SCALING PROPERTIES OF DENSE WATER OVERFLOWS ON A CONTINENTAL SLOPE

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Abstract :

Dense overflows on a continental slope play an important role in renewing deep water as part of the global thermohaline convective cycle of the oceans. We report here laboratory experiments reproducing this phenomenon on the large 'Coriolis' turntable in Grenoble, providing good dynamical similarity with the oceanic case.
The gravity current is created by salty water injected with a constant flux, which flows down the incline slope (2m wide, 10m long, 15 degrees of inclination) with intense turbulent mixing. It is deviated by the Coriolis force to a cross-slope horizontal direction. We study both the cases of a homogeneous and density stratified ambient fluid.
Velocity fields are measured by particle image velocimetry (PIV). Density profiles are also measured to determine the width, thickness and position of the gravity current, and to measure the mixing process. A self-similar behaviour is observed generalizing results for turbulent self-similar plumes and jets to this situation.

Résumé :

Key-words :

gravity currents ; turbulence; mixing

1 Introduction

Plumes are flows generated by a density contrast between a continuous source fluid and its environment, modifying the global distribution of temperature and salinity. In oceanography, these dense overflows on a continental slope are very active as they take part in the production of the North Atlantic deep waters. Cold water from Nordic seas or salty water from the Mediterranean Sea descend into the Atlantic ocean over a sill, resulting in mass exchange with high density gradient, instabilities and generation of mesoscale vortices. Observation of the dense overflow in the Denmark strait is possible from in-situ measurements of density (1). Cooling of warm and salty waters from the Gulf stream in the Nordic seas generates the descent and spreading of the denser water masses created, which then propagate along the East Greenland coast This overflow is schematically reproduced in laboratory experiments described below.

The bottom friction effects and the turbulent mixing process involved in these dense currents has been studied by theoretical, numerical and experimental analysis, usually in non-rotating systems, as reviewed by Simpson (2). The first experiments performed to study the gravity current front, on a non-rotating slope, were carried out by Ellison and Turner (3). When the dense current flows down the continental slope, entrainment of the ambient fluid causes mixing. In the case of a two-dimensional plume on a slope (of inclination α) in a non-rotating system, Ellison and Turner (3) suggested that the entrainment is proportional to the mean velocity U in the downslope direction x, with a proportionality constant E. The mixing and turbulent entrainment theory has been further developed by Turner (4), assuming that the entrainment parameter is a function of the Richardson number $E(R_i)$.

The actual parameterization in oceanic numerical models make use of these theories, even though the Coriolis effect was missing in the experiments. These mixing model have been extended to density stratified environments by Baines (5), but the experiments show that it is not appropriate. The resulting downflow has a uniform thickness until it reaches its level of equal density. A model based on observations of the flow has been derived, describing the turbulent transfers in term of local entrainment, detrainment and drag coefficients.

But the Coriolis effect due to the earth rotation, induces significant changes on large-scale flows dynamics (Griffiths (6)). Laboratory experiments have been performed in rotating systems like Whitehead et al. (7) who observed the generation of cyclonic vortices, similar to eddies seen in the Denmark strait. Other experiments in quasi-laminar regime with no turbulent mixing confirmed this behaviour (Lane-Serff and Baines (8) or Etling et al. (9)). In fact several types of flows are observed in rotating experiments, as characterized by Cenedese et al. (10): A laminar regime where no mixing occurs between the current and the ambient fluid; a wave regime also described by Shapiro and Zatsepin (11) where wave perturbation appear at the interface between the dense fluid and the ambient; and an unstable regime with generation of periodic cyclonic vortices in the ambient fluid, over the gravity current, modifying its propagation.

In fact, the Coriolis facility at LEGI (Grenoble) is the only turntable which allows the study of a fully turbulent gravity current strongly influenced by rotation. Thanks to its large dimension (13m in diameter), inertial regimes that characterize the ocean dynamics are approached.

The purpose of this study is to determine experimentally the main characteristics of a gravity current flowing down a slope in a rotating system. It is important to measure the effects of bottom friction influencing the current's final stabilized position along the slope, and the effects of mixing due to entrainment and detrainment with the ambient fluid, that controls the density of the gravity current and its velocity. Development of instabilities generating large cyclonic eddies propagating along the incline slope, is also observed.

