Frontal instability, inertia-gravity wave radiation and vortex formation

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Abstract :

This paper reports on an experimental investigation of the stability of a baroclinic front, as generated by the spin-up of a differentially rotating lid at the surface of a rotating two-layer fluid. In contrast to formerly reported experiments, we consider miscible fluids in a relatively wide annular tank. In the parameter space set by rotational Froude number and dissipation (i.e. ratio of spin-down time to disk rotation time), different flow regimes are observed, ranging from axisymmetric to irregular baroclinic instable flows. These regimes adjoin the regimes found for immiscible fluids by Williams et al. (2005) in a small device. Differences are the baroclinic unstable regime for lower Froude number than reported by Williams et al. (2005) suggesting Sakai Rossby-Kelvin waves and the formation of vortices. Observations suggest spontaneous emission of inertia gravity waves, which interact with the large-scale baroclinic wave and lead to intense mixing and the rapid formation of intense cyclonic vortices.

Résumé :

Cette article représente une étude expérimentale sur l'instabilité d'un front barocline qui a été généré par la mise en rotation différentielle d'un fluide bi-couche. Contrairement à d'autres expériences précédentes de ce type, nous considérons des fluides miscibles dans une cuve relativement grande. Dans l'espace déterminée par le nombre de Froude et le nombre de dissipation, nous observons différents régimes, allant des écoulements axisymétriques aux écoulements instables et irréguliers. Ces régimes adjoignent les régimes obtenus pour un fluide bicouche immiscibles par Williams et al. (2005) dans une cuve petite. Différente est l'apparition du régime barocline pour des nombres de Froude plus bas, suggérant les ondes Rossby-Kelvin de Sakai, et la formation des tourbillons. Les observations suggèrent l'émission spontanée des ondes inertie-gravitée lesquelles interagissent avec l'onde barocline à grande échelle, et ainsi déclenche du mélange et la formation rapide des tourbillons intenses.

Key-words :

Fronts, waves, vortices

1 Introduction

Frontal structures play a key role for the transport of heat and mass in many geophysical flows. In the atmosphere, they determine our daily weather, whereas in the oceans, large scale jets such as e.g. the gulf stream or Kuro-Shio stream separate water masses of different temperatures and salinities. Instabilities of these fronts may cause the formation of meso-scale vortices which favor transport of mass and heat over larger distances. In the atmosphere, the potential-vorticity barrier of the polar vortex separates polar air from the warmer ambient air. In the oceans, vortex lenses equally separate different water densities. In the perspective of the inverse energy cascade in quasi two-dimensional flows and the self organisation of geophysical flows into large scale flow structures, frontal instabilities are relevant to the downscale energy transfer such as due to small scale turbulence. Inertia gravity waves and their spontaneous emission may play a key role in exciting this local turbulence.

In this context, baroclinic fronts as generated by means of a differential rotation disk at two-layer fluid surface, have been investigated in detail over the past decades (see e.g. Hart, 1979).

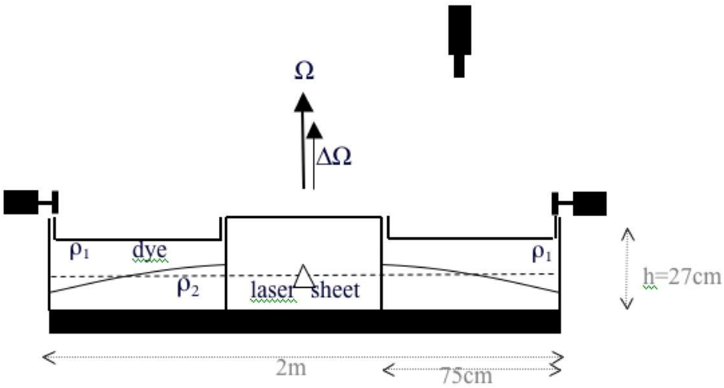

Figure 1: *Sketch of the experimental setup, with ρ_1 and ρ_2 the upper and lower layer fluid densities of depth H; the annular disk at the surface is driven by three motors with rotation $\Delta\Omega$.*

Most of these studies report, as a function of rotational Froude number and dissipation, the different regimes known as axi-symmetric flow, Kelvin Helmholtz instability, baroclinic unstable flow and its route to chaos. Recently it has been shown by Williams et al. (2005) (further referred to as WHR) and Lovegrove et al. (2000), that in the regimes with baroclinic waves, inertia gravity (IG) waves are emitted that were not observed before.
The spontaneous emission of IG waves has been predicted by a number of theoretical works under different flow conditions. Ford (1994) has shown the spontaneous IG wave emission in the shallow water approximation. For elliptical vortices Plougonven and Zeitlin (2002) consider wave radiation of an elliptical vortex in a linearly stratified fluid. Recently, Bühler and McIntyre (2005) have considered the three dimensional wave-capture in a vertical shear and horizontal strain field, and predict wave breaking without critical layer. For the case of a baroclinic lifecycle, numerical simulations of Plougonven and Snyder (2005) demonstrate the predicted spatial organization of the waves and show the alignment of the wave vector and wave emission in the regions of intense strain.
In order to model the instability properties of a baroclinic front, the formation of vortices and possible spontaneous emission of IG waves, we use an about 6 to 7 times larger setup than used in WHR, and filled with miscible fluids. In consequence, small scale motions are less affected by viscosity. Mixing and diffusion between the layers may lead to a more realistic interface thickness with different dynamics, whereas mixing processes may also enhance local vortex formation.

