LABORATORY EXPERIMENTS ON MOUNTAIN INDUCED ROTORS

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We present here laboratory experiments on stratified flows over isolated obstacles which were aimed at the simulation of atmospheric rotors. The development of mountain induced rotors seems to be favoured by an elevated density inversion. This effect was introduced in our experiments as compared to the classical laboratory experiments with continuous stratification. In fact our experimental setup was guided by the simulations of Vosper (2004), which provided systematically the upstream conditions under which mountain rotors are expected. We were able to confirm the results from these numerical simulations over a wide range of parameters.

1. INTRODUCTION

The problem of mountain-induced rotors has received considerable interest in recent years, which cumulated in the large international field experiment T-REX (Grubisic et al, 2008). Also several numerical simulations on the formation of rotors have been published recently (e.g. Vosper 2004, Doyle and Durran 2007). Although much insight into the rotor problem has been gathered through these activities, some additional information might be provided by laboratory experiments in stratified towing tanks. This kind of research has been used frequently with respect to the lee wave problem (e.g. Eiff and Bonneton 2000), but not many systematic laboratory experiments on the rotor problem have been performed.

The mayor finding of recent numerical simulations that an elevated inversion above the mountain greatly supports the rotor formation has motivated our experimental work because this kind of stratification profile has not been used very often before.

2. EXPERIMENTAL SET UP

The experiments have been performed in the fluid dynamical facilities CNRM-GAME (METEO-FRANCE and CNRS) at Toulouse consisting of two towing tanks. The dimensions of the tanks are: length: 22 m, width: 3 m; height: 1 m (large tank) and 7 m x 0.8 m x 0.7 m (medium tank).

In both tanks we used a bell-shaped obstacle of 13 cm respectively 3.5 cm height. A picture of the tank and the schematic of towed obstacle is shown in Fig.1. The stratification was set up as guided by the simulations of Vosper (2004): A neutral bottom layer below a density jump $\Delta\rho$ at the height z_i (inversion heigth) followed by a linear density profile above ($N > 0$). In practice, inversion height and density jump were not as sharp as in the principle schematic in Fig. 2.

The simulations by Vosper have shown, that rotor formation depends on the non dimensional mountain height H/z_i and the inversion Froude number F_i defined as:

$$F_i = \frac{U}{\sqrt{g \frac{\Delta\rho}{\rho_0} z_i}}$$

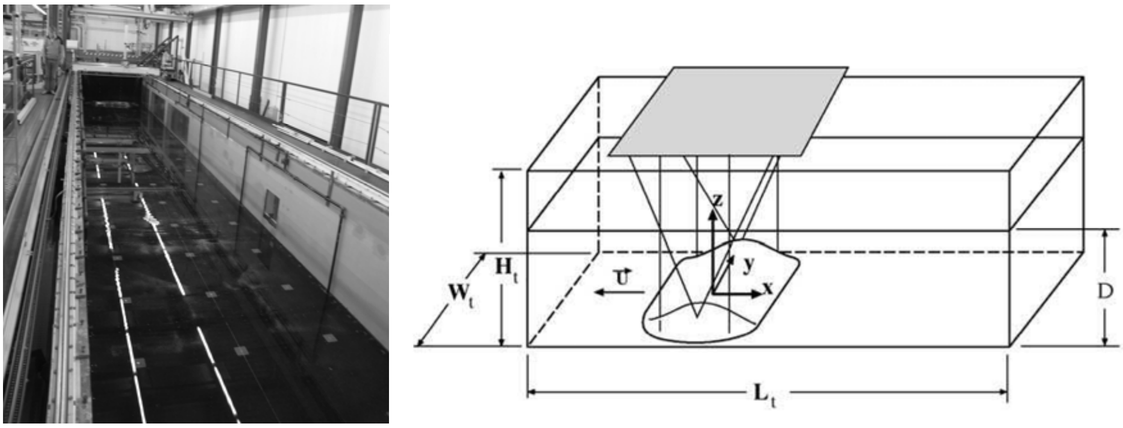

Figure 1: Large water tank (left), scheme of towing obstacle (right).