The experiments are performed on the large Coriolis turntable (Grenoble) with the experimental setup described in figure 1. The gravity current is created by salty water injected with a constant flux, in the ambient fluid of uniform lower density. The controlled parameters are: the initial density difference between the gravity current and the environment $g'_o = \Delta\rho/\rho_o$; the initial flow flux Q_o (generally expressed as the buoyancy flux $B_o = g'_o\, Q_o$); and the rotation period T of the turntable giving the Coriolis parameter $f = 4\pi/T$.

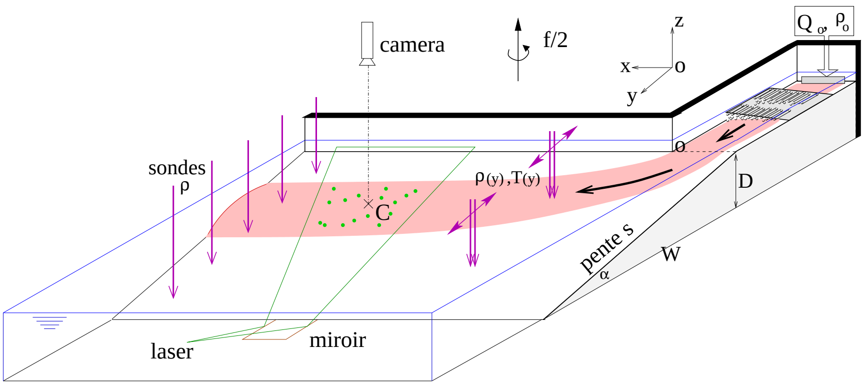
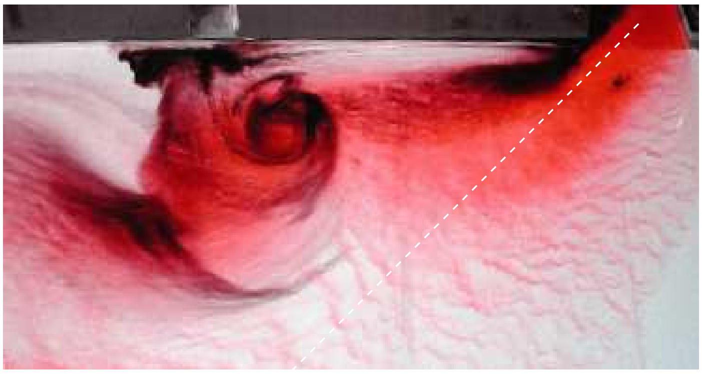


Figure 1: Schematic representation of the experimental setup, with the position of the probes and laser.

The dense fluid starts flowing down the incline slope s of 2m wide, 10m long and 15^o of inclination. It behaves as a gravity current in self-similarity, with intense mixing occurring at the interface with the ambient fluid, as visualized in figures 2. It is then deflected by the Coriolis force and reaches an equilibrium depth, in a state of geostrophic balance along the slope, with nearly horizontal mean velocities. However a small part of the fluid moves downward in the bottom viscous boundary layer. It is subject to a friction driven instability, as seen in figure 2a. Another instability, of baroclinic kind, is observed over the main current, generating large vortices stretching over the whole water depth, which greatly modifies the current propagation.



