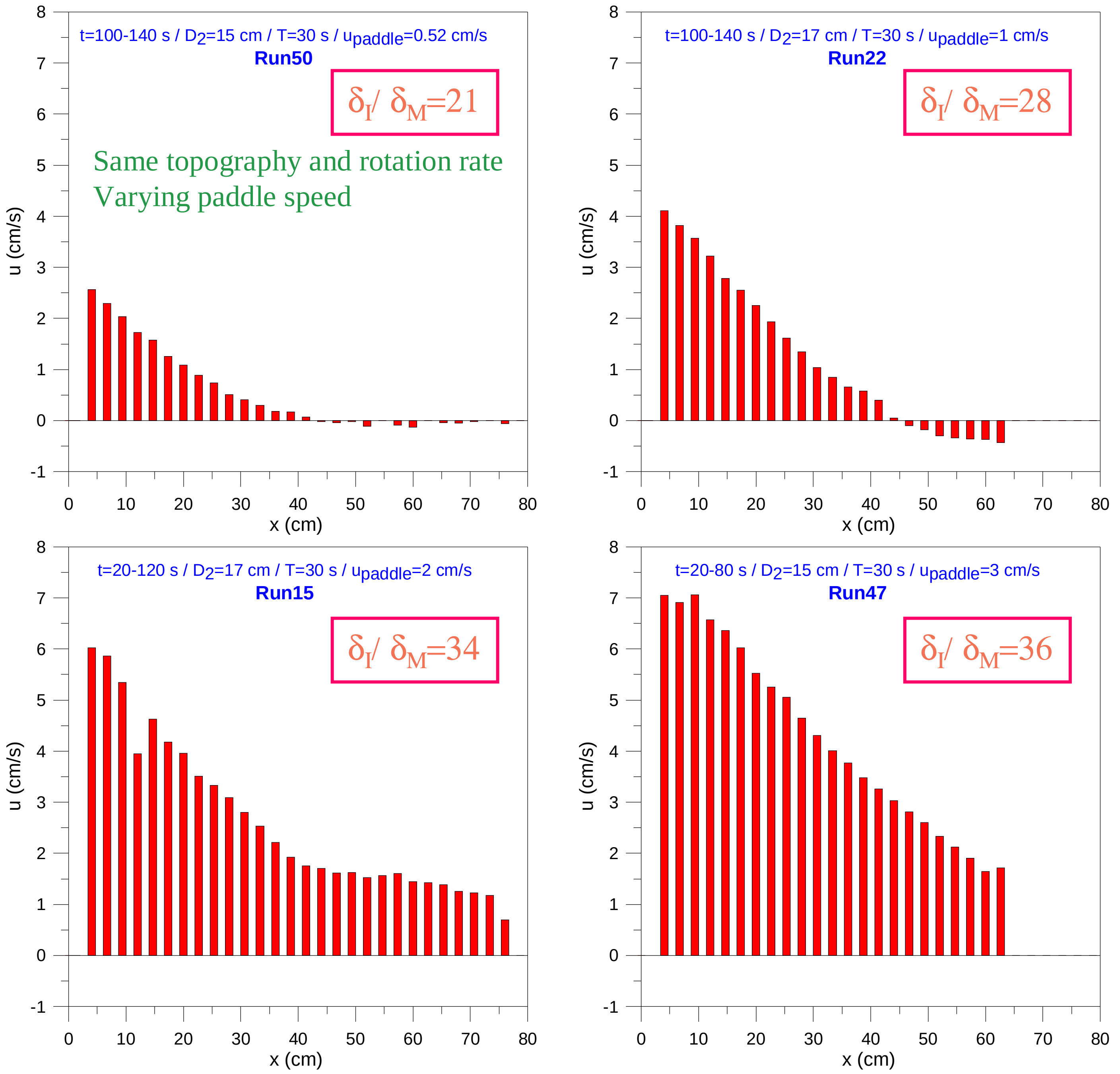
(D_2=27.5 cm)