2 Experimental device

The experiments are conducted in an annulus of $R_1 = 200$cm outer- and $R_2 = 50$cm inner-diameter tank of 40cm working depth. The tank was filled with a stable two-layer salt-stratified fluid, with layers of depth H=13.5cm. The fluid surface was covered with a rigid Perspex lid, which, in order to apply a vertical shear, was brought into rotation by three wheels, driven by stepper motors. The wheels were placed at equal distances at the rim of the lid (see figure 1) and care was taken to minimize the disk perturbation, which was less than 1mm in vertical amplitude.

The tank was filled while rotating at a low rotation rate, Ω, of typically 0.05 rad/s. At t=0s, the rotation rate was slowly increased with an acceleration of $2.5\ 10^{-5}$rad/s, while the annular disk at the surface was started to rotate cyclonically with a constant rotation, $\Delta\Omega$, chosen in the range between 0.1 and 0.4 rad/s. The rotation speed of the tank was chosen below the critical rotation for centrifugal instability at the inner side-wall. For a final rotation speed of 0.5rad/s, the experiment could take up 5 to 6 hours. During the course of an experiment, the two-layer stratification remained in tact and apart from the final irregular flow stage, relatively little mixing occurred between the two layers. The flow Reynolds number, $Re = \Delta\Omega R^2/\nu$ where R is the radius at half-width of the gap, based on the disk rotation, was O(10^4); the Rossby number, $Ro = \Delta\Omega/(2\Omega)$ was initially O(1) and at the end of the experiment O(0.1). In coherence with former studies on annular two-layer flows, the experimental parameter regime was set by the rotational Froude number **Fr**= $4\Omega^2(R_2-R_1)^2)/(g'H)$ where the reduced gravity $g' = 2g(\rho_2-\rho_1)/(\rho_2+\rho_1)$, and the dissipation number, **d**= $\sqrt{(\nu\Omega)}/(H\Delta\Omega)$ determined by the ratio of the typical forcing time scale $1/\Delta\Omega$ and the Ekman spin-up time $\tau_{su} = H/\sqrt{\nu\Omega}$ at the interface.

To visualize the flow, fluorescent dye was dissolved in the top layer, which was illuminated by a horizontal laser sheet that intersected the inclined front at mid depth. In addition, in some experiments a vertical light-sheet visualized a radial section and allowed to visualize the mixing between the two layers, and the thickening of the interface. The flow evolution was recorded with two 8bit 25Hz CCD cameras. In a separate series of experiments, the horizontal velocity field in both layers was measured using PIV measurements, which served to know the induced velocity field by the rotating disk at the surface. For each experiment the values of **Fr** and **d**, which increase with $\Omega(t)$ in time, were plotted in a single graph (see figure 2) and the different regimes were determined qualitatively by scrutinizing theăevolution of the front from the recordings.

3 Observations

The results of these experiments are resumed in the logarithmic plot figure 2 and the different flow regimes represented in figure 3. In a typical experiment, after starting the rotation of the disk at t=0, the two-layers adjusted to a balanced shear flow in the form of a stable axi-symmetric front (see figure 3a). For higher Froude number and dissipation d, Kelvin Helmholtz instabilities started to grow (see figure 3b). The wave length of these KH waves decreased with background rotation, and disappeared within the regime RK.

In the regime RK a longer but new wavelength is observed. The shear profile, induced by the rotating disk at the sruface, has an increasing azimuthal velocity with a maximum approximately near 3/4 of the gap width and decreases to zero near the outer wall. The negative vorticity region near teh wall showed an oscillation with a wavelength that was of the order of the width of the negative vorticity region suggeting centrifugal instability as a mechanism. This wavelength is much smaller than that of the general baroclinic waves found in WHR. It is present over the entire front, but its amplitude saturated rather quickly (see figure 3c). Another possibility is the Rossby-Kelvin instability Sakai (1989) that occurs for a Froude number smaller than 1 (personal communication V. Zeitlin and R. Plougonven). This instability is due to the resonance between Rossby and Kelvin waves, and has so far not been reported in experimental studies. Further research is going on to determine whether this hypothesis is correct.