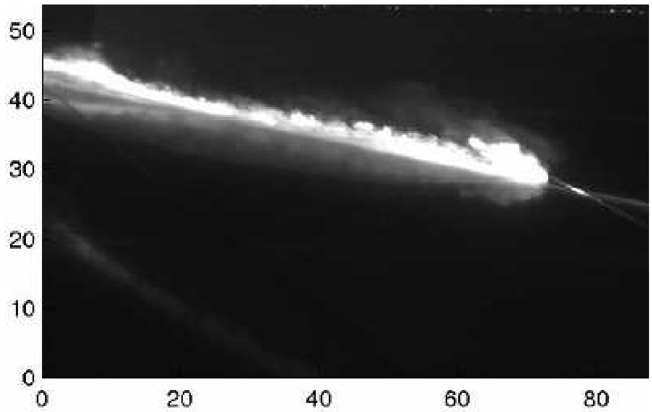


Figure 2: Visualization of the gravity current: **a.** The current (red dye) splits into a geostrophically balanced jet flowing along the slope and a thin viscous layer descending the slope. The main current is subjected to baroclinic instabilities which induce cyclonic vortices. These extend over the whole water depth, as visualized by the black dye released above the current. **b.** The vertical cut (fluorescein illuminated by a vertical laser sheet along the oblique line drawn in figure a) shows that the current thickness decreases at the beginning of the slope before growing because of turbulent mixing.

Velocity fields are measured by particle image velocimetry (PIV). The current is seeded with particles illuminated by a laser sheet directed along the slope at different heights from the bottom. Probes are also used to record density variations at different locations.

1.1 Similarity between laboratory and oceanic scales

The similarity between experiments and the oceanic scale is determined by keeping non-dimensional numbers constant. From the six dimensional parameters, one can define four independent non-dimensional parameters. These are usually defined in terms of the initial current thickness h_o, width L_o and velocity V_o. These quantities are indirectly set by the flow rate $Q_o = \frac{h_o\,L_o}{2} V_o$, or the related buoyancy flux $B_o = g'_o\,Q_o$. To connect them to the known parameters, it is assumed that the gravity current has an initial speed $V_o = c_1\sqrt{g'_o\;h_o}$ (where $c_1 = 0.5$, resulting from measurements), and that the dense fluid adjusts itself in geostrophic equilibrium in the hydrostatic approximation (for large scales): $f\;V_o = \frac{g'_o\,h_o}{L_o}$.
From these relations, the thickness, width and velocity can then be expressed as:

$$V_o = \frac{1}{2}\,(2\;f\;B_o)^{1/4} \tag{1}$$

From the initial parameters (the Coriolis parameter f, the initial buoyancy flux B_o and the gravity acceleration projected onto the horizontal ($s\;g'_o$)), only one non-dimensional number can be derived:

$$M = s\;g'_o\;f^{\text{-5/4}}\;B_o^{\text{-1/4}}\;2^{\,3/4} = \frac{sg'_o}{f\,V_o} = \frac{\text{topographic slope}}{\text{initial geostrophic slope}} \tag{2}$$

This important quantity is also the ratio of the topographic slope s over the natural slope of the isopycnals given by the initial geostrophic equilibrium (h_o / L_o = $f\;V_o$ / g'_o).

The Burger number based on the initial width and velocity of the current is always constant: $R_o = \sqrt{g'_o\, h_o} \Big/ (f\ L_o) = 1/2$

Finally, the Reynolds number based on the initial current height $R_e = V_o\, h_o / \nu = \nu^{-1} (f\ B_o)^{3/4}\ \ g'^{\,-1}_o\ \ 2^{-1/4}$ is of the order of 2000 or higher in most experiments. Even though this value is much smaller than an oceanic case, it is admitted that global entrainment and turbulent mixing properties do not depend on the Reynolds number for values higher than 1000. This similarity explained in table **??** shows that a typical experiment reproduces a continental slope of 122km wide and 3km deep.

1.2 Scaling laws on the overflow

In order to analyse all the data obtained from the experiments, some scaling laws have been introduced.

The parameter M introduced in the similarity assumption can also be interpreted as a representation of the mixing. If M is small, there is no mixing and the current stays in the same state. While if M is large, the current will reach a new state of geostrophic equilibrium along the slope. The gravitational acceleration is balanced by the Coriolis effect, so that the slope of the interface of the dense current is equal to the topographic slope. The along-slope speed (known as the Nof velocity) is then:

$$U = g'\ s\ /\ f$$

As the flow is deviated by the Coriolis effect, the associated length scale is $L = U\ /\ f$, with a velocity also expressed as $U = c_2\sqrt{g'\ h}$.

