Stratified water tank experiments of lee wave and rotor development in flow over double ridges

I. Stiperski[1], H. Ágústsson[2], P.G. Baines[3], A. Belleudy[4], V. Grubišić[5], K. Horvath[6], C. Knigge[7], A. Paci[4], J. Sachsperger[8], S. Serafin[8], L. Strauss[8]

[1]University of Innsbruck, Institute of Meteorology and Geophysics, Innsbruck, Austria. [2]Icelandic Meteorological Office, Reykjavík, Iceland. [3]University of Melbourne, Department of Infrastructure Engineering, Melbourne, Australia.
[4]National Centre for Meteorological Research, Experimental & Instrumental Meteorology Department, Toulouse, France. [5]National Center for Atmospheric Research, Earth Observing Laboratory, Boulder CO, USA.
[6]Croatian Meteorological and Hydrological Service, Zagreb, Croatia. [7]Leibniz Universität Hannover, Institute of Meteorology and Climatology, Hannover, Germany.
[8]University of Vienna, Department of Meteorology and Geophysics, Vienna, Austria.

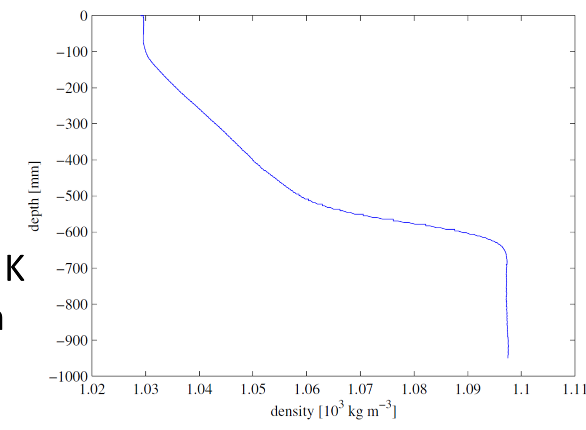
INTRODUCTION

- We study two-layer flow (lower neutral /upper stable layer), separated by a sharp density discontinuity. This type of layered flow over mountains is known to generate different responses: from hydraulic jumps to lee waves and highly turbulent rotors, i.e., vortices with horizontal axis parallel to the mountain (1).
- Direct observations of rotors are scarce. We run experiments in a large stratified water tank to extend the exploration of rotor formation to a broad range of flow regimes. We concentrate on flow over double obstacles (e.g., representative of valleys oriented across the flow) and explore the occurrence of wave interference phenomena (2).
- Using high-resolution reconstructions of the time-dependent 2D velocity field, we aim at reconstructing the flow field and, possibly, the distribution of turbulence within rotors (3).

Photos: Stratified water tank at CNRM-GAME in Tolouse, France. **Top**: View of the tank. The towing tank, reservoir, wave absorbers and towing carriage are visible. **Bottom**: Obstacle being towed (foreground). The reservoir in the background helps maintain the stratification profile approximately constant through many tests.

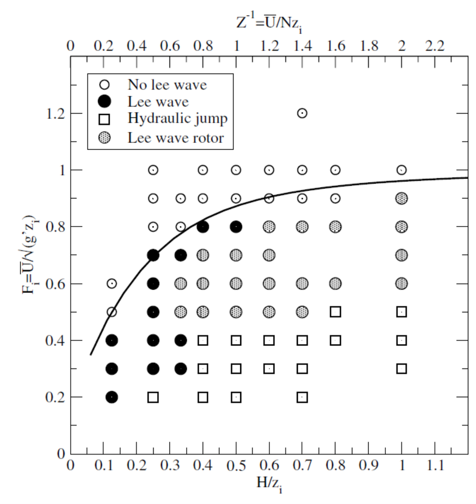
1 EXPERIMENTAL DESIGN

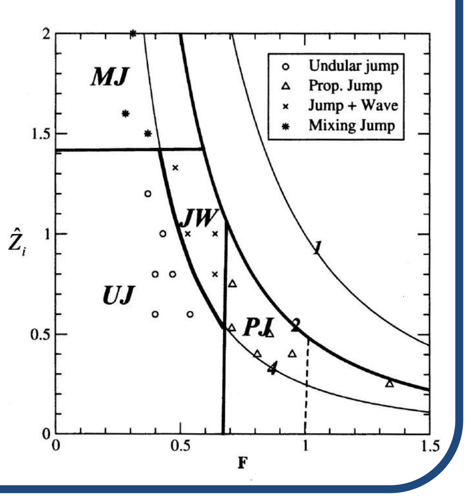
- The water tank size (22 x 3 x 1 m) and typical flow speeds (U ≈ 10 cm s^{-1}) allow to simulate high Reynolds number flows, O(10^5).
- A typical density profile in the tank is shown on the right: The density jump $\Delta\rho \approx 0.04$ kg/m^3 at height z_i, corresponds to $\Delta\vartheta \approx 12$ K in the atmosphere. N ≈ 0.8 s^{-1} above. This profile differs from both Long's laboratory and theoretical investigations [1] and Scorer's linear lee wave theory [2].