Eventually, in the regime MRW, the larger and faster growing baroclinic waves dominated (see figure 3d). These waves start in the regime RK for a much lower Froude number than that for

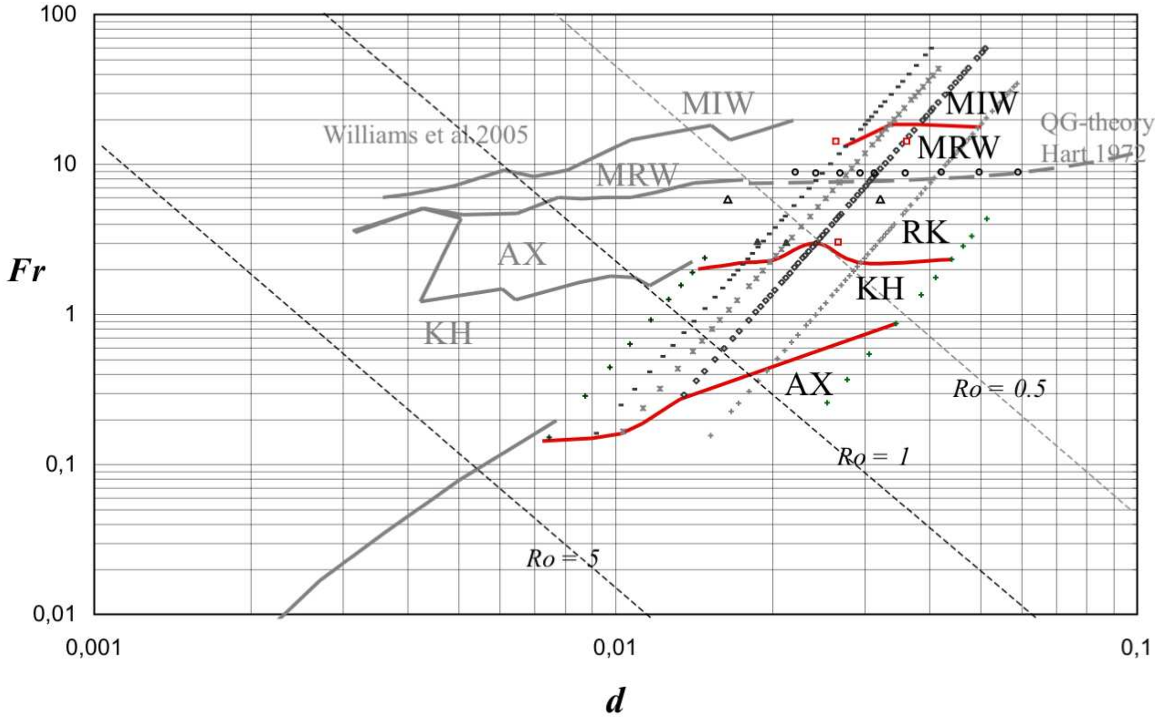

Figure 2: *Regime diagram, with the regimes (AX) Axisymmetric flow (KH) Kelvin Helmholtz instability, (RK) possibly Rossby Kelvin waves (see text) (MWR) Mixed Regular Waves with baroclinic and IG waves, and (MIW) Mixed Irregular Waves, separated by lines. RK differs from MRW in that baroclinic waves start in RK; in MRW only baroclinic waves are dominant, and IG waves are observed. The inclined dashed lines indicate the Rossby number based on the disk rotation $\Delta\Omega$. Each line of points corresponding to one experimental run in which the background rotation was increased; single points represent verifications with $\Delta\Omega$ varied for a constant rotation. Grey lines, left, represent results of Williams et al 2005. The grey dashed curve (right) represents the quasi-geostrophic neutral curve for baroclinic instability Hart (1972).*

baroclinic instability, and the predicted value by QG- instability theory of Hart (1972).

In the regimes MRW and MIW (see figure 3) baroclinic waves are dominant, and coexist with inertia gravity waves that are observed sporadically to propagate along the front. These waves have a relatively small wavelength (see figures 3d,f), their direction is aligned with the shear and they seem to be generated in regions of high strain. Their appearance is similar to the that shown in the simulations of Plougonven and Snyder (2005). The wavelength of these waves showed a tendency to increase with Ro number. Other experiments showed waves with the wave crests perpendicular to the front, similar to those shown by WHR.

The formation of vortices emerged from the interaction with the IG waves. While propagating faster than the large baroclinic waves, they moved up to the cusp of the baroclinic wave, where their breaking lead to intense mixing and the eventual formation of an intense vortex. The duration of this vortex formation took place in approximately a quarter rotation period, suggesting a possible mechanism for the formation of intense cyclones (see figure 3e).