It is assumed that the initial buoyancy flux is conserved $B_o = h_o\ L_o\ V_o\ g'_o\ /\ 2 = h\ L\ U\ g'$. The dynamics of the current depends only on the initial buoyancy flux, and not on the other initial parameters. Far enough from the source, the flow seems to forget its initial mass (g'_o) and momentum (Q_o) fluxes. It depends only on the buoyancy flux B_o. This is equivalent to the classical self-similarity assumption for turbulent plumes or jets, which has been extended here to gravity currents on a sloping bottom, in presence of rotation.

A very important parameter is therefore the typical length scale L_o (equation **??**) as it depends only on the buoyancy flux, and scales with the Rossby radius of deformation.

From these estimates, some simple scaling laws are derived on the ratio of flow quantities along the slope to their initial values, as a function of M:

$$\frac{g'}{g'_o} = \frac{c_2^{1/2}\ 2^{3/4}}{M} \propto \frac{1}{M} \qquad (3)$$

$$\frac{h}{h_o} = c_2^{-3/2}\ 2^{-5/4}\ M \propto M \qquad (4)$$

$$\frac{U}{V_o} = c_2^{1/2}\ 2^{3/4} \quad \text{, independent of M} \qquad (5)$$

The characteristics of the current along the slope depend only on the initial buoyancy flux conserved (or equivalently on the length scale $L_o \propto f^{-3/4}\ B_o^{1/4}$) and not on the initial conditions.

1.3 Experimental analysis

It is possible to check experimentally the assumption made to derive these scaling laws from the PIV measurements in planes parallel to the sloping bottom. Density profiles also enable to determine the width or thickness of the gravity current, and to quantify the mixing process.

The first result concerns the depth reached by the flow in equilibrium along the slope. It is determined by measuring the position of the maximum mean velocity along the slope at a distance L_o from the inlet channel . This distance scales with the Rossby radius of deformation ($L_o c_1 = (2\ B_o\ f^{-3})^{1/4}$). The downslope excursion is found to be $(2.32 \pm 0.05)\ (L_o\ c_1)$, as obtained by Lane-Serff and Baines (8) for smaller Rossby numbers.

Those results confirm that the fluid dynamics only depends on the initial buoyancy flux. The fluid is in geostrophic equilibrium along the sloping bottom and M is the important parameter with the length scale L_o. This behaviour is also obtained from the mean along-slope velocity U profiles (made in the downslope direction), performed at the distance L_o from the channel. Those profiles are normalized in velocities by U/V_o and in position by y/L_o. All the curves of the experiments performed superimposed, even for runs with completely different initial parameters. This emphasizes once again that there is a kind of universal law predicting the pattern of the flow such as the along-slope velocity, the position of equilibrium or the width of the gravity current.

1.4 Cyclonic eddies

The frequency of the cyclonic vortices is obtained either from density records at a fixed position, or from velocity variations over the current. In both cases, the oscillations observed correspond to the passing vortices. The ratio of the vortices period over the turntable period is found constant. This is compatible with vortices created by a baroclinic instability.

1.5 Mean velocities and turbulent stress

The velocity fields, averaged in time, can be used to investigate the intensity of velocity fluctuations due to horizontal turbulence, and the Reynolds shear stress. These intensities strongly depend on the cyclonic vortex formation and propagation. Different kind of trajectory for the cyclones are observed, depending on the dense current thickness. When the current is thick, eddies are carried along in its wake, and they stay over it. Velocity fluctuations are therefore significant. But if the gravity current thickness is smaller, the cyclones propagation is controlled by the beta effect corresponding to the sloping bottom, and eddies leave the current to follow their own trajectory. Velocity fluctuations are weaker in that case. This shows that the thickness of the gravity current over the height of the water column over it, is an important parameter that has not been taken into account in the scaling set previously.

1.6 Conclusions

The dynamics of a dense water overflow on a continental slope has been reproduced in a laboratory, including small scale turbulent mixing: effects of rotation and density stratification are reproduced in dynamical similarity, and the gravity current is fully turbulent.

The existence of a self-similar gravity current on a slope in a rotating system has been demonstrated by experimental results. The scaling laws for such flows has been obtained. The mixing of this current with the surrounding fluid has then been characterized, providing support for modeling of turbulence in such systems.

Acknowledgements

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