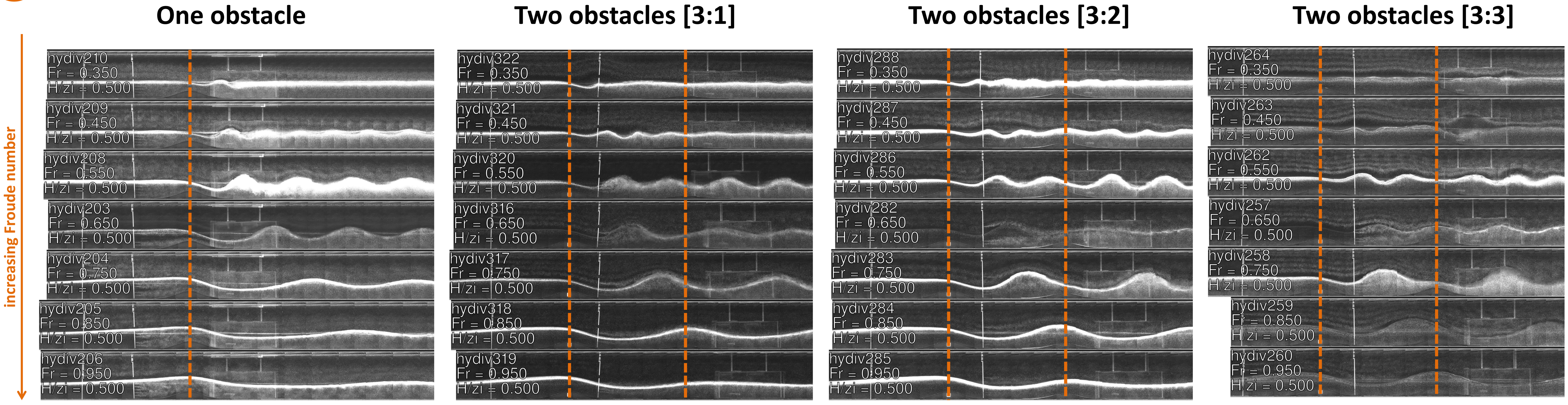
- Leeside flow response in the is governed by:
  - shallow-water Froude number ($F = U/\sqrt{g'z_i}$),
  - ratio obstacle height / inversion height (H/z_i),
  - non-dimensional inversion height ($Z = Nz_i/U$).

  (see diagrams on the right, [3] and [4]).
- When wave-induced pressure gradients are large, the boundary layer may separate from the surface. Rotors then form underneath trapped waves or undular hydraulic jumps.





2 FLOW OVER DOUBLE OBSTACLES



- These figures show the flow response over one and two obstacles of different height ratios. Images are created by stitching consecutive photos taken from a fixed camera, as the obstacles are towed in front of it. Laser light illuminates the tank from above and is diffused by neutrally buoyant particles dispersed in the fluid, mostly along the density jump.

INFLUENCE OF FROUDE NUMBER

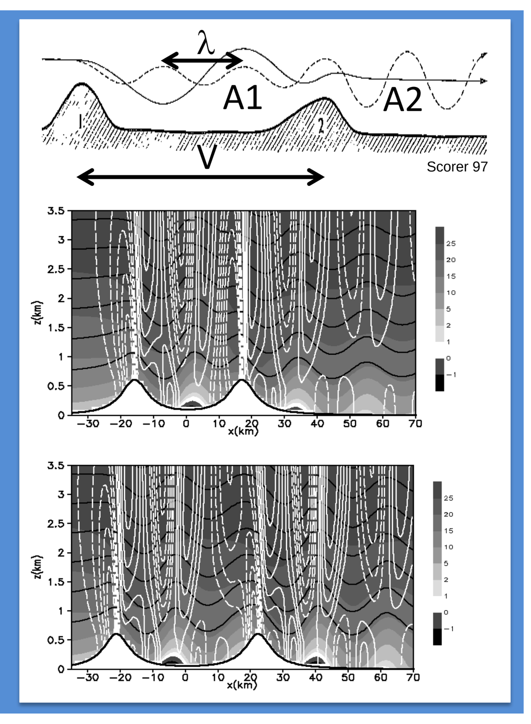
- With increasing Froude number, the flow response changes from undular jump to trapped lee waves.
- For intermediate Froude number, the response has the largest amplitude and rotors can form.
- Wave amplitude decreases and wavelength increases with the distance from the initial perturbation. This is attributed to wave energy absorption in the BL [5].