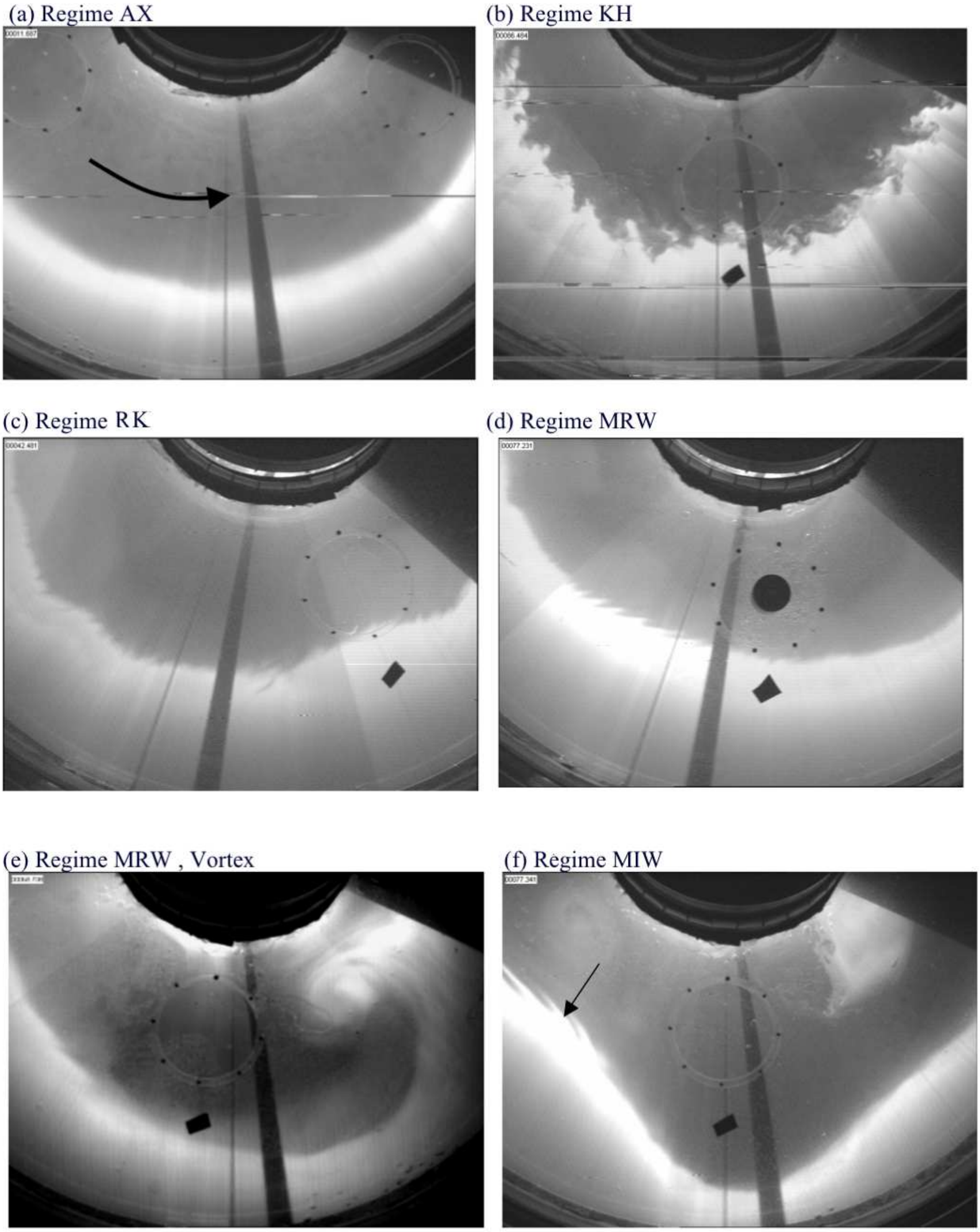

Figure 3: *Series of top view images, visualizing the characteristics of the different flow regimes. The arrow in figure a) indicates the direction of (cyclonic) rotation of the tank and disk at the surface. Experimental parameters are g' = 6 cm.s^{-2} and: a) F = 0.3 d = 0.018 ; b) F = 1.0 d = 0.024 ; c) F = 3.0 d =0.024 ; d) F = 3.2 d = 0.025 ; e) F =5.9, d=0.025; f) F = 20.4 d = 0.051*

4 Conclusions

These experimental results show that two layer flows in large annular tanks are more complicated because of additional instabilities, but the essential flow features observed in small tanks are preserved (see figure 2). Further, the experimental observations suggest spontaneously emitted IG waves near fronts in the baroclinic unstable regimes, in agreement with former experimental and numerical observations of WHR. The interaction of the IG waves with the front caused in some cases the formation of cyclonic vortices which confirms their capability of generating small scale turbulence near the front and their relevance to downscale energy transport in geophysical flows.

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