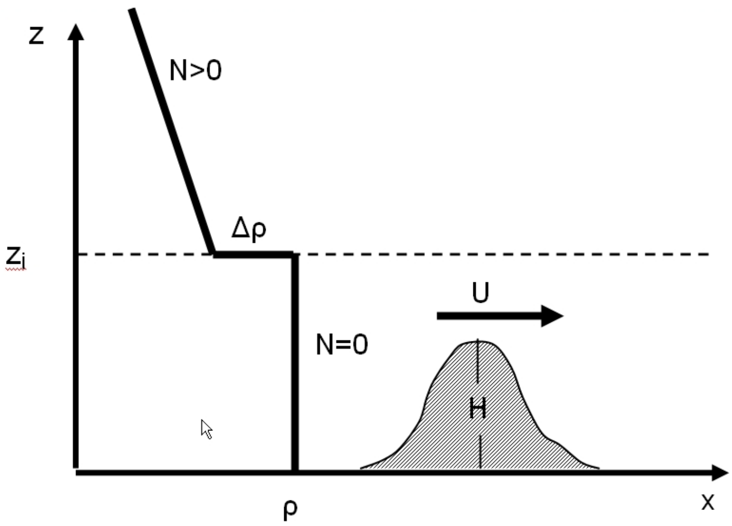

Figure 2: Schematic of the set up for the towing tank experiments.
The symbols are mentioned in the text.

The experiments were run for different combinations of F_i and H/z_i by varying the towing speed U, the inversion height z_i and the density jump $\Delta\rho$.

The documentation of the experiments was performed by different cameras making photos (for PIV and streak lines) and videos of the flow field. The velocity fields within lee waves and rotors were obtained by a PIV method. To get a quantitative impression of the flow, streak line photos were made. Due to the differences in the used laser systems (continuous laser in the large tank and pulsed laser in the medium tank), streakline photos could only be made in the large tank.

3. RESULTS

53 experiments in the medium tank and 26 experiments in the large tank have been performed for various combinations of the inversion Froude number F_i and the non-dimensional obstacle height H/z_i. The former were mainly used for checking the parameters under which rotors can be observed in the laboratory experiments and also helped us in preparing the experiments in the large tank, which were more complex to set up.

Here we present detailed analyses of the rotors flows only for the large towing tank, where the quality of the PIV pictures was better due to the bigger obstacle and hence the larger rotors. Also streakline photos could be made due to the continuous laser sheet.

All flow phenomena described in the simulations by Vosper (2004) have been found in the laboratory, which are lee waves, hydraulic jumps and rotors.

We define a rotor as a flow situation where there is a counter-rotating vortex behind the obstacle beneath the first wave crest. In the strict sense there should be also a near surface flow toward the obstacle (full rotor) but a stagnant fluid in this region might be also termed as rotor.

Figure 2 shows a rotor case for F_i = 0.51 and H/z_i = 0.65. A vortex structure under the wave crest can clearly be seen as indicated by somewhat chaotic behaviour of the streak lines (Fig. 3, left). This is also evident in the velocity field as obtained by a PIV (Fig. 3, right). A clear flow towards the obstacle can be observed in the layer close to the surface, which is even more evident in the zoom in Figure 4, where the velocity vectors are shown and only the flow component backwards toward the obstacle is shaded.

