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Comparison of lab experiments and numerical simulations on the behavior of source flows

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Abstract :

Source flows in a rotating tank are carried out to investigate the behavior of boundary currents. In the laboratory experiments, there is a northern boundary current which thickness increase with source strenght and a thin western boundary current which shows meandering behavior as the flow rate is increasing. The comparison with numerical simulations using the Miami Isopycnal Coordinates Ocean Model shows similarities but also some discrepancies with lab experiments mainly near the source and in the western boundary current.

Résumé :

Des écoulements avec source dans une cuve tournante sont effectués pour étudier le comportement des courants de bord. Dans les expériences de laboratoire, il y a un courant de bord nord dont l'épaisseur augmente avec le débit de la source et un fin courant de bord ouest qui méandre quand le débit augmente. La comparaison avec des simulations numériques employant le modèle MICOM montre des similitudes mais également quelques différences avec des expériences de laboratoire principalement au voisinage de la source et dans le courant de bord ouest.

Key-words :

Source flows, Lab experiments

1 Introduction

The choice for boundary dynamical conditions in ocean circulation models is a very discussed topic and western boundary currents are shown to be very sensitive to the chosen boundary conditions and friction parametrization (Dengg (1993), Haidvogel et al. (1992), Chassignet & Garraffo (2001)). The relevant nondimensional numbers for western boundary currents are the Rossby $Ro = \frac{U}{f.L}$ and Ekman $Ek = \frac{A_H}{f.L^2}$ numbers, where U is the velocity, f the coriolis parameter, L the current thickness and A_H the horizontal eddy viscosity. The typical values for western boundary currents are $Ro = 0.1$ and $Ek = 0.01$. Western boundary currents can be reproduced in the laboratory with source/sink flows. Fluid is injected within a pie-shaped or half-cylinder tank at some location, the parabolic shape of the free-surface acts like a topographic β effect. The injection leads to the rising of the free-surface and, as the interior is geostrophic, fluid columns move northward to conserve their depth and a western boundary current closes the mass transport. Those experiments were first developed by Stommel, Arons & Faller (1958) to study abyssal circulation and further described by Kuo & Veronis (1971) and Veronis & Yang (1972).

2 Description of the Experiments

The experimental setup is composed of a 1,5 meters wide rotating table. It is powered with a Labview monitored Omron DC motor which angular speed Ω ranges from 0.3 to 2.2 rad.s⁻¹. Experiments are performed in a square tank which length is $L = 92$ cm with a sloping bottom to reproduce the earth β effect. Fluid is injected within the tank from a separated reservoir with an Ismatec Reglo-Z digital pumping motor and Micropump gear pump head, which are the most efficient to keep a continuous flow rate and are not sensitive to pressure head. The fluid is injected at the norwestern (with respect to the β plane) corner of the tank through a diffusive unit to reduce turbulence near the source. The flow rates S ranges from 3 to 20 mL/min and the water height at rest is $H = 25$ cm.