INFLUENCE OF THE SECOND OBSTACLE

- The height of the second obstacle modulates the amplitude and the length of the wave inside the valley and downstream of the second obstacle, facilitating rotor formation.
- For Fr > 0.5, the lee wavelength over double obstacles is considerably shorter than over the single obstacle.

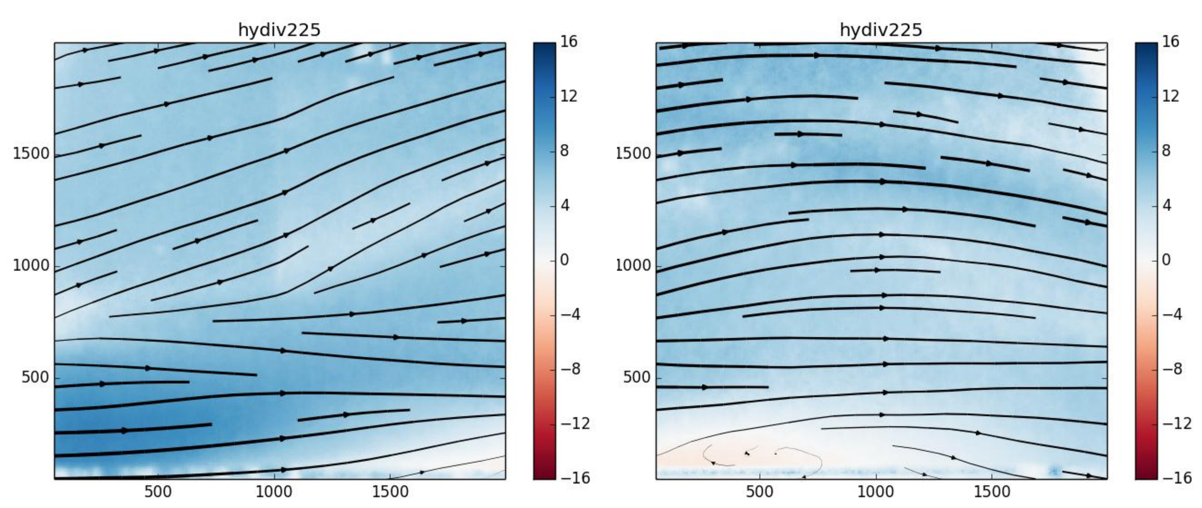
Theory of lee wave interference [6]

- Lee waves over double obstacles experience interference depending on the wavelength λ and on the obstacle distance V:
  - Constructive: V/λ is integer
  - Destructive: V/λ is half-integer
- Numerical simulations and aircraft observations confirm the existence of interference patterns.
- Linear theory predicts resonant wavelength well even with surface friction but nonlinear effects influence wave amplitudes and rotor strengths.
- Water tank experiments suggest that lee wave interference can be reproduced also in the laboratory.



3 PARTICLE IMAGE VELOCIMETRY

- These images are elaborated from photos taken from two mobile cameras (mounted side by side on the carriage and moving along with obstacle). Tracking the motion of particles between consecutive frames, the fluid velocity on a two-dimensional plane can be reconstructed (Particle Image Velocimetry, PIV).



- Adjacent snapshots of the flow field (u and streamlines) between two equal-height mountains.
- $H/z_i = 0.7$, F = 0.95.
- Distance and velocity scales are in pixels and pixels/s respectively.
- 1 cm ≈ 30 ± 2 pixels.

CONCLUSIONS AND OUTLOOK

- Here we present only 29 experiments out of a total of 395 performed.
- Experiments spanned different values of F, H/z_i, obstacle separation distance and secondary obstacle height.
- PIV analysis of all runs is currently in progress.
- A few of these experiments adopted experimental techniques other than PIV, e.g. synthetic Schlieren photography to estimate density perturbations induced in the propagating IGW in the stratified water above the density jumps.
- Ongoing investigations aim at:
  - Constructing phase diagrams for double obstacles of varying height and obstacle separation distances.
  - Test the theory of lee wave intereference.
  - Elucidate the role of secondary obstables on formation of rotors.
  - Look into the turbulence characteristics of rotors.
- After these experiments, the CNRM-GAME stratified water tank (actually a flume) was closed.

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Contact:
Stefano Serafin
University of Vienna
Department of Meteorology and Geophysics
Althanstraße 14 / UZA II, 1090 Vienna, Austria
Stefano.serafin@univie.ac.at