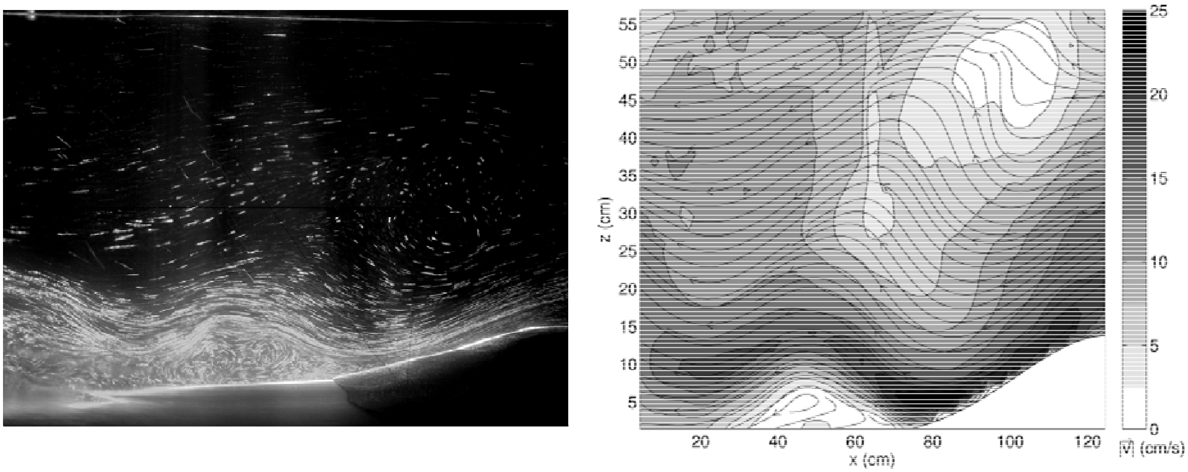

Figure 3: Observations of a rotor case for H/z_i= 0.65 and F_i= 0.51 showing part of the lee wave and a rotor below the crest. Flow is from left to right.
Left: Streak lines; right: Streamlines and velocity field.

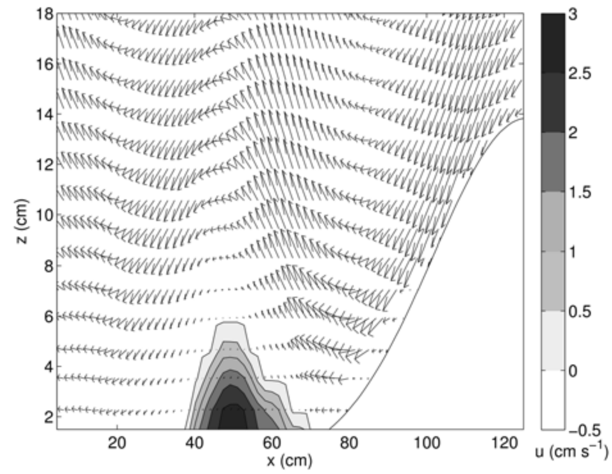

Figure 4: Close-up of the velocity field of the rotor case shown in Fig. 3.
The area of backward flow to the obstacle is shaded.

4. CONCLUSIONS

Our experiments guided by recent numerical simulations of Vosper (2004) confirm, that an elevated inversion is supporting the formation of rotors in the lee side of mountains, as was already indicated in numerical simulations mentioned above.

A flow regime diagram as in Vosper (2004) is showing the dependence of the observed phenomena (lee wave, rotor and hydraulic jump) of the relevant flow parameters F_i and H/z_i is presented in Fig.5. This is quite similar to the regime diagram obtained from numerical simulations by Vosper (2004). Further details of the results from our laboratory experiments will be published in Knigge et al. (2009).

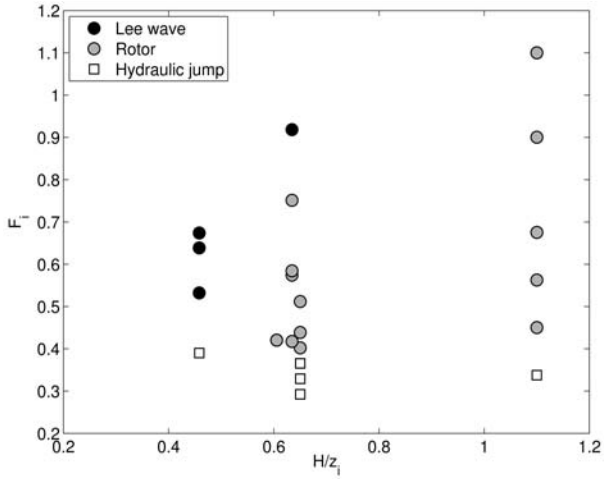

Figure 5: Flow regimes as observed in the experiments depending on F_i and H/z_i.

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