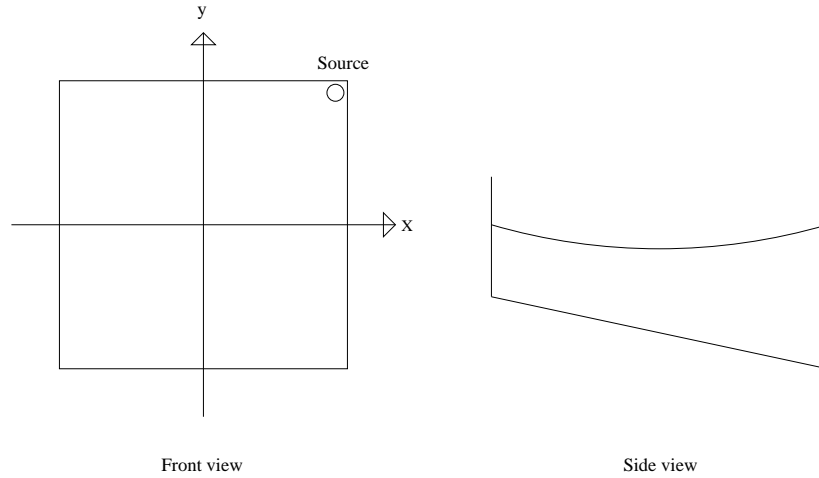


Figure 1: Details of the experimental setup

As the studied flows are weak, the wind-stress can greatly affects them so the tank is covered by a lid away from the free-surface. Once rigid rotation is achieved, the fluid is injected within the tank during 20 to 30 minutes before the measurements begin in order to allow Rossby waves to decay. As proposed by the pionnering article by Stommel, Arons & Faller (1958), the circulation in the tank can be considered as steady if the amount of fluid injected during one period is much smaller than the whole tank volume, which is always the case in the experiments. In addition with the β plane whose slope is $\alpha = 0.12$ rad, there is also a free-surface β effect. Provided the rotation rate is not too high, the effect of the paraboloid is small compared to the sloping bottom but for higher rates its impact become comparable so that all the experiments were made with weak rotation rates.

In those experiments, theory predicts that the geostrophic interior would have northward velocities and a southward western boundary current to close the circulation. As the free-surface vertical velocity is $w = \frac{S}{L^2}$, the interior geostrophic velocities given by $\tan \alpha \cdot v = w$ are very weak (about 10^{-3} mm/s). The mass closure involves that $T_w = S(\frac{3}{2} + \frac{H_0}{L \tan \alpha})$ where T_w is the transport of the boundary current and H_0 the fluid depth in the center of the tank, which leads to velocities in the western boundary current of order 0.1 mm/s. Laboratory experiments are carried out with various source strenght ranging from $S = 3$ to $S = 20$ mL/min and a rotation period of $T = 10$ s, the fluid from the source is then deflected to the right by the coriolis force

and follow the northern boundary in a thin layer of a few centimeters thick and diverges at some point near the norwestern corner and enters the western boundary layer (see figure 2). When flow rate is increased (see Figure 3 & 4), the northern boundary current gets thicker with distance from the source. The western boundary current velocity is then order 1 mm/s and increase with source strenght. In addition, the western boundary current shows a meandering behavior which is enhanced by the flow rate.



Figure 2: Experiment with $S = 3$ mL/min and $T = 10$ s

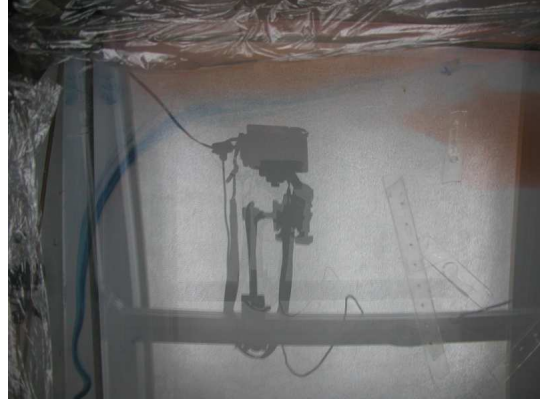


Figure 3: Experiment with $S = 14$ mL/min and $T = 10$ s



Figure 4: Experiment with $S = 20$ mL/min and $T = 10$ s

3 Model description

The numerical model used for the simulations is the Miami Isopycnal Coordinates Ocean Model (see Bleck & Boudra (1986), Bleck & Smith (1990) for details) in a one-layer square basin with sloping bottom and parabolic free-surface. The model's resolution is slightly less than one centimeter and features no-slip boundary conditions, which seemed to be the more relevant in order to compare with lab experiments. Bottom friction is parametrized using a linear drag similar to the ekman layer dynamics with friction coefficient equal to the inverse spin-down time