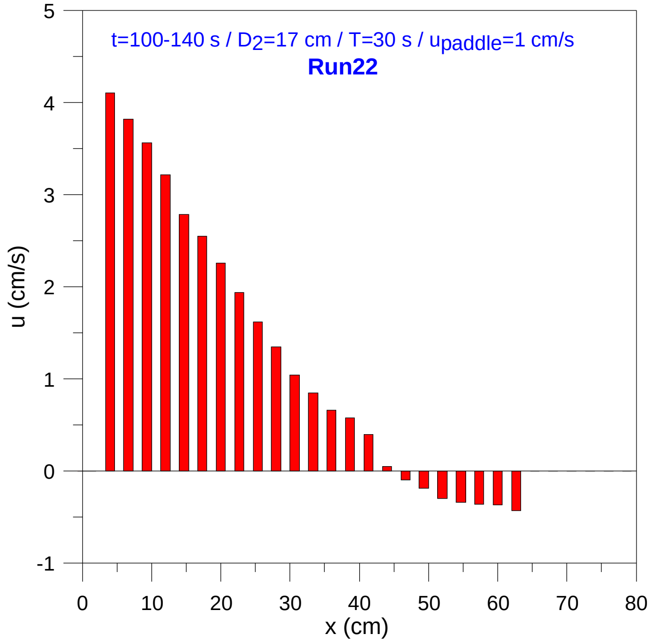

t=100-140 s / D_2=27.5 cm / T=45 s / u_{paddle}=1 cm/s

Run26

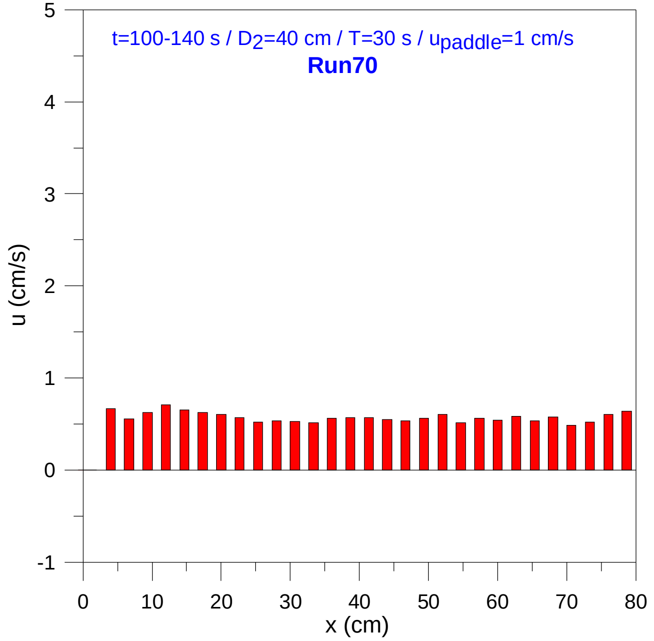

t=100-140 s / D_2=27.5 cm / T=60 s / u_{paddle}=1 cm/s

Run27

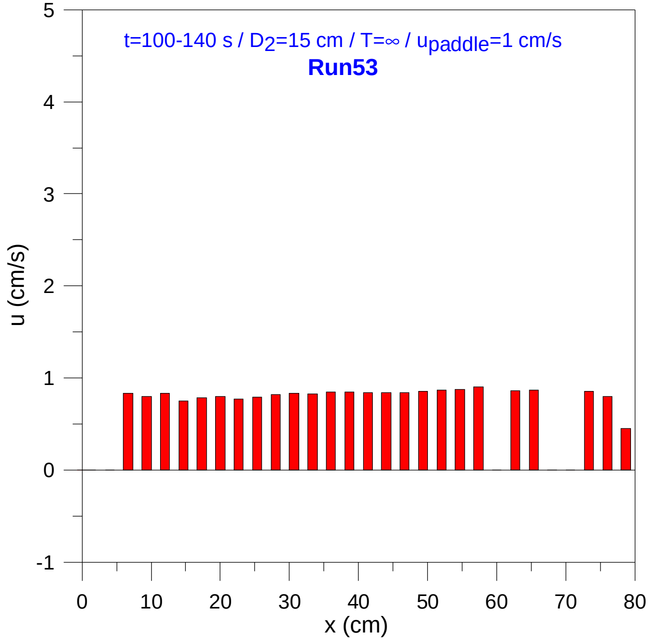

Same topography and rotation rate
Varying paddle speed



flat bottom



non-rotating platform



Conclusions

Western boundary currents along a straight coast have been modeled in the rotating basin available at *SINTEF* (Trondheim, Norway) with the aim of investigating the character of *WBC* variability through the study of the zonal structure of the flow, with particular attention to its dependence on total transport.

The laboratory setup consisted of two parallel rectangular channels separated by an island and linked by two curved connections.
In the first rectangular channel a piston was forced at a constant speed, producing a virtually un-sheared current at the entrance of the second rectangular channel. In the latter, an alongshore variation of the water depth provided the topographic *beta*-effect necessary for the formation of *WBCs*.

Before starting the piston, **several hundred small buoys were seeded** over the entrance of the second channel. These were then advected by the induced currents to the region of interest. **The velocities of the buoys were measured photogrammetrically** over a window of about 1 m^2 adjacent to the coast where the *WBC* was present.

A complete set of sensitivity experiments was carried out by varying the Coriolis parameter, the piston speed, the topographic beta-effect (bottom slope) and the island width.

The choice of the appropriate nondimensional numbers insures that **the flows reproduced experimentally at small scale include the most significant examples of *WBCs* in the world oceans**.

The application of a **numerical circulation model** based on the shallow water equations helped in defining an optimal experimental setup.
The same model was used throughout the experimental activity in order to provide a preliminary interpretation of the results.

In all the experiments ***nonlinear* effects are very relevant**, as in real *WBCs*. The possibility of analyzing the role played by nonlinearities, made possible by a large set of sensitivity experiments in which the transport is varied, appears to be a particularly original and useful result.