$r = \frac{\sqrt{\nu\Omega}}{H_0}$. Lateral dissipation is achieved with an harmonic operator which coefficient is chosen to be equal to the molecular diffusion. The model's equations have been slightly changed to include a source of fluid in the continuity and free-surface equations. The models equations are then :

$$\partial_t \mathbf{u}_i + (\mathbf{u}_i \cdot \nabla) \mathbf{u}_i + \mathbf{f} \mathbf{k} \otimes \mathbf{u}_i = \nabla M_i \quad (1)$$

$$\partial_t h_i + \nabla(h_i \mathbf{u}_i) = w_{si} \quad (2)$$

with i the layer index, h_i the layer's depth, $\mathbf{u}_i(u_i, v_i)$ the horizontal velocities, M_i the Montgomery potential, \mathbf{k} the vertical unit vector, w_{si} , the vertical velocity due to fluid injection in the layer.

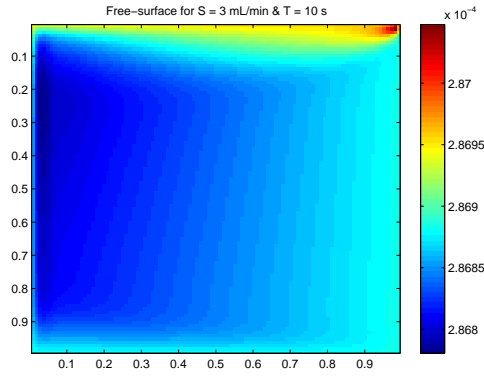


Figure 5: Numerical simulation with $S = 3$ mL/min and $T = 10$ s

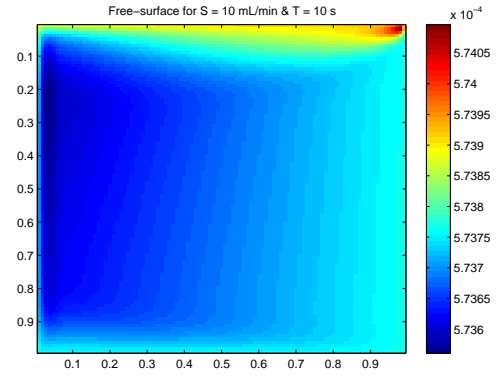


Figure 6: Numerical simulation with $S = 10$ mL/min and $T = 10$ s

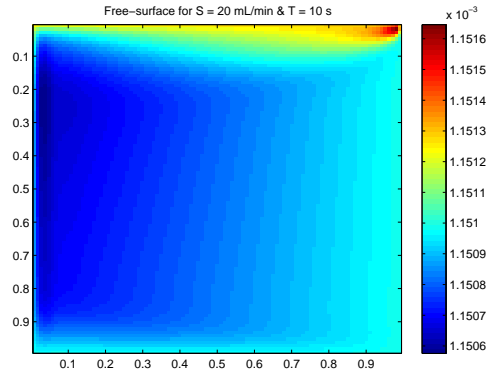


Figure 7: Numerical simulation with $S = 20$ mL/min and $T = 10$ s

The model exhibits a small anticyclonic vortex near the source due to the vertical velocities involved by the fluid injection, the northern boundary current near the source is weaker than in the experiments due to this anticyclonic vortex and converges in the western half of the northern boundary with velocities similar to the laboratory experiments and feeds the western boundary current in which velocities are also in agreement with those measured in the tank. The rest of the basin is then a western intensified cyclonic gyre as predicted by the theory. Nevertheless, no meandering features are found inside the numerical simulations.

4 Conclusions

Laboratory experiments and numerical simulations were carried out to investigate the behavior of source flows in a rotating tank. In the tank, one can see the presence of a northern boundary current which thickness increase with source strength and a meandering behavior of the western boundary current enhanced by flow rate. The model and the lab experiments shows similarities but also some discrepancies. The model is in agreement with experiments for the overall circulation and the order of magnitude of boundary currents velocities. Though, the numerical simulations exhibits a larger anticyclonic vortex than in the experiments, the northern boundary thickness is independant of the source strenght and the western boundary current does not have any meanders.

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